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HARMONICS REDUCTION USING NEURO FUZZY CONTROLLER FOR GRID CONNECTED DOUBLY FED INDUCTION WIND GENERATORS

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ABSTRACT

This paper proposes a new computational control strategy. The control and analysis of Doubly Fed InductionGenerators (DFIG) based wind turbines have been proposed. The dynamic modelling of DFIG wind turbine has been carried out at first with the conventional control strategies for both rotor side and grid-side converters. However, the conventional control strategies have their own limitations such as power control at very high wind speed or turbulence, unable to control harmonics within the permissible values and instability issues at critical conditions. These limitations are overcome by Neuro Fuzzy Control Algorithm.

A DFIG consists of a wound rotor induction generator with its stator windings. The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage sourceconverter that controls both the rotor and the grid currents. A Neuro Fuzzy Control schemewas presented where the harmonics was controlledto independently improvethe generated active and reactive power as well as the rotor speed to track the maximum wind power point.

The simulation results indicate that the active and reactive powers in the system are controlled effectively to maintain the grid power constant. This is primarily due to the many advantages doubly-fed induction generators offer over other types of generators in applications where the mechanical power provided by the prime mover driving the generator varies greatly. The control strategy is developed and simulation studies are carried out in MATLAB/Simulink.

INTRODUCTION

Wind energy has potential growth in the energy market and plays vital role to achieve the sustainable energy across the globe. Various control strategies for the speed and power control of wind turbines have been adopted and presented. These control strategies are used to control the smooth active power generated by wind turbine generator fed to power grids. However, the conventional control strategies have their own limitations such as power control at very high wind speed or turbulence, unable to control harmonics within the permissible values and instability issues at critical conditions. These limitations are overcome by intelligent controllers now-a-days in wind turbines. In this study, Neuro-Fuzzy control strategy for Doubly Fed Induction Generator (DFIG) based variable speed wind turbine has been presented to prove the ability of the proposed algorithm. Actual wind profile, grid code and generator characteristics have been considered as inputs for the simulation in this study. By using proposed control strategy, torque and current ripple are controlled and hence power loss is drastically reduced.

Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings. Most doubly-fed electric machines in industry today are three-phase wound-rotor induction machines. Doubly-fed induction generator s (DFIGs) are by far the most widely used type of doubly-fed electric machine, and are one of the most common types of generator used to produce electricity in wind turbines. Doubly-fed induction generators have a number of advantages over other types of generators when used in wind turbines. The primary advantage of

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doubly-fed induction generators when used in wind turbines is that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor. Because of this, doubly-fed induction generators can be directly connected to the ac power network and remain synchronized at all times with the ac power network.

AREA

This system deals with integration and neuro fuzzy based control algorithm for power management of wind energy source. Wind energy electric systems have been built in many places around the world. In rural and isolated areas, stand alone power systems are used. When conventional machines are used as generators in these isolated systems, the output voltage will be of variable magnitude and frequency. Synchronous and induction generators are widely used in wind energy systems. A DFIG consists of a wound rotor induction generator with its stator windings. The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. The Main objectives of the project are to manage power loss from the power system grid faults.

OBJECTIVE

The main objective of the Neuro-Fuzzy based control to design a global optimal controller to deal with the time-varying grid faults and nonlinear characteristic of the DFIG-WT. The primary reason for using a doubly-fed induction generator is generally to produce three-phase voltage whose frequency of stator is constant, i.e., whose stator frequency remains equal to the frequency of network of the ac power network to which the generator is connected, despite variations in the generator rotor speed caused by fluctuations of the mechanical power provided by the wind turbine rotor driving the generator. To achieve this purpose, the frequency of rotor of the ac currents fed into the rotor windings of the doubly-fed induction generator must be continually adjusted to counteract any variation in the rotor speed caused by fluctuations of the mechanical power provided by the prime mover driving the generator. Wind turbines (WTs) can either operate at fixed speed or variable speed.

For a fixed speed wind turbine the generator is directly connected to the electrical grid. For a variable speed wind turbine the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines; among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power. These large wind turbines are all based on variable-speed operation with pitch control using a direct driven a doubly-fed induction generator. The main objective of this system is the fault detection using Neuro-Fuzzy Algorithm.

PROPOSED SYSTEM

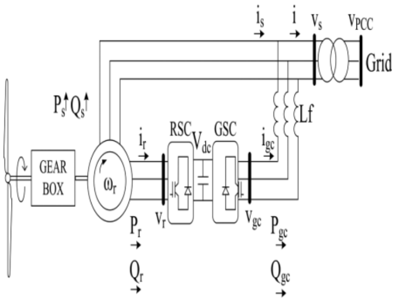
The proposed system deals with the control and analysis of Doubly Fed Induction Generators (DFIG) based wind turbines (DFIG-WT).The DFIG-WT is one of the mostly employed wind power generation systems (WPGS), due to its merits including variable speed operation for achieving the maximum power conversion, smaller capacity requirement for power electronic devices, and full controllability of active and reactive powers of the DFIG. The dynamic modelling of DFIG-WT has been carried out at first with the conventional control strategies for both rotor-side and grid-side converters. This control strategy works in a synchronous reference frame, aligned with the stator-flux vector, became very popular for control of the DFIG. Compared with other control methods which are designed based on linear model obtained from one operation point, nonlinear control methods can provide consistent optimal performance across the operation envelope rather than at one operation point. To provide satisfactory performance under voltage sags caused by grid faults or load disturbance of the grid, input-output feedback linearization control has been applied to develop a fully decoupled controller of the active and reactive powers of the DFIG using Neuro-Fuzzy control algorithm. This control strategy also proposed for power regulation of DFIG-WT, which can provide better performance against the varying operation points and grid disturbance.

EXISTING SYSTEM

A new computational intelligence based control strategy has developed, to enhance the low voltage ride-through capability of grid-connected wind turbines (WTs) with doubly fed induction generators (DFIGs). Grid codes world-wide require that WTs should supply reactive power to the grid during and after the fault, in order to support the grid voltage. The conventional crowbar-based systems that were initially applied in order to protect the rotor-side converter at the occurrence of grid faults, do not fulfill this requirement, as during the connection of the crowbar, the DFIG behaves as a squirrel cage machine, absorbing reactive power from the grid. This control scheme, achieving an optimal coordination between the two converters, manages to attenuate the system disturbances caused by the fault, even in the case where the WT feeds a relatively weak ac grid.

As the control system has to act efficiently in a very short period of time, it should be insensitive to the measurement noise and to the lack of accurate information concerning the machine parameters. In order to encounter these difficulties and considering the nonlinearity of the system, the controllers were designed based on fuzzy control system. This drawback led to the design of control systems that eliminate or even avoid the use of the crowbar. In order to conform to the above-mentioned requirement, this paper proposes a coordinated control strategy of the DFIG converters during a grid fault, managing to ride-through the fault without the use of any auxiliary hardware. The coordination of the two controllers is achieved via a fuzzy controller which is properly tuned using genetic algorithms. To validate the proposed control strategy, a case study of a 1.5-MW DFIG supplying a relatively weak electrical system is carried out by simulation.

BLOCK DIAGRAM



Block diagram of existing system

The Fig shows the schematic diagram of a grid connected DFIG WT. The WT is connected to the DFIG through a mechanical shaft system, which consists of a low speed turbine shaft connected to the high speed generator shaft via a gearbox. The DFIG consists of a wound rotor induction generator with its stator windings directly connected to the grid and its rotor windings connected to the grid via an arrangement of two ac/dc back-to-back converters, as depicted in Fig 2.1. The rotor side converter (RSC) and the grid side converter (GSC) are pulse width modulated (PWM), IGBT voltage-source converters (VSCs). A synchronously rotating d-q reference frame has been selected to model the dynamic behaviour of the DFIG. This system would normally be combined with an auxiliary hardware such as a crowbar.

The conventional DFIG control system, presented in several papers, is divided to RSC control and GSC control. Its objective is to independently regulate the stator active and reactive power. The reference value of the active power is obtained using a maximum power tracking (MPPT) technique. The measured value of stator active power is subtracted from reference power and the error is driven to the power controller. The output of this controller is the reference value of the q-axis rotor current. This signal is compared to the actual value of q axis rotor current and the error is passed through the current controller whose output is the reference voltage for the q-axis component.

The reactive-power control of RSC can be tuned to keep the stator voltage within the desired range, when the DFIG feeds into a weak power system without any local reactive compensation. When the DFIG feeds a weak ac grid, ac voltage control is used instead of reactive power control. The actual stator voltage at the generator terminals is compared to its reference stator voltage value and the error is passed through the AC voltage controller to generate the reference signal for the d-axis current. This signal is compared to the d-axis current value and the error is sent to the current controller, which determines the reference voltage for the d-axis component. The rotor d-axis and q-axis signals are transformed back to abc quantities which are used by the PWM module to generate the IGBT gate control signals to drive the RSC. The objective of the GSC control system is mainly to keep the dc-link voltage constant. Reactive power is designed neutral by setting grid reactive power zero. This control scheme, achieving an optimal coordination between the two converters, manages to attenuate the system disturbances caused by the fault, even in the case where the WT feeds a relatively weak ac grid.

DISADVANTAGES

- Produce heat which damages the device
- Sudden change in stator flux
- Leads over-current due to magnetic coupling, damages occurs
- partial loss of power control during the crowbar action in RSC
- Poor efficiency
- Large transients are generated after the fault, which may lead to the disconnection of the machines from the grid

EXPLAINATION OF PROPOSED SYSTEM

The aim of the proposed system is to evaluate the use of power system fault detection of doubly fed induction generator with the integration of Neuro-Fuzzy control algorithm. A control strategy for Doubly Fed Induction Generator in which stator is directly connected to grid, but the rotor terminals are connected to grid via power converter. The need for renewable energy sources for electric power generation has been increased due to limitations in the conventional power generations such as decreasing reserves and adverse effect on the environment. Among all the renewable energy sources the contribution of the wind energy conversion system (WECS) is effective and it is reliable energy resource. The wind is fluctuating in nature and needs variable speed generator and it is most acceptable for WECS. When conventional machines are used as generators in these isolated systems, the output voltage will be of variable magnitude and frequency. Power electronic converters are then necessary to obtain a constant frequency supply.

Synchronous and induction generators are widely used in wind energy systems and each type of these machines has its own advantages and disadvantages and also its own methods of control. This control, whether mechanical or electrical, is necessary to obtain a voltage of constant magnitude and frequency which can be connected to the grid. 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. In the wind driven DFIG, the stator terminals is directly connected to the grid, but the rotor terminals are connected to the grid through a variable frequency AC/DC/AC converter. 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. Fuzzy logic is used to control both the active, and reactive power generation. The 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. The error signal of the controlled variable was the single variable used as an input to the fuzzy system. 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 control technique is proposed to effectively tune the MFs of the fuzzy logic controller while allowing independent control of the DFIG speed, active, and reactive power. DFIG based wind turbines is chosen in such a way that to achieve bi-directional real and reactive power flow. The proposed Neuro-Fuzzy 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 two-axis (direct and quadrature axes) dynamic machine model is chosen to model the wind-driven DFIG due to the dynamic nature of the application. Since the machine performance significantly depends on the saturation conditions, both main flux and leakage flux saturations have been considered in the induction machine modelling. A Neuro-Fuzzy control scheme was presented where the rotor side voltage source converter was controlled to independently control the generated active and reactive power as well as the rotor speed to track the maximum wind power point. The wind generator mathematical model and control strategy is developed and simulation studies are carried out in MATLAB/Simulink. The simulation results indicate that the active and reactive powers in the system are controlled effectively to maintain the grid power constant.

DOUBLY FED INDUCTION GENERATOR (DFIG)

Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings. Most doubly-fed electric machines in industry today are three-phase wound-rotor induction machines. Although their principles of operation have been known for decades, doubly-fed electric machines have only recently entered into common use. This is due almost exclusively to the advent of wind power technologies for electricity generation. Doubly-fed induction generators (DFIGs) are by far the most widely used type of doubly-fed electric machine, and are one of the most common types of generator used to produce electricity in wind turbines. Doubly-fed induction generators have a number of advantages over other types of generators when used in wind turbines. The primary advantage of doubly-fed induction generators when used in wind turbines is that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor. Because of this, doubly-fed induction generators can be directly connected to the ac power network and remain synchronized at all times with the ac power network.

Other advantages include the ability to control the power factor (e.g., to maintain the power factor at unity), while keeping the power electronics devices in the wind turbine at a moderate size. This manual covers the operation of doubly-fed induction generators, as well as their use in wind turbines. It also covers the operation of three-phase wound-rotor induction machines used as three-phase synchronous machines and doubly-fed induction motors. Although it is possible to use these machines by themselves, they are primarily studied as a stepping stone to doubly-fed induction generators. A three-phase wound-rotor induction machine can be set up as a doubly-fed induction motor. In this case, the machine operates like a synchronous motor whose synchronous speed (i.e., the speed at which the motor shaft rotates) can be varied by adjusting the rotor frequency of the ac currents fed into the rotor windings.

The same wound-rotor induction machine setup can also serve as a doubly-fed induction generator. In this case, mechanical power at the machine shaft is converted into electrical power supplied to the ac power network via both the stator and rotor windings. Furthermore, the machine operates like a synchronous generator whose synchronous speed (i.e., the speed at which the generator shaft must rotate to generate power at the ac power network rotor frequency) can be varied by adjusting the frequency of the ac currents fed into the rotor windings. The remainder of this exercise discussion deals with the operation of three-phase wound-rotor induction machines used as doubly-fed induction generators. The same operating principles apply in a doubly-fed induction generator as in a conventional (singly-fed) induction generator.

The only difference is that the magnetic field created in the rotor is not static (as it is created using three-phase ac current instead of dc current), but rather rotates at a rotor speed proportional to the frequency of the ac currents fed into the generator rotor windings. This means that the rotating magnetic field passing through the generator stator windings not only rotates due to the rotation of the generator rotor, but also due to the rotational effect produced by the ac currents fed into the generator rotor windings. Therefore, in a doubly-fed induction generator, both the rotation speed of the rotor and the frequency of the ac currents fed into the rotor windings determine the speed of the rotating magnetic field passing through the stator windings, and thus, the frequency of the alternating voltage induced across the stator windings.

The frequency f_{stator} of the voltages induced across the stator windings of the generator can thus be calculated using the following equation:

$$f_{Stator} = \frac{n_{Rotor} \times N_{Poles}}{120} + f_{Rotor} \qquad \textbf{(5.1)}$$

Principle of Doubly Fed Induction Generator for Wind Turbines

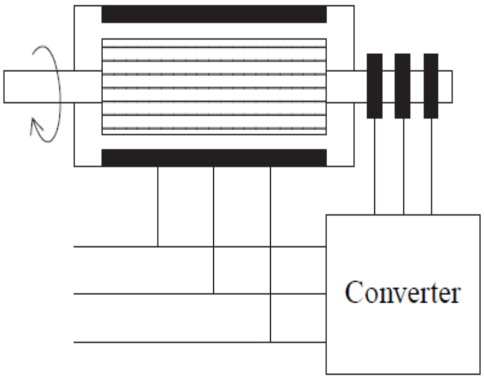


Fig Principle of Doubly Fed Induction Generator

For variable-speed systems with limited variable-speed range, the DFIG can be an interesting solution. As mentioned earlier the reason for this is that power electronic converter only has to handle a fraction (20–30%) of the total power. This means that the losses in the power electronic converter can be reduced compared to a system where the converter has to handle the total power. In addition, the cost of the converter becomes lower. The stator circuit of the DFIG is connected to the grid while the rotor circuit is connected to a converter via slip rings, see Fig.

USING DOUBLY-FED INDUCTION GENERATORS TO PRODUCE FIXED-FREQUENCY VOLTAGES

The primary reason for using a doubly-fed induction generator is generally to produce three-phase voltage whose stator frequency is constant, i.e., whose stator frequency remains equal to the frequency of the ac power network to which the generator is connected, despite variations in the generator rotor speed caused by fluctuations of the mechanical power provided by the prime mover (e.g., a wind turbine rotor) driving the generator. To achieve this purpose, the frequency of the ac currents fed into the rotor windings of the doubly-fed induction generator must be continually adjusted to counteract any variation in the rotor speed caused by fluctuations of the mechanical power provided by the prime mover driving the generator. The frequency f_{Rotor} of the ac currents that need to be fed into the doubly-fed induction generator rotor windings to maintain the generator output frequency f_{stator} at the same value as the stator frequency $f_{Network}$ of the ac power network depends on the rotation speed of the generator rotor n_{Rotor}, and can be calculated using the following equation:

$$f_{Rotor} = f_{Network} - \frac{n_{Rotor} \times N_{Poles}}{120} \tag{5.2}$$

Where,

f_{Rotor} is the frequency of the ac currents that need to be fed into the doubly-fed induction generator rotor windings for f_{stator} to be equal to $f_{Network}$, expressed in hertz (Hz).

$f_{Network}$ is the frequency of the ac power network to which the doubly fed induction generator is connected, expressed in hertz (Hz).

n_{Rotor} is the rotational speed of the generator rotor, expressed in rotations per minute (r/min).

N_{Poles} is the number of magnetic poles per phase in the doubly-fed induction generator.

The rotor frequency of AC current to be fed into generator rotor winding, so that the frequency f_{Rotor} of the generator output voltage is equal to the frequency $f_{Network}$ of the ac power network. The negative polarity of the frequency f_{Rotor} indicates that the magnetic field created in the rotor windings must rotate in the direction opposite to the direction of the rotor. When a doubly-fed induction generator is used to produce power at the ac power network voltage and frequency, any deviation of the generator rotor speed n_{Rotor} from the synchronous speed n_s is compensated by adjusting the frequency $f_{Rotor}$of the ac currents fed into the generator rotor windings so that the frequency f_{Stator} of the voltage produced at the stator remains equal to the ac power network frequency $f_{Network}$. In other words, the frequency f_{Rotor} is adjusted so that the speed $n_{\varphi,stator}$ of the rotating magneting field passing through the stator windings remains constant. Consequently, to maintain the voltage produced at the stator equal to the ac power network voltage, a specific magnetic flux value must be maintained in the machine (more precisely at the stator windings). This can be achieved by applying a voltage to the generator rotor windings that is proportional to the frequency of the voltages applied to the rotor windings (this maintains the V/f ratio constant and ensures a constant magnetic flux value in the machine). The value of the V/f ratio is generally set so that the reactive power at the stator Q_{stator} is equal to zero. This is similar to the common practice used with conventional (singly-fed) synchronous generators where the exciter current (dc current in the rotor) is adjusted so as to zero the reactive power at the stator Q_{stator}.

DOUBLY-FED INDUCTION GENERATORS USED IN WIND TURBINES

Most doubly-fed induction generators in industry today are used to generate electrical power in large (power-utility scale) wind turbines. This is primarily due to the many advantages doubly-fed induction generators offer over other types of generators in applications where the mechanical power provided by the prime mover driving the generator varies greatly (e.g., wind blowing at variable speed on the bladed rotor of a wind turbine). To better understand the advantages of using doubly-fed induction generators to generate electrical power in wind turbines, however, it is important to know a little about large-size wind turbines. Large-size wind turbines are basically divided into two types which determine the behaviour of the wind turbine during wind speed variations: fixed-speed wind turbines and variable-speed wind turbines. In fixed-speed wind turbines, three phase asynchronous generators are generally used. Because the generator output is tied directly to the grid (local ac power network), the rotation speed of the generator is fixed and so is the rotation speed of the wind turbine rotor. Any fluctuation in wind speed naturally causes the mechanical power at the wind turbine rotor to vary and, because the rotation speed is fixed, this causes the torque at the wind turbine rotor to vary accordingly.

Whenever a wind gust occurs, the torque at the wind turbine rotor thus increases significantly while the rotor speed varies little. Therefore, every wind gust stresses the mechanical components (notably the gear box) in the wind turbine and causes a sudden increase in rotor torque, as well as in the power at the wind turbine generator output. Any fluctuation in the output power of a wind turbine generator is a source of instability in the power network to which it is connected.

Fig circuit topology of DFIG in variable speed wind turbine

The power electronics devices used in doubly-fed induction generators, on the other hand, need only to process a fraction of the generator output power, i.e., the power that is supplied to or from the generator rotor windings, which is typically about 30% of the generator rated power. Consequently, the power electronics devices in variable-speed wind turbines using doubly-fed induction generators typically need only to be about 30% of the size of the power electronics devices used for comparatively sized three-phase synchronous generators. This reduces the cost of the power electronics devices, as well as the power losses in these devices.

The doubly-fed induction generators allow the generator output voltage and frequency to be maintained at constant values, no matter the generator rotor speed, By adjusting the amplitude and frequency of the ac currents fed into the generator rotor windings, it is possible to keep the amplitude and frequency of the voltages (at stator) produced by the generator constant, despite variations in the wind turbine rotor speed (and, consequently, in the generator rotation speed) caused by fluctuations in wind speed. By doing so, this also allows operation without sudden torque variations at the wind turbine rotor, thereby decreasing the stress imposed on the mechanical components of the wind turbine and smoothing variations in the amount of electrical power produced by the generator.

Using the same means, it is also possible to adjust the amount of reactive power exchanged between the generator and the ac power network. This allows the power factor of the system to be controlled (e.g., in order to maintain the power factor at unity). Finally, using a doubly-fed induction generator in variable-speed wind turbines allows electrical power generation at lower win wind speeds than with fixed-speed wind turbines using an asynchronous generator. f_{Rotor} is the frequency of the ac currents that need to be fed into the doubly-fed induction generator rotor windings for f_{stator} to be equal to $f_{Network}$, expressed in hertz (Hz).

DYNAMIC MODEL OF DFIG

Nowadays doubly fed induction machine has been widely used in WPGS. These types of machines can be used resolutely as a generator or a motor. Though demands as motor is less because of its mechanical wear at the slip rings but they have gained their prominence for generator application in wind and hydro power plant because of its obvious adoptability capacity and nature of controllability of power. In this section, detailed model of DFIG has been given.

STATE SPACE MODEL IN THE A-B-C NATURAL FRAME

The DFIM is provided with laminated stator and rotor cores with uniform slots in which three-phase winding are placed as shown in Figure. Usually, the rotor winding is connected to copper slip-rings. Brushes on the stator collect the rotor currents from the rotor-side static power converter.

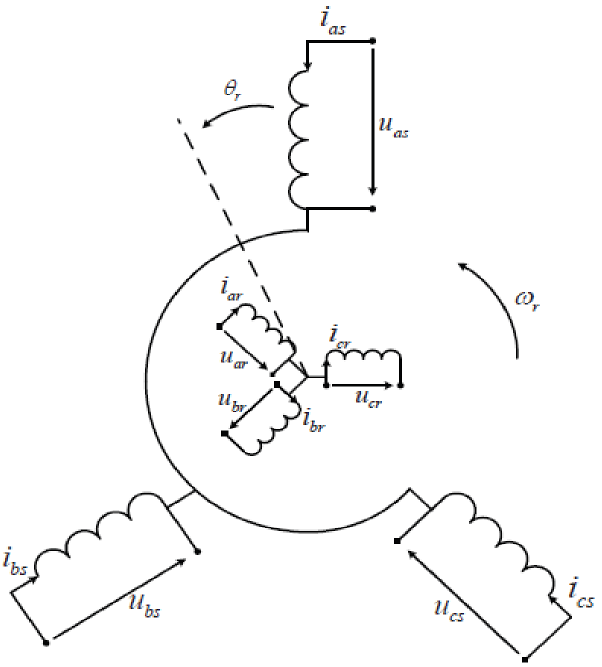


Fig DFIM Phase Circuits

For the time being, the resistances of slip-ring-brush system are lumped into rotor phase resistances, and the converter is replaced by an ideal controllable voltage source. The three-phase model of a DFIG can be described as:

$$\begin{cases} u_{as} = \dfrac{d\psi_{as}}{dt} + i_{as}R_s \\ u_{bs} = \dfrac{d\psi_{bs}}{dt} + i_{bs}R_s \\ u_{cs} = \dfrac{d\psi_{cs}}{dt} + i_{cs}R_s \end{cases}$$

(5.3)

$$\begin{cases} u_{ar} = \dfrac{d\psi_{ar}}{dt} + i_{ar}R_r \\ u_{br} = \dfrac{d\psi_{br}}{dt} + i_{br}R_r \\ u_{cr} = \dfrac{d\psi_{cr}}{dt} + i_{cr}R_r \end{cases}$$

(5.4)

where i_{as}, i_{bs}, i_{cs} are the three-phase stator currents; i_{ar}, i_{br}, i_{cr} are the three-phase rotor currents; u_{as}, u_{bs}, u_{cs} are the three-phase stator voltages; u_{ar}, u_{br}, u_{cr} are the three-phase rotor voltages; ψ_{as}, ψ_{bs}, ψ_{cs} are the three-phase stator flux linkages; ψ_{r}, ψ_{br}, ψ_{cr} are the three-phase rotor flux linkages; R_s and R_r are stator and rotor resistances.

WIND ENERGY SYSTEM

Wind energy has become the least expensive renewable energy technology in existence. The wind turbine is the first and foremost element of wind power systems. Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it to rotating mechanical power. The number of blades is normally three.

AERODYNAMIC POWER CONTROL

At high wind speeds it is necessary to limit the input power to the wind turbine, i.e., aerodynamic power control. There are three major ways of performing the aerodynamic power control, i.e., by stall, pitch, or active stall control. Stall control implies that the blades are designed to stall in high wind speeds and no pitch mechanism is thus required. Pitch control is the most common method of controlling the aerodynamic power generated by a turbine rotor, for newer larger wind turbines. Almost all variable-speed wind turbines use pitch control. Below rated wind speed the turbine should produce as much power as possible, i.e., using a pitch angle that maximizes the energy capture. Above rated wind speed the pitch angle is controlled in such a way that the aerodynamic power is at rated.

In order to limit the aerodynamic power, at high wind speeds, the pitch angle is controlled to decrease the angle of attack, i.e., the angle between the chord line of the blade and the relative wind direction. It is also possible to increase the angle of attack towards stall in order to limit the aerodynamic power. This method can be used to fine-tune the power level at high wind speeds for fixed-speed wind turbines. As in a variable-speed wind turbine, the generator is controlled by power electronic equipments, which makes it possible to control the rotor speed to maximize the energy conversion efficiency. In this way, the power fluctuations caused by wind variations can be absorbed by changing the rotor speed. Thus power variation originating from the wind variations and the stress of the drive train can be reduced.

AERODYNAMIC CONVERSION

Some of the available power in the wind is converted by the rotor blades to mechanical power acting on the rotor shaft of the WT. For steady-state calculations of the mechanical power from a wind turbine, the so called *Cp* (*λ, β*)-curve can be used.

The mechanical power, P_{mech}, can be determined by:

$$P_{\text{mech}} = \frac{1}{2}\rho A_r C_p(\lambda, \beta) w^3 \quad (5.5)$$

$$\lambda = \frac{\Omega_r r_r}{w} \quad (5.6)$$

WIND TURBINE SYSTEMS

Wind turbines can operate with either fixed speed (actually within a speed range about 1 %) or variable speed. For fixed-speed wind turbines, the generator (induction generator) is directly connected to the grid. Since the speed is almost fixed to the grid frequency, and most certainly not controllable, it is not possible to store the turbulence of the wind in form of rotational energy. Therefore, for a fixed-speed system the turbulence of the wind will result in power variations, and thus affect the power quality of the grid. For a variable-speed wind turbine the generator is controlled by power electronic equipment, which makes it possible to control the rotor speed. In this way the power fluctuations caused by wind variations can be more or less absorbed by changing the rotor speed and thus power variations originating from the wind conversion and the drive train can be reduced. Hence, the power quality impact caused by the wind turbine can be improved compared to a fixed-speed turbine. The rotational speed of a wind turbine is fairly low and must therefore be adjusted to the electrical frequency. This can be done in two ways: with a gearbox or with the number of pole pairs of the generator. The number of pole pairs sets the mechanical speed of the generator with respect to the electrical frequency and the gearbox adjusts the rotor speed of the turbine to the mechanical speed of the generator.

FIXED-SPEED WIND TURBINE

For the fixed-speed wind turbine the induction generator is directly connected to the electrical grid according to Fig. The rotor speed of the fixed-speed wind turbine is in principle determined by a gearbox and the pole-pair number of the generator. The fixed-speed wind turbine system has often two fixed speeds. This is accomplished by using two generators with different ratings and pole pairs, or it can be a generator with two windings having different ratings and pole pairs. This leads to increased aerodynamic capture as well as reduced magnetizing losses at low wind speeds.

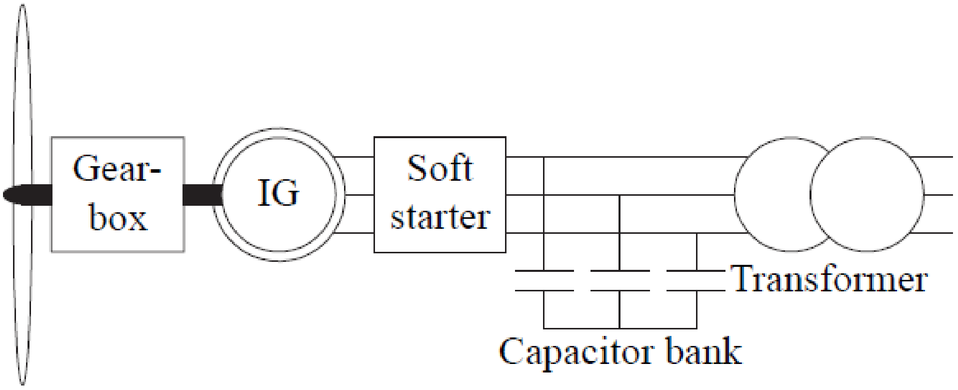


Fig Fixed-speed wind turbine

VARIABLE-SPEED WIND TURBINE

The system presented in Fig. consists of a wind turbine equipped with a converter connected to the stator of the generator. The generator could either be a cage-bar induction generator or a synchronous generator. The gearbox is designed so that maximum rotor speed corresponds to rated speed of the generator. Synchronous generators or permanent-magnet synchronous generators can be designed with multiple poles which imply that there is no need for a gearbox. Since this “full-power” converter/generator system is commonly used for other applications, one advantage with this system is its well-developed and robust control.

$$P_m = 0.5\rho A C_p (\lambda, \beta) v_w^3 \quad (5.7)$$

Where ρ - air density, A - rotor swept area, $Cp\ (\lambda, \beta)$ - power coefficient function, λ - tip speed ratio, β - pitch angle, w -wind speed.

Wind turbine can be modelled based on the steady-state power characteristics. In per unit (pu system), equation (5.7) can be written as:

$$P_{m\ pu} = K_p\ C_{p\ pu}\ V_{w\ pu}^{3} \quad (5.8)$$

Where, P_m pu is the power in pu of nominal power for particular values of ρ and A, Kp is the power gain which is equal to 1 pu, Cp pu is the performance coefficient in pu of the maximum value of Cp, V_w is the wind speed in pu of the base wind speed.

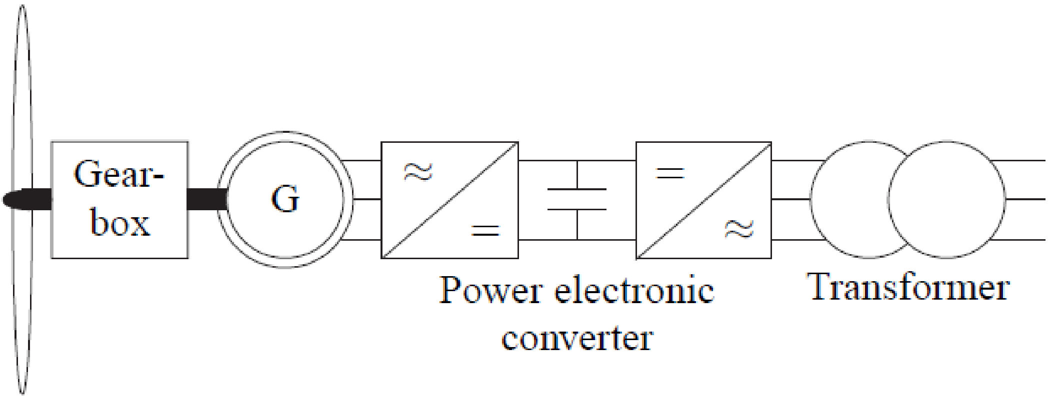


Fig Variable-speed wind turbine

This mechanical power is delivered to the rotor of an electric generator where this energy is converted to electrical energy.

The mechanical power that is generated by the wind is given by:

Wind is a form of solar energy and it is available everywhere. Always wind blows from a higher atmospheric pressure region to the lower atmospheric pressure region due to the non uniform heat by the sun and due to the rotation of the earth. In other wards we can say that wind is a form of solar energy available in the form of that kinetic energy of air.

Wind energy can change into many form of energy, such as wind turbine is used to generate electricity, mechanical power windmills for water lifting wind pumps, also in propelling ships. Wind energy is capable of supplying large amount of power and the total amount of obtainable power available from the wind is considerably more than the present human power used from all the sources. Wind power is an alternative of fossil fuels, is plenteous, widely expanded, clean, and renewable and during operation no greenhouse gas produced. Wind power is the fast growing source of energy. Day by day, the development of the wind energy improving and if it is use properly then it is capable to fulfil the growing demand of the consumer, also growing of the force acting on blades moving through air. There is also development of turbines with two or three blades. For successful electricity generation high speed and high efficiency of turbines were the necessary conditions. By using the power of the wind turbines produce electricity by drive an electrical generator. A moving force is exerted and generates lift when wind is passing over the blades.

The rotating blades rotate the shaft which is connected with the gearbox. The gearbox adjusts the rotational speed which is convenient for the generator to get a desired output. There are two primary physical principles by which energy can be extracted from the wind; these are through the creation of either lift or drag force (or through a combination of the two). The difference between drag and lift is illustrated by the difference between using a spinnaker sail, which fills like a parachute and pulls a sailing boat with the wind, and a Bermuda rig, the familiar triangular sail which deflects with wind and allows a sailing boat to travel across the wind or slightly into the wind. Drag forces provide the most obvious means of propulsion, these being the forces felt by a person (or object) exposed to the wind. Lift forces are the most efficient means of propulsion but being more subtle than drag forces are not so well understood.

The basic features that characterize lift and drag are:

- Drag is in the direction of air flow
- Lift is perpendicular to the direction of air flow
- Generation of lift always causes a certain amount of drag to be developed
- With a good aerofoil, the lift produced can be more than thirty times greater than the drag
- Lift devices are generally more efficient than drag devices

From the swept area of the blades a wind turbine extracts kinetic energy. So the power contained in the wind is given by the kinetic energy of the flowing air mass per unit time. The above equation is for power available in the wind, but it is different from power transferred from the wind turbine. The power available and the power transform are different by the factor of power coefficient. So the aerodynamic power generated by wind turbine is given by

$$P = 0.5\rho A c_p V_w^3 \quad (5.9)$$

The power coefficient (Cp) is a nonlinear function that represents the efficiency of the wind turbine to convert wind energy into mechanical energy. It is dependent on two variables, the tip speed ratio (TSR) and the pitch angle. The TSR, λ, refers to a ratio of the turbine angular speed over the wind speed. The mathematical representation of the TSR is given by equation. The pitch angle, β, refers to the angle in which the turbine blades are aligned with respect to its longitudinal axis.

Because the TSR is a ratio between the turbine rotational speed and the wind speed, it follows that each wind speed would have a different corresponding optimal rotational speed that gives the optimal TSR.

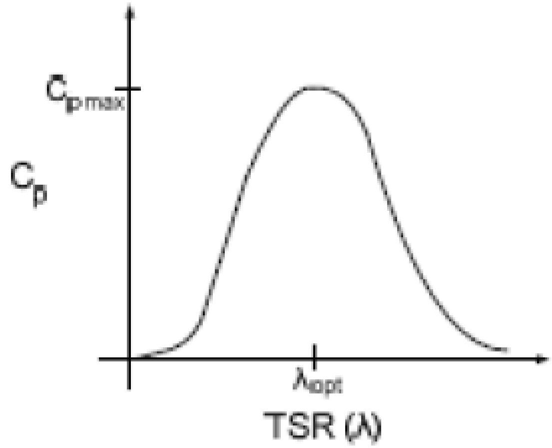


Fig Power Coefficient curve for a typical wind turbine

For each turbine there is an optimal TSR value that corresponds to a maximum value of the power coefficient (Cp, max) and therefore the maximum power. Therefore by controlling rotational speed, (by means of adjusting the electrical loading of the turbine generator) maximum power can be obtained for different wind speeds. The wind systems that exist over the earth's surface are a result of variations in air pressure. These are in turn due to the variations in solar heating. Warm air rises and cooler air rushes in to take its place. Wind is merely the movement of air from one place to another. There are global wind patterns related to large scale solar heating of different regions of the earth's surface and seasonal variations in solar incidence.

There are also localized wind patterns due the effects of temperature differences between land and seas, or mountains and valleys. Wind speed generally increases with height above ground. This is because the roughness of ground features such as vegetation and houses cause the wind to be slowed. Wind speed data can be obtained from wind maps or from the meteorology office. Unfortunately the general availability and reliability of wind speed data is extremely poor in many regions of the world. The Fig shows structure of wind turbine.

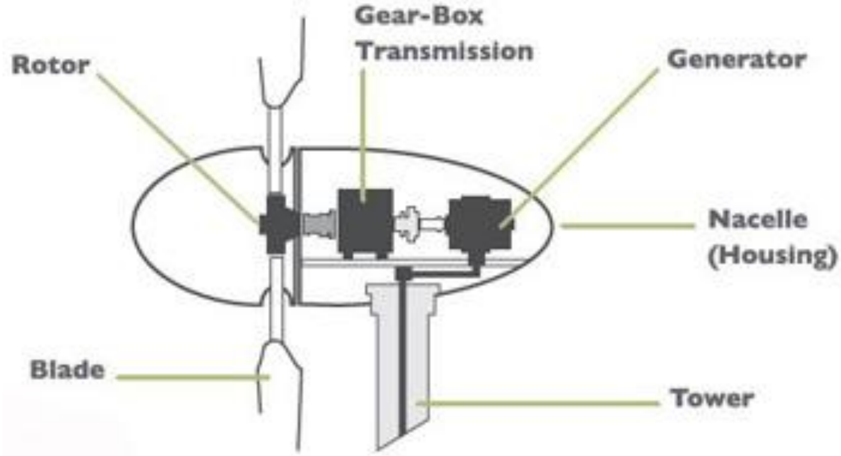


Fig Structure of wind turbine

ROTOR – Wind moves the rotor transferring energy to the turbine. The rotor is connected to a shaft that spins when the rotor spins. The shaft transfers the mechanical energy of the rotor to the generator.

GENERATOR – The generator converts the energy from the spinning rotor into electricity.

NACELLE – The nacelle (housing) protects the gearbox, generator and other components of the wind turbine.

TOWER – The tower places the rotor in the path of the wind. The tower at the Yukon College Renewable Energy demonstration site is a guyed tilt-up tower. It has guy wires securing the tower to the ground, and can be tilted down to ground level to repair the turbine.

ANEMOMETER – the anemometer tells the turbine's computer how fast the wind is blowing. This turbine is designed with a shape that allows it to automatically face into the wind.

NEURO-FUZZY SYSTEM

Fuzzy control provides a formal methodology for representing, manipulating and implementing a human’s heuristic knowledge about how to control a system. Fuzzy control design methodology can be used to construct fuzzy controllers for challenging real-world applications. In fuzzy control the focus is on gaining an understanding of how to best control the process, then we load this information directly into the fuzzy controller. When we are going to design a fuzzy logic controller we should first understand the behaviour of the plant. For example how it reacts to inputs, what effects does disturbances have, and what fundamental limitations are present (non-minimum phase or unstable behaviour). Also we should take into account the specifications in closed loop. Next an initial control design is performed, for example with a PID or some other simple controller. If the simple controller works there is no reason to implement something more complex; a fuzzy controller will always be computationally more expensive and also it is more difficult to develop. There are a number of control applications in which fuzzy logic can be useful. An experienced operator can summarize his control as a set of rules with roughly correct membership functions. Later we could refine this function with a trial and error process or with learning algorithms.

The transformation of expert's knowledge in terms of control rules to fuzzy frame work has not been formalized and arbitrary choices concerning, for example, the shape of membership functions have to be made. The quality of fuzzy controller can be drastically affected by the choice of membership functions. Thus, methods for tuning the fuzzy logic controllers are needed. In this paper, neural networks are used in a novel way to solve the problem of tuning a fuzzy logic controller. The neuro fuzzy controller uses the neural network learning techniques to tune the membership functions while keeping the semantics of the fuzzy logic controller intact.

Both the architecture and the learning algorithm are presented for a general neuro fuzzy controller. From this general neuro fuzzy controller, a proportional neuro fuzzy controller is derived. Fuzzy systems and neural networks have attracted the interest of researchers in various scientific and engineering areas. The number and variety of applications of fuzzy logic and neural networks have been increasing, ranging from consumer products and industrial process control to medical instrumentation, information systems and decision analysis. The main idea of fuzzy logic control (FLC) is to build a model of a human control expert who is capable of controlling the plant without thinking in terms of a mathematical model. The control expert specifies his control actions in the form of linguistic rules. These control rules are translated into the framework of fuzzy set theory providing a calculus which can simulate the behaviour of the control expert. The specification of good linguistic rules depends on the knowledge of the control expert, but the translation of these rules into fuzzy set theory framework is not formalized and arbitrary choices concerning, for example, the shape of membership functions have to be made. The quality of fuzzy logic controller can be drastically affected by the choice of membership functions. Thus, methods for tuning fuzzy logic controllers are necessary.

Neural networks offer the possibility of solving the problem of tuning. Although a neural network is able to learn from the given data, the trained neural network is generally understood as a black box. Neither it is possible to extract structural information from the trained neural network nor can we integrate special information into the neural network in order to simplify the learning procedure. On the other hand, a fuzzy logic controller is designed to work with the structured knowledge in the form of rules and nearly everything in the fuzzy system remains highly transparent and easily interpretable. However, there exists no formal framework for the choice of various design parameters and optimization of these parameters generally is done by trial and error. A combination of neural networks and fuzzy logic offers the possibility of solving tuning problems and design difficulties of fuzzy logic.

The resulting network will be more transparent and can be easily recognized in the form of fuzzy logic control rules or semantics. This new approach combines the well established advantages of both the methods and avoids the drawbacks of both. In this paper, neuro-fuzzy controller architecture is proposed, which is an improvement over the existing neuro fuzzy controllers. It overcomes the major drawbacks of the existing neuro-fuzzy approaches; of either keeping neural networks and fuzzy logic as separate entities (co-operative models) working towards a common goal or in most of the existing neuro-fuzzy approaches, the trained controller no longer can be interpreted as fuzzy logic controller. The novelty of this scheme is that the fuzzy controller itself is interpreted as a neural network. So, an error in the resulting control value can be distributed back among the control rules, instead of the integrating neural networks in certain parts of the controller.

Fuzzy logic and neural networks are natural complementary tools in building intelligent systems. While neural networks are low-level computational structures that perform well when dealing with raw data, fuzzy logic deals with reasoning on a higher level, using linguistic information acquired from domain expert. However fuzzy systems lack the ability to learn and cannot adjust themselves to a new environment. On the other hand, although neural networks can learn, they are opaque to the user. Integrated neuro-fuzzy systems can combine the parallel computation and learning abilities of neural networks with the human-like knowledge representation and explanation abilities of fuzzy systems. As a result, neural networks become more transparent, while fuzzy systems become capable of learning. A neuro-fuzzy system is a neural network which is functionally equivalent to a fuzzy inference model. It can be trained to develop IF-THEN fuzzy rules and determine membership functions for input and output variables of the system. Expert knowledge can be incorporated into the structure of the neuro-fuzzy system. At the same time, the connectionist structure avoids fuzzy inference, which entails a substantial computational burden. The structure of a neuro-fuzzy system is similar to a multi-layer neural network. In general, a neuro-fuzzy system has input and output layers, and hidden layers that represent membership functions and fuzzy rules.

THE NEURO-FUZZY CONTROLLER

We consider a multi-input, single-output dynamic system whose states at any instant can be defined by “n” variables X1, X2,...,Xn. The control action that derives the system to a desired state can be described by a well known concept of “if-then” rules, where input variables are first transformed into their respective linguistic variables, also called fuzzification. Then, conjunction of these rules, called inferencing process, determines the linguistic value for the output. This linguistic value of the output also called fuzzified output is then converted to a crisp value by using defuzzification scheme. All rules in this architecture are evaluated in parallel to generate the final output fuzzy set, which is then defuzzified to get the crisp output value. The conjunction of fuzzified inputs is usually done by either min or product operation (we use product operation) and for generating the output max or sum operation is generally used. For defuzzification, we have used simplified reasoning method, also known as modified center of area method.

For simplicity, triangular fuzzy sets will be used for both input and output. The whole working and analysis of fuzzy controller is dependent on the following constraints on fuzzification, defuzzification and the knowledge base of an FLC, which give a linear approximation of most FLC implementations.

CONSTRAINT 1: The fuzzification process uses the triangular membership function.

CONSTRAINT 2: The width of a fuzzy set extends to the peak value of each adjacent fuzzy set and vice versa. The sum of the membership values over the interval between two adjacent sets will be one. Therefore, the sum of all membership values over the universe of discourse at any instant for a control variable will always be equal to one. This constraint is commonly referred to as fuzzy partitioning.

CONSTRAINT 3: The defuzzification method used is the modified center of area method. This method is similar to obtaining a weighted average of all possible output values.

An example of a very simple neuro fuzzy controller with just four rules is depicted in Fig. This architecture can be readily understood as a "neural-like" architecture. At the same time, it can be easily interpreted as a fuzzy logic controller. The modules X1 and X2 represent the input 4 variables that describe the state of the system to be controlled. These modules deliver crisp input values to the respective membership modules (m-modules) which contain definitions of membership functions and basically fuzzify the input. Now, both the inputs are in the form of linguistic variables and membership associated with the respective linguistic variables. The m-modules are further connected to R-modules which represent the rule base of the controller, also known as the knowledge base. Each m-module gives to its connected R-modules, the membership value m(xi) of the input variable Xi associated with that particular linguistic variable or the input fuzzy set. The R-modules use either min-operation or product-operation to generate conjunction of their respective inputs and pass this calculated value forward to one of n-modules.

The n-modules basically represent the output fuzzy sets or store the definition of output linguistic variables. If there are more than two rules affecting one output variable then either their sum or the max is taken and the fuzzy set is either clipped or multiplied by that resultant value. These n-modules pass on the changed output fuzzy sets to C-module where the defuzzification process is used to get the final crisp value of the output. The architecture given in Fig of a fuzzy logic controller resembles a feed forward neural network. The X-, R-, and C-modules can be viewed as the neurons in a layered neural network and the m- and n-units as the adaptable weights of the network.

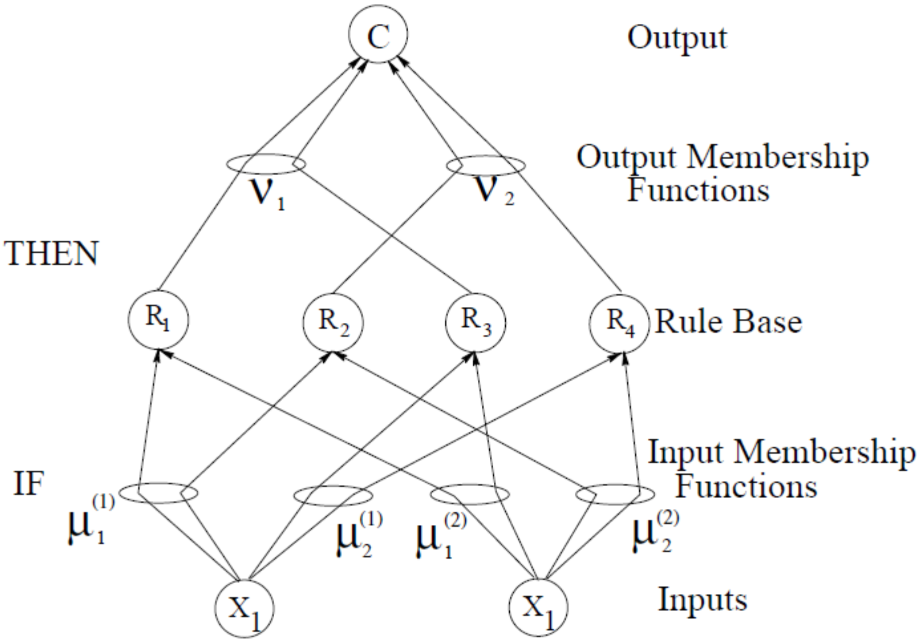


Fig Architecture of fuzzy controller from neural networks point of view

The X-module layer can easily be identified as the input layer of a multi-input neural network whereas the C-module layer can be seen as the output layer. The R-module layer serves as the hidden or intermediate layer that constitutes the internal representation of the network. The fact that one m-module can be connected to more than one R-module is equivalent to the connections in a neural network that share a common weight.

DESIGN OF NEURO-FUZZY CONTROLLER

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 modelling procedure to learn information about a data set. Then the parameters of membership functions that best allow the associated fuzzy inference system to track the given input/output data. 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. The developed neuro-fuzzy system is a first-order type which has a single input with six Gaussian distribution membership functions. It has six if–then rules. A simple structure of the developed neuro-fuzzy system is used where the input is the error signal of the controlled variable of speed, active, or reactive power. The training is performed using the hybrid back-propagation algorithm. The training data used are collected from extensive simulations of the vector controller system.

With the Neuro-fuzzy controller the value of the grid power is maintained to be constant in different wind speeds which are higher than the grid power. The reactive power is maintained at a stable value of zero, demonstrating a unity power factor operation. The neuro fuzzy inference system uses well defined parameter set for the delivery of maximum power output to the grid lines. The neuro-fuzzy inference system uses well defined parameter set for the delivery of maximum power output to the grid lines. Using neuro fuzzy control, we can produce controller outputs more reliable because the effect of other parameters such as noise and events due to wide range of control region and online changing of the controller parameters can be considered. The wind generation system is highly non-linear process since it is involved power electronic equipment. So non-linear controller is necessary for controlling non-linear process. So we are using an estimator based intelligent controller i.e. neuro-fuzzy controller.

THE LEARNING PROCEDURE

The actual output signal, Ca, is generated by the controller and now if the desired output of the controller, Cd, is also known at every instant, then error, ec, can be generated. The goal now is to generate the adjustments of the input and output membership functions, by back- propagating the error through the “neural-like” architecture of the fuzzy controller. The essence of back propagation algorithm in this case is to reward those rules which contribute towards taking the actual control action towards the desired control action and to discourage the rules which tend to take the control action away from the desired path. The error, ec, is assumed to be due to the bad choice of membership functions. Membership functions can be adjusted by laterally moving the domain or by bending the segments of the function. The error, ec, is due to a combination of errors resulting from wrong lateral placement of the domains and from specification of function shapes. These partial errors are then distributed back to the architecture. The error due to lateral placement of domain goes on to affect the output membership function domain, whereas the error due to function shapes modifies the input membership function in order to reduce that error. This subdivision of error is related to the position of actual output and the desired output values on the output domain. Using simplified reasoning defuzzification, there can be four different possible cases depending upon the relative position of actual and desired output values as shown in the Fig 5.9. It can be readily seen from simplified reasoning defuzzification scheme that the actual output is always going to lie between the mi and mi+1 adjacent active output fuzzy sets.

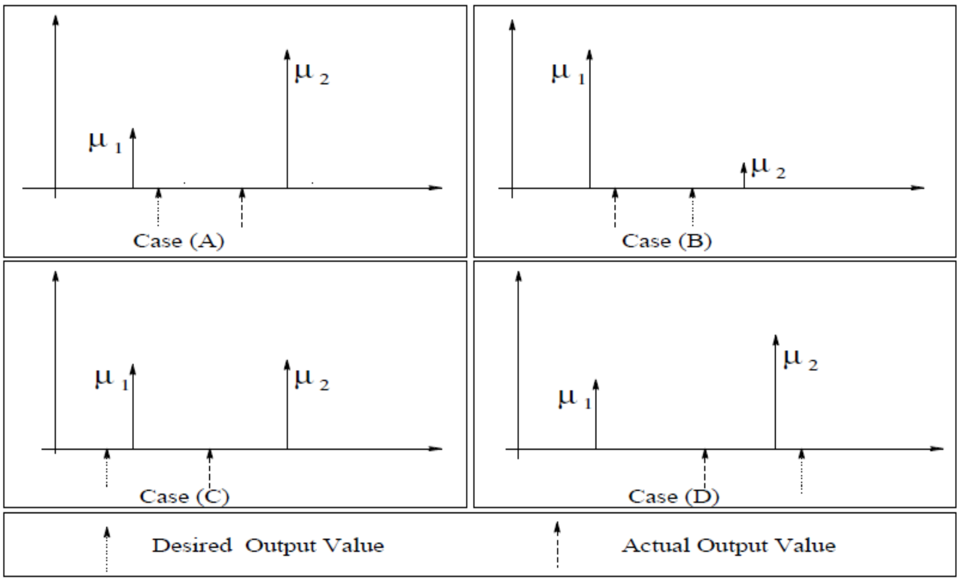


Fig Four Possible Cases of Error

Now, if the error is other than zero, i.e., the actual and desired output values are different, the following four cases can arise,

1. The desired value is located in between the center values for mi and mi+1 function but to the left of the actual value.
2. The desired value is located in between the center values for mi and mi+1 function but to the right of the actual value.
3. The desired value is not located in between the center values for mi and mi+1 functions but lies to the left of the center of mi.
4. The desired value is not located in between the center values for mi and mi+1 functions but lies to the right of the center of mi+1.

In the first two cases the output value is being produced by the correct fuzzy sets, but we need to adjust the shape of input membership functions. So, we try to change the form of active input membership sets such that error is reduced. For the cases 3 and 4, since the desired output does not lie in the range of centres of adjacent active output fuzzy sets, no amount of modification of input fuzzy sets can result in error going to zero. So, in this case the problem lies with the lateral displacement of the output sets or in some cases it is due to the wrong choice of the rule base. In this paper, as will become clear later, such error is considered to be due to the wrong position of the output set and the output set is moved to cover the desired value. It is seen that if rule base is chosen with care occurrence of such errors is rare. 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 modelling procedure to learn information about a data set. Most neuro-fuzzy systems are developed based on the concept of neural methods on fuzzy systems. The idea is to learn the shape of membership functions for the fuzzy system efficiently by taking the advantage of adaptive property of the neural methods.

CONCLUSION

Various control strategies for the speed and power control of wind turbines have been adopted and presented. These control strategies are used to control the smooth active power generated by wind turbine generator fed to power grids. Neuro-Fuzzy control strategy for Doubly Fed Induction Generator (DFIG) based variable speed wind turbine has been presented. Actual wind profile, grid code and generator characteristics have been considered as inputs for the simulation. Using this control strategy, torque and current ripple are controlled and hence power loss is drastically reduced. By using a doubly-fed induction generator three-phase voltage produced whose frequency of stator is constant, i.e., whose stator frequency remains equal to the frequency of network of the ac power network to which the generator is connected, despite variations in the generator rotor speed caused by fluctuations of the mechanical power provided by the wind turbine rotor driving the generator. This system achieves the purpose of the rotor current fed into the rotor windings of the doubly-fed induction generator must be continually adjusted to counteract any variation in the rotor speed caused by fluctuations of the mechanical power provided by the prime mover driving the generator. Compared with other control methods which are designed based on linear model obtained from one operation point, nonlinear control methods can provide consistent optimal performance across the operation envelope rather than at one operation point. To provide satisfactory performance under voltage sags caused by grid faults or load disturbance of the grid, input-output feedback linearization control has been applied to develop a fully decoupled controller of the active and reactive powers of the DFIG using Neuro-Fuzzy control algorithm. A diverse set of voltage excursions are conducted to evaluate the effectiveness of the proposed control strategy using MATLAB/SIMULINK platform.