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Research Paper

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

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This paper proposes a new computational control strategy. The control and analysis of Doubly Fed Induction Generators (DFIG) based wind turbines have been proposed. The dynamic modeling 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 Neuro Fuzzy Control scheme was presented where the harmonics was controlled to independently improve the generated active and reactive power as well as the rotor speed to track the maximum wind power point. The control strategy is developed and simulation studies are carried out in MATLAB/Simulink.

Keywords: Doubly Fed Induction Generators (DFIG), Neuro-Fuzzy Control Algorithm, Harmonics, Wind power generation systems

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.

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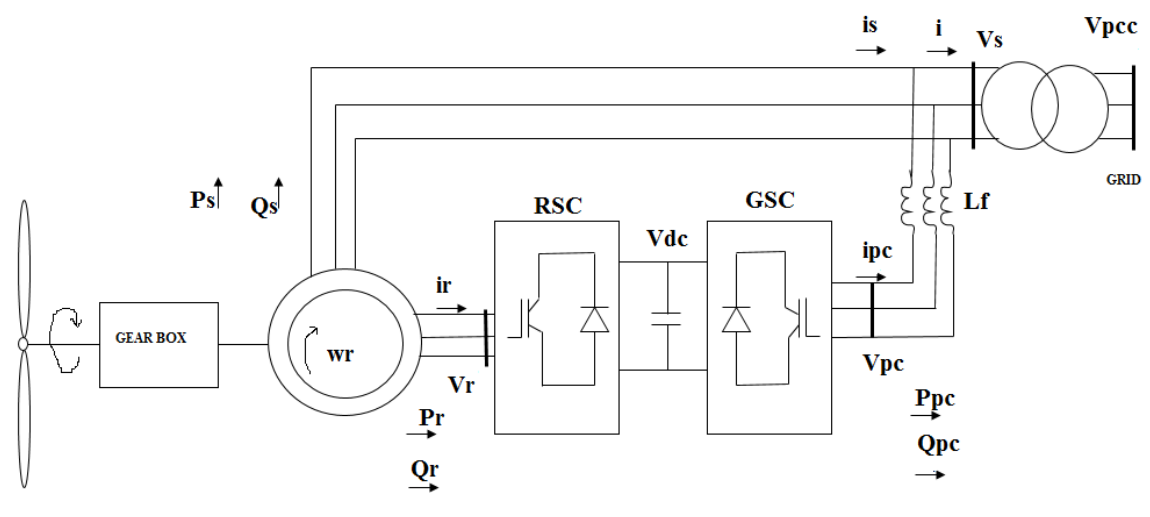
This system deals with integration and neuro fuzzy based control algorithm for power management of wind energy source. Wind energy electric systems have been built in many places around the world. In rural and isolated areas, stand alone power systems are used. When conventional machines are used as 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 is to manage power loss from the power system grid faults. Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings Figure 1. 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 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 (Babak, 2003).

Harmonic filtering technique is the one of the most used and earliest technology present in the system used to address the harmonic mitigation. The filters have been used very widely because of its very simple designing process and low cost factor (Theodora, 2013). Due to harmonics generated output power can be affected. To eliminates the harmonics using harmonic filter. The term the Total Demand Distortion (TDD) is

Figure 1: Configuration of the DFIG WT



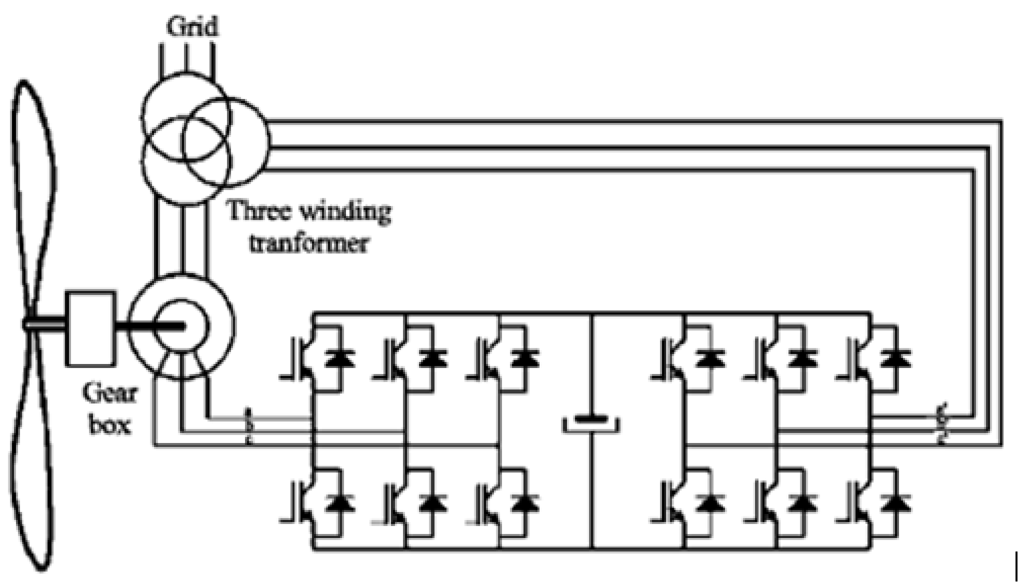
usually used which is the same as THD except that the distortion is expressed as a percentage of some rated load current rather than as a percentage of the fundamental current magnitude. The main objective of the Neuro-Fuzzy based control to design a global optimal controller to deal with the time-varying grid faults and nonlinear characteristic of the DFIG-WT and to control the harmonics in the wind system. The primary reason for using a doubly-fed induction generator is generally to produce three-phase voltage whose frequency of stator is constant. 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 (Pena, 1996).

PROPOSED METHOD

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 DFIG in which stator is directly connected to grid, but the rotor terminals are connected to grid via power converter in Figure 2. 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.

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

Figure 2: Block Diagram for Proposed System



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.

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.

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 modeling. 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.

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

$$f_{stator} = \frac{n_{Rotor} \times N_{poles}}{120} + f_{Rotor} \quad ...(1)$$

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:

$$f_{stator} = f_{Network} - \frac{n_{Rotor} \times N_{poles}}{120} \quad ...(2)$$

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).

Harmonics and Its Effects

Today in modern age fashion of electronics load increased rapidly. These electronics component are very much responsible for change in the electrical characteristics which are if when analyzed with analyzer become the evident of change of line voltage and line current waveform from pure sinusoidal to some other signal form, this distortion in waveform is given as Harmonic Distortion [14]. To improve power from wind without harmonics, so we are using fuzzy controller to control or eliminate harmonics.

- Harmonic filters reduce distortion by diverting harmonic currents in low impedance paths.
- The Total Harmonic Distortion (THD) can be calculated as

$$THD = \frac{I_{an}}{I_{a1}}$$

$$I_{an} = \sqrt{I_2^2 + I_3^2 + ... + I_n^2} \quad ...(3)$$

where,

- I_{an} - Phase RMS of the nth Component; and
- I_{a1} - Fundamental Component of Phase RMS

Effect of Harmonic Filters

Two cases are considered to investigate the impact of harmonic filters on power grid connected with wind energy.

- Harmonic filters are not connected to power grid, Harmonic filters connected to AC power grid.

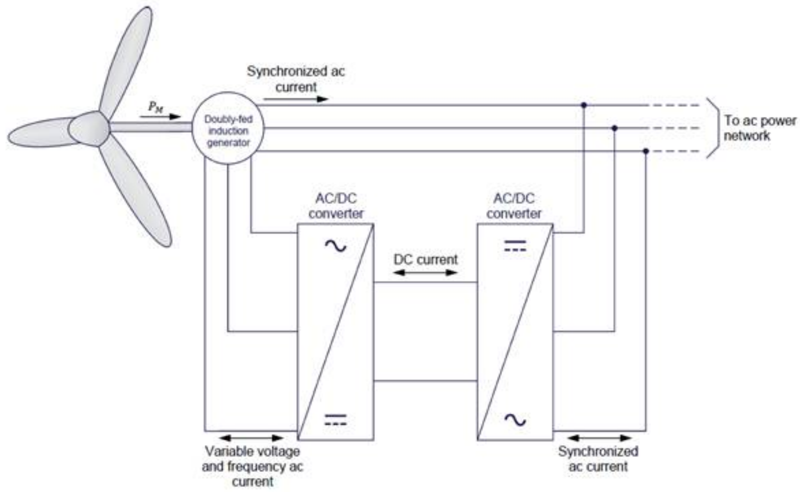
Harmonic Distortion Indices

The presence of harmonics in the system is measured in terms of harmonic content, which is defined as the ratio of the amplitude of each harmonic to the amplitude of the fundamental component of the supply system voltage or current. Harmonic distortion levels are described by the complete harmonic spectrum with magnitude and phase angle of each individual harmonic component. The most commonly used measure of the effective value of harmonic distortion is THD or distortion factor. This factor is used to quantify the levels of the power flowing in the wind system.

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. Large-size wind turbines are basically divided into two types which determine the behavior of the wind turbine during

Figure 3: Circuit Topology of DFIG in Variable Speed Wind Turbine



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. 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 in Figure 3.

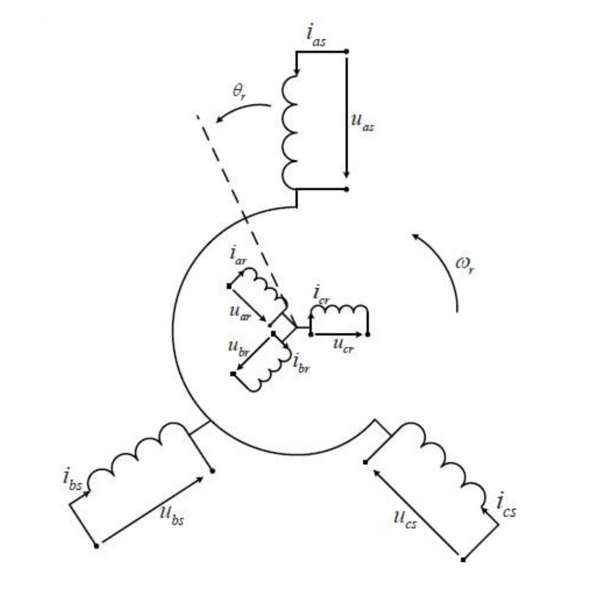
Wind Energy System

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 aero-dynamically designed blades and convert it to rotating mechanical power. The number of blades is normally three.

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 4.

Figure 4: DFIM Phase Circuits



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. 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

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:

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

$$\lambda = \frac{\Omega_r r_r}{w} \qquad ...(4)$$

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:

$$P_m = 0.5\rho A C_p (\lambda, \beta)\ vw3 \qquad ...(5)$$

where ρ - air density, *A* - rotor swept area, *Cp* (λ, β) - power coefficient function, λ - tip speed ratio, β - pitch angle, *w* -wind speed.

Wind turbine can be modeled based on the steady-state power characteristics. In per unit (Pu system), equation (5) can be written as:

$$P_{m\ pu} = K_p C_{ppu} V_{wpu}^3 \qquad ...(6)$$

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, Cppu 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.

So the aerodynamic power generated by wind turbine is given by

$$P = 0.5\rho A c_p V_w^3 \qquad ...(7)$$

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.

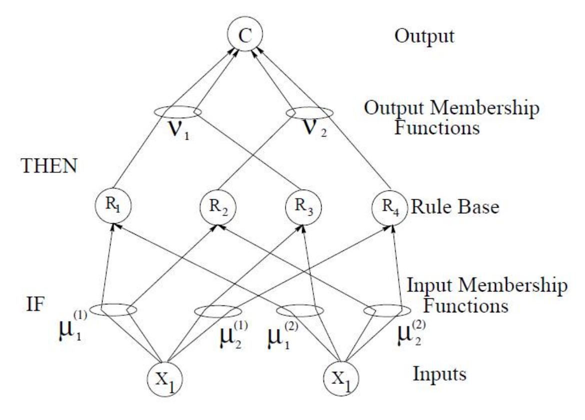
Neuro Fuzzy System

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. 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 (Thao, 2010; Xiaojin, 2009). 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 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.

Figure 5: Architecture of Fuzzy Controller from Neural Networks Point of View



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 he 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.

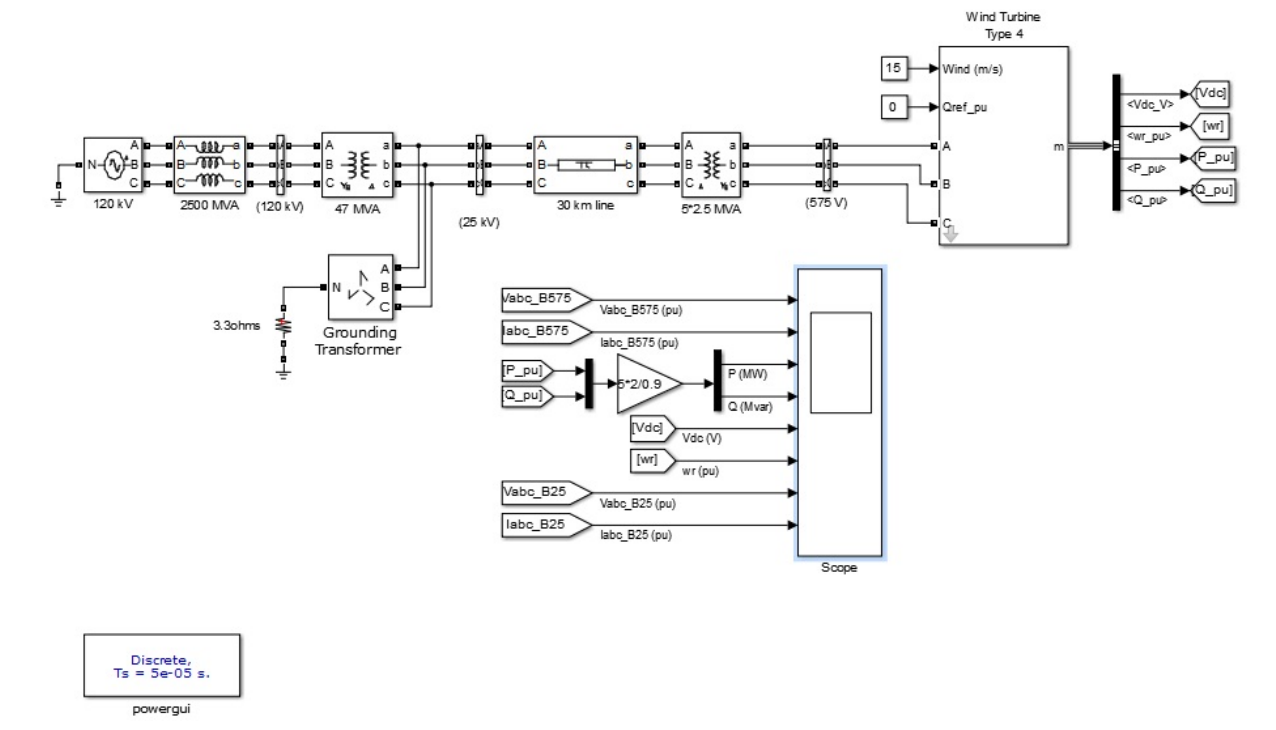
SIMULATED CIRCUIT DIAGRAM

The model of WECS shown in Figure 6 is developed in the MATLAB-SIMULINK as described and results are presented to demonstrate the control of active and reactive power at different wind speeds. The performance of the presented strategy has been tested in a scaled experimental setup, where not only the capability for reducing the rotor currents under fault conditions with the proposed strategy has been tested but also the evolution of the rotor voltage has been monitored. In addition, reactive power has been injected through the stator after the rotor currents are under control. Once the over-currents are avoided, the injection of reactive power is enabled.

Therefore, the results presented shows that it is possible to control the stability of a DFIG during severe contingencies in the power network, without the need of external auxiliary circuits. This issue enables the rotor-side power converter to remain connected to the grid in faulty scenarios without getting damaged.

The wind turbine is designed to having the capacity of 9 MW. Mentioned units are connected to grid by a 500/25 kV transformer and a 25 kV, 2 lined distribution line with 30 km length and 47 MVA transformer. Used generators in this model are doubly fed induction generators and stator windings are directly connected to the grid and at the junction point in order to compensate part of required reactive power. The wind generation system is highly non-linear process since it is involved power electronic equipment. So, the non-linear controller is necessary for controlling non-linear process. So, we are using an estimator based intelligent controller, i.e., Neuro-Fuzzy controller.

Figure 6: Simulation Circuit for Proposed System



RESULTS AND DISCUSSION

The below Figure 7. Waveforms are the simulation result of the proposed system which is implemented in MATLAB/SIMULINK. The waveforms for stator voltage (Vabc), stator current (Iabc), active and reactive powers and rotor speed are presented for different wind speeds.

The convention for the power is chosen as to be negative if the source discharges any power to the grid and positive if power is stored. In all three cases, the value of the grid power is maintained to be constant at by grid power control strategy. The reactive power is maintained at a stable value of zero, demonstrating a unity power factor operation.

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.

Figure 7: Simulated Output Waveform of Proposed System

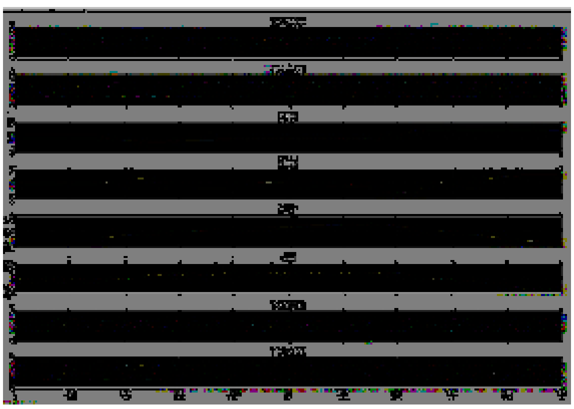


Figure 7 show the performance of the system with Neuro-fuzzy controller at synchronous speed, sub-synchronous speed and super-synchronous speed respectively. The waveforms for stator voltage (V_{abc}), stator current (I_{abc}), active and reactive powers and rotor speed are presented for different wind speeds. With the Neuro-fuzzy controller the value of the grid power is maintained to be constant at 65 kW in different wind speeds which is higher than the grid power in case of system with PI controller. Thus, the modified control strategy with neuro-fuzzy controller is able to negotiate the grid power gusts due to the variable wind speeds in an efficient way.

Harmonic Analysis

In this section, the results of the performed harmonic analysis are reported. Simulations are carried out with and without the filters to investigate the effectiveness of the wind power in mitigating harmonics.

Figure 8: Output Waveform of Overall System When Connected to Grid without filter

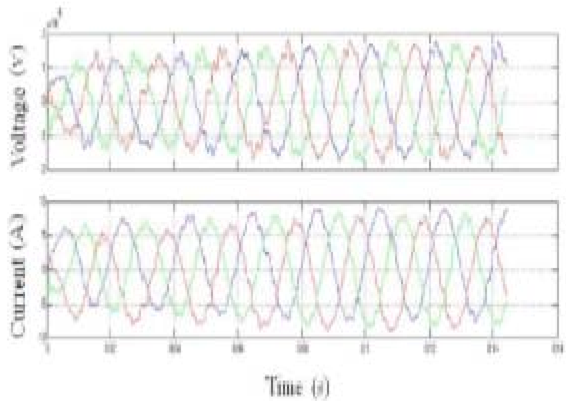
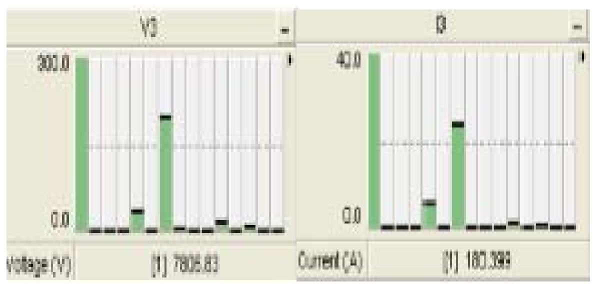


Figure 9: FFT Analysis for Voltage and Current Waveform



Then the THD also calculated from FFT analysis. From the above graph of the Fast Fourier Transform analysis, it shows that the THD of 3.77% in the inverter which is connected to grid. Thus harmonic content is much reduced by the use of fuzzy controller in the proposed system. From the simulation results, the line voltage THD of the 3-level waveform with a modulation index M=0.413, has a reduced harmonic content of about 3.77%. Thus, the higher order and most unwanted harmonics generated are reduced and the generated reactive power is also improved in the proposed system.

CONCLUSION

The control strategies for the speed and power control of wind turbines have been adopted and presented. Neuro-Fuzzy control strategy for 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. 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. Harmonics can be controlled and hence wind power attains maximum power point. A diverse set of voltage excursions are conducted to evaluate the effectiveness of the proposed control strategy using MATLAB/SIMULINK platform.

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