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Fuzzy PI controller for wind Energy conversion system

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ABSTRACT

A Wind Energy Conversion System (WECS) differs from a conventional power system. The power output of conventional system can be controlled where as power output of a WECS depends on the wind. This paper describes fuzzy logic control of induction generator speed in wind turbine application. The aim of fuzzy controller is to established maximum power delivery to the grid from available wind power. Fully-controlled wind turbine which consists of induction generator and back-to-back converter is under estimate. This configuration has full control over the electrical torque, full control of the speed, and also supports reactive power compensation and operation under grid disturbances. Fuzzy logic control algorithm has been applied and validated by detailed simulation in MATLAB/Simulink. All system components have been described in detail. All power system components are simulated in MATLAB software for fuzzy control. For studying the performance of controller ,different abnormal condition are applied even the worst case .simulation result can prove the excellent performance of fuzzy control as improving power quality and stability of wind turbine.

Keywords

A wind turbine, Doubly Fed Induction Generator, Modelling, simulation, Fuzzy logic controller, wind energy conversion system.

1. INTRODUCTION

Renewable energy including solar, wind, tidal, small hydro geothermal, refused derived fuel and fuel cell energy is sustainable, reusable and environmentally friendly and clean. With the increasing shortage in fossil fuel, and pollution problem renewable energy has become an important source .Among the other renewable energy sources wind energy has proven to be one of the most economical one. Earlier constant speed WECS were proposed to generate constant frequency voltages from the variable wind speed .Fuzzy logic. Control of DFIG wind turbine is on the most popular wind turbine which includes an induction generator with slip ring, a partial scale power electronic converter. Fuzzy logic controller is applied to rotor side converter as improving power quality and stability of wind turbine [1].Variable nature of WECS makes it difficult for analysis, design and management. The steady state characteristic of a WECS using doubly fed induction generator analysis is performed to investigate variety of DFIG characteristic, including torque-speed, real and reactive power over speed characteristic [2]. The paper describes a variable speed wind generation system where fuzzy logic principles are used for efficiency optimization and performance enhancement control. A squirrel cage induction generator feeds the power to a double-sided pulse width modulated converter system which pumps power to a utility grid or can supply to an autonomous system. The system has fuzzy logic control with vector control in the inner loops. A fuzzy controller tracks the generator speed with the wind velocity to extract the maximum power. A second fuzzy controller programs the machine for light load efficiency improvement and a third fuzzy controller gives robust speed control against wind gust and turbine oscillatory torque. The complete control system has been developed, analysed, and validated by simulation study. Performances have then been evaluated in detail[3].An adaptive nonlinear controller for wind energy doubly fed induction machine is based on the feedback linearization technique and includes a disturbance observer for estimate of parameter uncertainties[4].This paper describes the transient behaviour of DFIG driven by the stator disconnect from the grid and grid connection[5,6].energy reliability optimization of wind energy conversion operation can be achieved by the sliding mode control in which a horizontal-axis-grid-connected variable speed DFIG based wind power system and minimizing its mechanical stress[7].

The variable speed wind turbine concept with doubly fed induction generator and partial-scale back-to-back converter on the rotor circuit are most popular. This is due the fact that the partial-scale power converter is typically only 30% of the power fed to the electrical grid. This makes this concept attractive from an economic point of view.

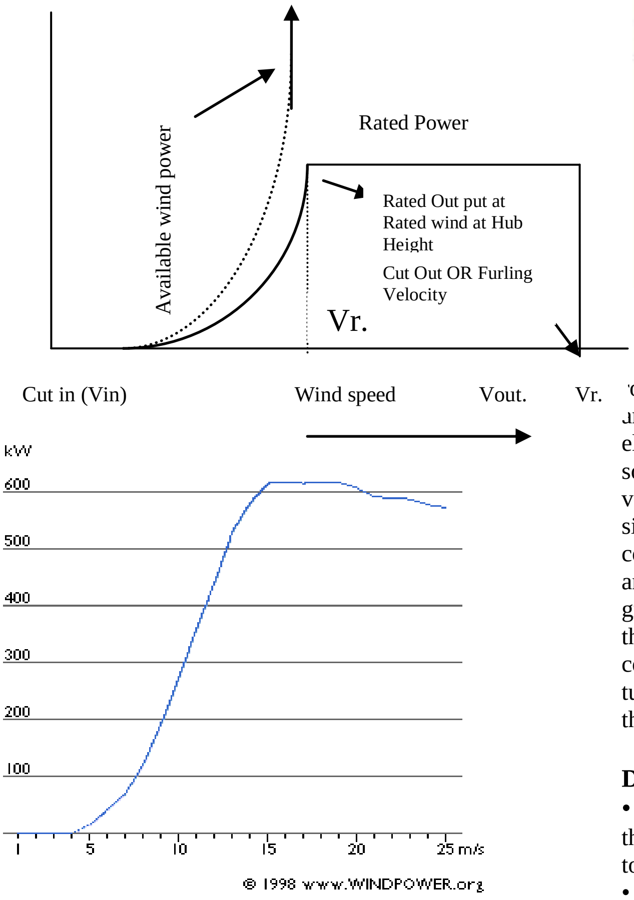
2. WIND POWER

*The power in wind is proportional to the cubic wind speed (v3).

P/m2 = 6.1 x 10-4 v3

~ Kinetic energy of an air mass is proportional to v2
~ Amount of air mass moving past a given point is proportional to wind velocity (v)

Set of turbine power curves are given in Fig. 2. It could be noticed that there is the operating point of maximum power delivery for each wind speed. The main goal of the controller is to run wind turbine generator at that operating point. These set of curves could be replaced with only one diagram which gives dependence of wind turbine power related to parameter λ, through turbine power coefficient
marked as Cp(λ). Particularly, the wind turbine is characterized by the power coefficient Cp(λ) (see Fig. 3), which is defined as the ratio of actual delivered power to the free stream power flowing through a same but uninterrupted area. The tip speed ratio λ, is the ratio of turbine speed at the tip of a blade to the free stream wind speed. It could be noticed from Fig. 3 that there is the optimal tip speed ratio λopt, which has to be maintained in order to extract maximum power from the wind.



fig(1)

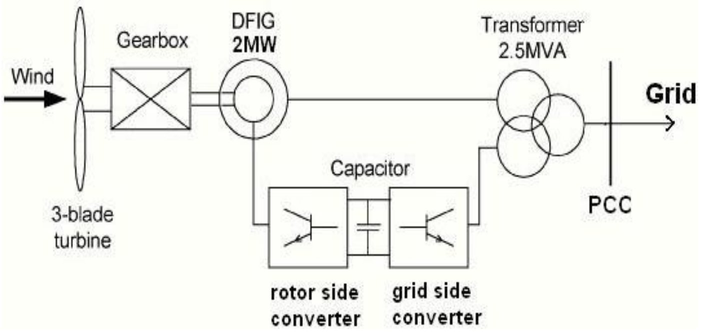
The mechanical power extracted from the wind by a wind turbine depends on many factors . A simple equation is often used to describe the torque and power characteristics of wind turbine, that is

Pm=0.5 ρ A Cp (λ) V3w (W)
where:
Cp :-power coefficient;
λ :- tip speed ratio (TSR) = (R ww / Vw)
Ww :-turbine angular speed
R :- turbine radius (m);
ρ :- air density (kg/m3);
A :-cross section area of the turbine (m2);
Vw :-wind velocity (m/s).

3. WIND ENERGY CONVERSION SYSTEMS USING DFIG

Figure 1 Shows a WECS using DFIG. A wind turbine Catches the wind through its rotor blades and transfers it to the rotor hub. The rotor hub is attached to a low speed to the rotor hub. shaft through a gear box. The high speed shaft drives an electric generator which converts the mechanical energy to electric energy and delivers it to the grid the wind

A doubly fed induction machine is basically a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid and its rotor windings connected to the grid through a converter.



Fig(2) ENERGY CONVERSION SYSTEMS USING DFIG

The AC/DC/AC Converter is divided to two components: the otor side converter and the grid side converter. These converters are voltage sourced converters that use force commutated power electronic devices to synthesize an AC Voltage from a DC source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor is used to connect the grid side converter to the grid. The three phase rotor winding is connected to the rotor side converter by slip rings and brushes and the three phase stator windings are directly connected to the grid. The control system generates the pitch angle command and the voltage command signals V and V for the rotor and grid side converters respectively in order to control the power of the wind turbine, the DC voltage and the reactive power or the voltage at the grid terminal.

DFIG offers the following advantages

- Reduced inverter cost, because inverter rating typically 25% of the total system power. This is because the converters only need to control the slip power of the rotor
- Reduced cost of the inverter filter and EMI filters because filters rated for 0.25 p.u. total system power and inverter harmonics represent a smaller fraction of total system harmonics
- Robustness and stable response of this machine facing against external disturbance

4. WIND AND WIND TURBINE MODEL

Wind effect plays a fundamental rule in wind turbine modelling especially for interaction analysis between wind turbines and the power system to witch they are connected. Wind model describes wind fluctuation in wind speed which causes power fluctuation in generator. For wind model four components can be considered, as describe in [6],[10]

Vwind = Vbw + Vgw + Vrw + Vnw

Where,

Vbw = Base wind component
Vgw = Gust wind component
Vrw = Ramp wind component
Vnw = Noise wind component,

The base component is a constant speed; wind gust component may be expressed as a sine or cosine function or their combination [7]; a simple ramp function will be used for ramp component and triangle wave for noise function which it's frequency and amplitude will be accordingly adjusted. Wind speed this study is illustrated in Fig. 9 and includes all of four components For electrical analysis, a simplified aerodynamic model of wind turbine is normally used. Accordingly wind blade torque from wind speed will be produced which is as follows

$\lambda = (R\,ww / Vw)$…………. .(7)

$Pm = 0.5\,\rho\,A\,Cp(\lambda)\,V3w$………….. (8)

$Tw = Pm / Ww$ ……………………… (9)

Where Tw is an aerodynamic torque extracted from the wind (Nm), ρ is the air density (Kg/m3) 0 is the pitch angle of the rotor R is the wind turbine rotor radius(m), Vwind is the equivalent wind speed (m/s), Ww is the mechanical speed of the generator(rad/s)Cp is the power coefficient.

$Cp(\lambda,\theta) = 0.22(116/\lambda - 0.40 - 5)e{-}125/\lambda$ …………(10)

Where

$\lambda = 1/(1/\lambda + 0.08\,0 - 0.035\theta 3 + 1)$

By increasing pitch angle, power coefficient and therefore torque decreases moreover Cp growth rate changes in different speed by λ .

Set of turbine power curves are given in Fig. 2. It could be noticed that there is the operating point of maximum power delivery for each wind speed. The main goal of the controller is to run wind turbine generator at that operating point. These set of curves could be replaced with only one diagram which gives dependence of wind turbine power related to parameter, through turbine power coefficient marked as Cp. Particularly, the wind turbine is characterized by the power coefficient Cp (see Fig. 3), which is defined as the ratio of actual delivered power to the free stream power flowing through a same but uninterrupted area The tip speed ratio (λ) , is the ratio of turbine speed at the tip of a blade to the free stream wind speed.

It could be noticed from Fig. 3 that there is the optimal tip speed ratio (λ) , which has to be maintained in order to extract maximum power from the wind

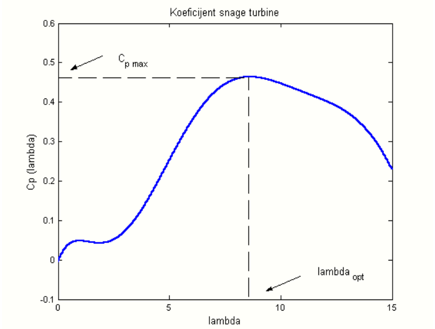
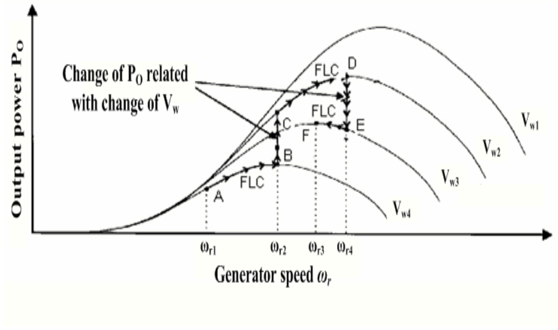


Fig. (3)

Hence Fuzzy logic controller (FLC) can be used in order to achieve maximum power delivery for each wind speed and to have more robustness. Maximum output power operating point deviates from the maximum torque point. The torque follows the square-law characteristics and the output power follows the cube law.

The optimums fuzzy logic control of an induction generator require controller which will track wind speed in order to achieve λ opt and thus extract maximum power. The product of torque and speed gives turbine power, and by assuming a steady state lossless system it is equal to the grid power. The curves in (Fig. 2) show the grid power P in dependence of generator speed in terms of wind velocities v.

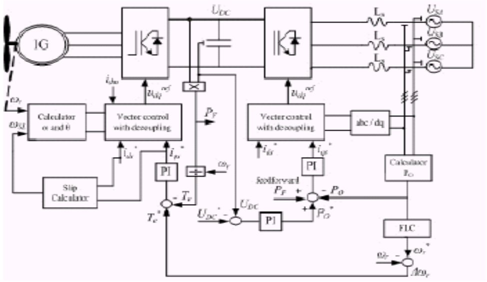
What is the exact task of fuzzy controller it could be best seen from these set of power curves. For a particular value of wind velocity, the function of the fuzzy controller FLC is to seek the generator speed in steps until the system settles down at the maximum output power operating point.



Therefore, the principle of the fuzzy controller is to increment or decrement the generator speed in accordance with the corresponding increment or decrement of the estimated output power.

5. MODELING OF WIND TURBINE CONTROL SYSTEM

Wind turbine control block diagram is shown in Fig. 4. The system consists of squirrel-cage induction generator and back-to-back PWM converter connected to the grid through the coupling inductances. The voltage equations which describe the behavior of induction machine contain time-varying coefficients in real domain, due to the fact that some of the machine inductances are functions of the rotor displacement. A change of variables suggested by reference-frame theory is often used to reduce the complexity of these differential voltage equations [5].



It could be shown that in synchronously rotating reference frame a constant amplitude balanced 3-phase set of variables will appear as constants. This enables, among reduction of complexity of induction machine voltage equations and their analysis, also simplify in controlling the alternating systems because ac quantities became constants in steady-states. In system analysis it is also often convenient to express machine selected, and all parameters and variables are normalized using these base quantities. Modeling of induction machine was done in synchronously rotating reference frame (field oriented, also called dq reference frame) based on equations (2-5):

$el.di/dt = u - r.i - Y1.\Psi.\omega e - Y2\,.\,\Psi.\omega$

$Tmeh\,.d\omega/dt = mc - mm$

$mc = \chi m\,.(isq - isd\,.isr)$

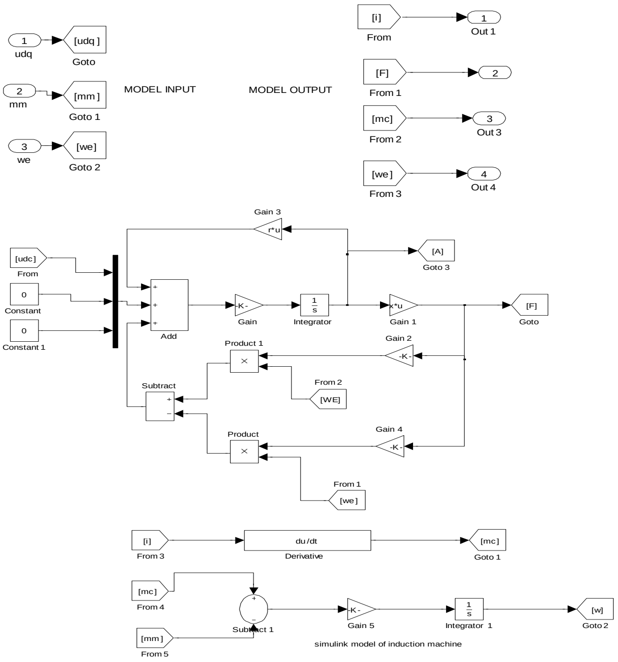
$\Psi = \chi\,.\,i$

u is the voltage vector, i is the current vector, ψ is the flux linkage vector, r is the machine resistances matrix, x is machine winding inductances matrix, xm is the mutual inductance between stator and rotor windings i.e. magnetizing

inductance, xs and xr among magnetizing inductance includes leakage inductances, τel is electrical time constant of the machine (xs/ωbase or xr/ωbase), ω is the rotor speed, ωe is the angular speed of the rotating magnetic field, τmeh is mechanical

time constant of the machine (together with the connected load, equals to J·ωbase/mbase, where J represents machine moment of inertia), mc is the electromagnetic torque generated by the machine and mm is the load torque. Based

on the equations (2-5) model of the machine was made in MATLAB



simulink model of induction machine

Back-to-back converter consists of two three-phase converters coupled through a common DC link. Generator side converter, i.e. rectifier, uses indirect field oriented or vector control in the inner current control loop. The aim of fieldoriented control is to establish and maintain perpendicular relationship between the stator current space vector and usually rotor flux linkage vector. In this approach, d-axis of the rotating reference frame is aligned with the rotor flux vector, ψr (ψrq=0). Under these conditions, the stator current component along qaxis, isq, defines machine electrical torque, whereas stator current component along d-axis, isd, defines machine flux linkage, similarly to a DC machine control.

Field orientation can be achieved by on-line estimation of the rotor flux vector position based on next equations (6-9):

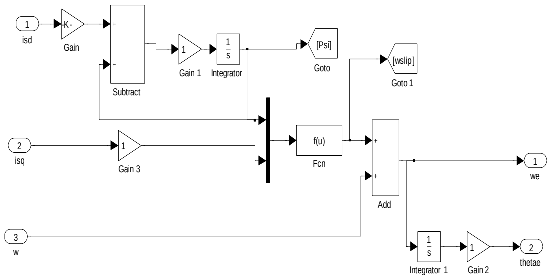
$$\theta e = \int \omega e.dt$$

$$\omega e = \omega + \omega slip$$

$$(\Gamma el /rr)(d\Psi rd /dt) + \Psi rd = xm.isd$$

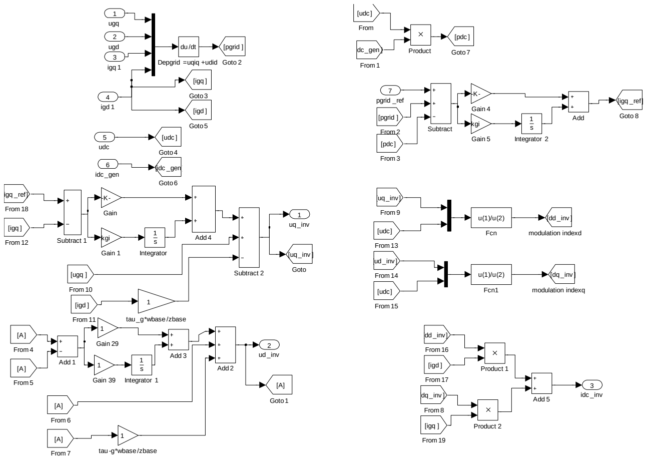
$$\omega slip = (xm / \Psi rd).(rr/xr).isq$$

$$mc = 3/2.p/2.(xm/xr). \Psi rd.isd$$



SIMULINK MODEL OF THE SLIP CALCULATOR

Now, controller gains could be obtained easily, based on symetrical criterion as:

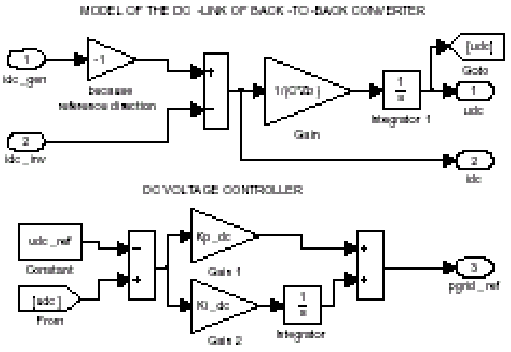


Although changes of variables are used in the analysis of ac machines to eliminate time-varying inductances, changes of variables, i.e. reference-frame theory, are also employed in the analysis of constant-parameter power system and control system associated with them. So it is convenient to perform the grid side converter control design in synchronously rotating reference frame, where alternating variables become constants in the steady state. In this approach, reference frame q-axis is aligned with the grid voltage vector, ug (ugd=0). Grid voltage vector orientation could be achieved by directly measuring grid phase voltages, so this method is often called direct vector control. It could be shown that under this case, active power flow between grid side converter and the grid is determined with converter current in q-axis, igq, and reactive power flow is determined with converter current in d-axis, igd.

providing that d voltage component is equal to zero. With the DC-link voltage maintained at fixed value, grid side converter controls active power flow so that all generated power is transferred to the grid. This is the reason why the DC voltage controller output is associated to the q current reference. In order to have an efficient DC-link voltage control, beside PI controller, it is needed to have feed forward signal of estimated output power in addition to the output of DC-link controller. In this way fluctuations of DC-linkvoltage are eliminated in transient periods. By appropriate connecting above described models, we have complete wind turbine model with reference generator speed as an input. Reference value of the generator speed would be set up by fuzzy logic speed controller with the aim to extract maximum power from available wind.

Fuzzy Logic Speed Controller

The optimum fuzzy logic control of an induction generator require controller which will track wind speed in order to achieve λopt and thus extract maximum power. The product of torque and speed gives turbine power, and by assuming a steadystate lossless system it is equal to the grid power. The curves in Fig. 2 show the grid power pO in dependence of generator speed ωr in terms of wind velocities vw. What is the exact task of fuzzy controller it could be best seen from these set of power curves.



For a particular value of wind velocity, the function of the fuzzy controller FLC is to seek the generator speed in steps until the system settles down at the maximum output power operating point. For example, at a wind velocity of Vw4, the output power will be at point A if the generator speed is ωr1. The FLC will change the speed in steps until it reaches the speed ωr2, where the output power is maximized at point B. If the wind velocity increases to Vw2, the output power will jump to point C, and then FLC will bring the operating point to D by searching the generator speed to ωr4. The strategy for decrease of wind velocity is similar. If wind velocity decreases to Vw3, output power is altered and settled at operating point E. FLC will now decrease generator speed to the optimum value ωr3 (point F) where output power is at maximum. Therefore, the principle of the fuzzy controller is to increment or decrement the generator speed in accordance with the corresponding increment or decrement of

the estimated output power pO. If ΔpO is positive with the last positive Δωr, the search is continued in the same direction. If, on the other hand, positive Δωr causes negative change ΔpO, the direction of search is reversed. So, during these

step changes of generator speed, controller observes changes in turbine output power and due to this it keeps searching generator speed for which this change of

output power would be zero. That would be the maximum power delivery point. If

ωr1 is far from ωr2, controller could give greater value of generator: increments, Δωr, for faster convergence to the maximum delivery point. Similar, if current generator speed is close to the ωr2 controller must give smaller value of speed increments, Δωr, to avoid oscillations and ensure stable system. Descriptive rules like this could be applied converting the system into the fuzzy system. Implemented control system is universal fuzzy control system, with block diagram

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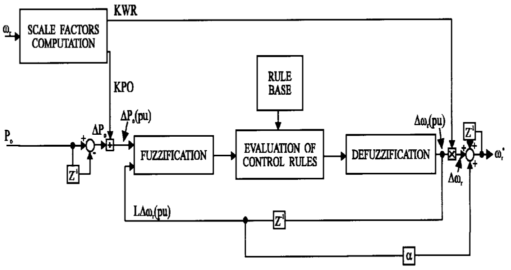


Actual values that indicates input variables, here change of output power, ΔpO, and last change of generator speed, LΔωr, are initially converted into the correspondent fuzzy sets with human descriptive and intuitive values such are terms BIG, MEDIUM, SMALL, ZERO. This is done in the "fuzzification block", where the variables ΔpO (variation of output power), Δωr (variation of generator speed) and LΔωr (last variation of generator speed) are described by membership functions given in Fig. 11. Afterwards, it is possible to apply descriptive rules of reasoning like "if the last change of output power ΔpO during maximum power searching was POSITIVE and BIG and the last change of desired generator speed LΔωr was POSITIVE then keep tracking the maximum power in the same POSITIVE direction with BIG increment Δωr". Rules like this are involved in block "rules table", and they are given in Table 1. Finally, the fuzzy set of output reference change of generator speed Δωr is back "deffuzified" to convert it to the

actual value. That means the output values such are BIG, MEDIUM, SMALL are translated to numbers which indicates a measurable (but normalized) value of the generator speed. It could be also noticed the output of controller Δωr is added by

some amount of LΔωr in order to avoid local minima in characteristics Cp(λ) due to the changes of wind speed. value. That means the output values such are BIG, MEDIUM, SMALL are translated to numbers which indicates a measurable (but normalized) value of the generator speed. It could be also noticed the output of controller Δωr is added by some amount of LΔωr in order to avoid local minima in

characteristics Cp(λ) due to the changes of wind speed. The controller operates on a per-unit basis so that the response is insensitive to system variables and the algorithm is universal to any system. Membership functions of FLC controller are implemented by using MATLAB/Simulink fuzzycontrol toolbox. In Fig. 12 realized model of fuzzy logic controller is shown. Heart of the controller is block of fuzzy logic controller from MATLAB/Simulink fuzzy control toolbox. With this powerful tool it is possible to define your fuzzy

controller in relatively easy way using graphical interface and intuitive dialogs,

From previously explanations, the advantages of fuzzy control are obvious. It provides adaptive step size in the search that leads to fast convergence, and controller can accept inaccurate and noisy signals. The FLC operation does not need any wind velocity information, and its search is insensitive to system

parameter variation which is helpful in installation of different scale windturbine

6. SIMULATION RESULTS

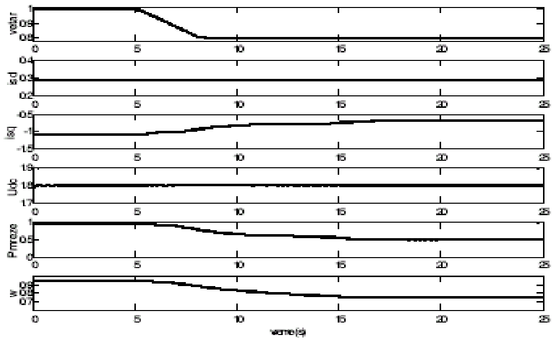
In order to verify control principle given in this paper, detailed model of the system in MATLAB/Simulink has been developed. The system data are shown in Table 2. Simulation results shown in Figs. 16 and 17 illustrate performance of

wind turbine with fuzzy controller which tracks the maximum power delivery operating point. They are given for the case of wind velocity decrease from nominal to 80% of nominal value. It could be noticed that before disturbance ($t <$

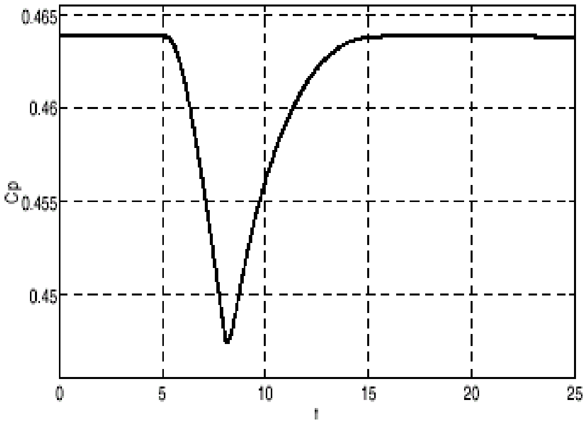
5 s) all variables are settled at nominal values. After wind velocities decrease power fed to the grid gradually decrease to value around 50% of nominal, which is expected because turbine power follows the cube law. Reference value of q current component isq also drops, and thus the value of electromagnetic torque. D current component isd remain the same, so the magnetic flux is unchanged. DClink voltage is maintained constant which means that all generated power is transferred to the grid. Generator rotational speed is changing consistent with changes of wind velocity. Speed response is without overshoot and abrupt transients, as a consequence of fuzzy controller usage.

In order to verify that maximum power is extracted from the available wind, power coefficient Cp(λ) has to be observed. In Cp(λ) is shown during the change of wind velocity. It could be noticed that during the change of wind velocity, power coefficient Cp(λ) differs from optimum value. Deviation is relatively small, but after the

transient period which lasts around 10 s, it settles at the optimum value.



Simulation results. From up to down: wind velocity Vw, d grid current component isd, q grid current component isq, DC link voltage UDC, grid power PO, and generator speed ωr



7. CONCLUSION

In this paper optimum fuzzy control of wind turbine in order to extract maximum power is described and verified through the simulation. The main goal of implemented fuzzy controller is to continuously adapt the rotational speed of the generator to the wind speed in a way that the turbine operates at its optimum level of aerodynamic efficiency. The advantages of using fuzzy controler are universal

control algorithm, fast response, and parameter insensitivity. Implemented system has satisfactory dynamic and static performances.

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