Maximum Wind Energy Extraction by Using Neural Network Estimation and Predictive Control of Boost Converter

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ABSTRACT

This paper proposes a new method to extract maximum energy from wind turbine systems. The artificial neural network (ANN) is used to estimate the wind speed based on the rotor speed and the output power. In addition to ANN, a predictive controller is used to maximize the efficiency of the boost converter. The method has been developed and analyzed by utilizing a turbine directly driven permanent-magnet synchronous generator (PMSG). The simulation results verify the performance of the proposed method. Results show that this method maximizes wind energy extraction with more accuracy and fastness.

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1. INTRODUCTION

Nowadays developed countries place great importance on using renewable energy sources due to their many advantages. As a renewable and non-polluting energy source, wind power has an important role in reducing harmful emissions and the impact of climate change. Since, fossil fuels like coal and oil are subjected to terrible price volatility, greater use of wind energy makes us less dependent on traditional fuels [1]. During last decay, wind turbine systems have been improved with variable speed turbines and directly connected generators. Variable speed wind turbines not only reduce power oscillations and mechanical stresses, but also increase output power and efficiency of the system.

Because of significant progress in the semiconductor devices and power electronics techniques, wind power becomes much more attractive in electrical power systems [2]. By using the methods of maximum power point tracking for conversion systems of wind-turbine energy, efficiency of wind-turbine generators is increased [3], [4]. In order to track maximum power point in wind turbines for different wind speeds, turbine speed must be changeable through a broad range [5]. In this case, we need to separate generation side from the demand side. So the three phase output voltage of generator should be rectified and the voltage of dc bus should be adjusted. In the power-speed characteristic curve of the turbine there is only a certain load that corresponds to the maximum power of turbine. So in order to obtain maximum power, load should be changed, but this is impossible. In order to overcome this problem, an interface part is considered to utilize the maximum turbine capacity for a constant power and different environmental condition. This interface part is a maximum power point tracker which includes a DC/DC converter and a controller [6].

Developed algorithms for controllers can be clustered into three control methods, which are named tip speed ratio (TSR) control [7], [8] and [9], power signal feedback (PSF) control [10], [11] and [12] and hill-climb search (HCS) control [13]. However, there are a lot of proposed methods in the literature. In [14] artificial neural network (ANN) is combined with particle swarm optimization (PSO) to use the maximum power point tracking (MPPT) by controlling the rotor speed of the wind generator. In [15] a variable-speed wind-generator maximum power point tracking (MPPT) based on adaptive neuro-fuzzy inference system (ANFIS) is presented. The optimal speed rotation is predicted by using the variation of the wind speed as the input and implementation of ANFIS model.

In [16] a maximum power point tracking (MPPT) technique for high-performance wind generators with induction generators based on the growing neutral gas (GNG) network is presented. A GNG network has been trained offline to learn the specification of turbine surface torque versus wind and machine speeds and has been used online to obtain the wind tangential speed on the basis of the estimated torque and measured machine speed (surface function inversion).

In this paper, the MPPT algorithm is based on the slope of the wind-turbine mechanical power versus rotation speed. The ANN estimator and the predictive controller of the boost converter are implemented together for improving the accuracy and fastness compared to traditional methods. The uncertainties in the wind turbine system are estimated by neural-network and the duty cycle of dc/dc converter is determined by a predictive controller. The paper is organized as follows: in section 2, the wind turbine and its characteristics are described. In section 3 the proposed method is illustrated. Finally, Simulation and results are done in section 4.

2. DESCRIPTION OF WIND TURBINE

The main parts of the wind conversion systems are: wind turbine, generator, rectifier, dc/dc converter, and control unit. For a wind turbine, the wind power can be expressed as Equation (1).

$$P_{wind} = \frac{1}{2}\rho A V_w^3 \tag{1}$$

Where ρ is the air density, A is the turbine blade sweep area and V_w is the wind speed. If the friction be neglected, mechanical characteristics of a turbine can be obtained as Equation (2-4).

$$T_m - T_{Load} = J\frac{d\omega}{dt} \tag{2}$$

$$P_m - P_{Load} = J\omega\frac{d\omega}{dt} \tag{3}$$

$$P_m = 0.5 \times C_p(\lambda,\beta) \times \rho \times A \times V^3 \tag{4}$$

Where T_m is the mechanical torque of the turbine, T_{load} is the load torque, J is the inertia of the total system, ω is the angular speed of the rotor, P_m is the mechanical power of turbine, V is the wind speed, C_p is the turbine power coefficient, λ is the blade tip speed ratio and β is the blade pitch angle. In (4), λ is defined as Equation (5).

$$\lambda = \frac{r\omega}{V_w} \tag{5}$$

Where r is the wind-turbine blade length and ω is the wind turbine rotation speed. C_p is the function of the tip speed ratio λ and the blade pitch angle β as shown in Equation (6). The typical function is [16]. Figure 1 shows that at different blade angles, the power coefficient vary with tip speed ratio [17].

$$C_p(\lambda,\beta) = 0.5176 \times \left(\frac{116}{\lambda_i} - 0.4\beta - 5\right) \times \frac{-21}{\lambda_i} + 0.0068\lambda$$
$$where \quad \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.0035}{1+\beta^3} \tag{6}$$

If β is at a given value, C_p has a maximum value of C_{pmax} and λ_{opt} is corresponding to the tip speed ratio. In order to obtain the best power coefficient, we could obtain an optimal line by connecting λ_{opt} points as shown in Figure 2. If C_P is maximal, the wind turbine output power will be maximized.

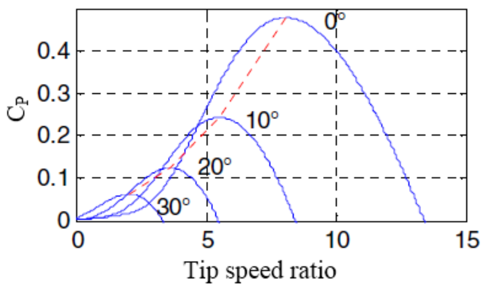

Figure 1.Wind turbine power coefficient of a wind turbine [17]

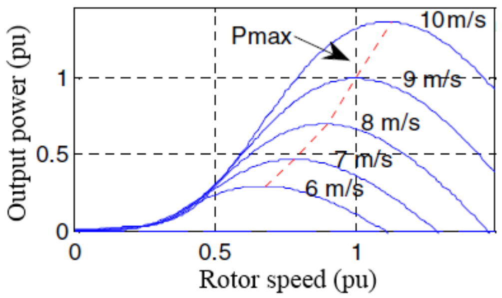

Figure 2. Power characteristic of a wind turbine [17]

3. PROPOSED WIND GENERATION SYSTEM and CONTROL PRINCIPLE

In this section, it is explained the results of research and at the same time is given the comprehensive discussion. Results can be presented in figures, graphs, tables and others that make the reader understand easily [3], [9]. The discussion can be made in several sub-chapters. In wind generation systems, the output power varies by the wind velocity. In order to obtain the maximum power, wind generation system should operate in variable speed state. To operate in this case, it is necessary to separate the generation part of the system from the consumption part. So, three phase voltage of PMSG generator is rectified by the AC/DC rectifier.

From the Equation (4) and (5), it can be seen that the maximum turbine power and the corresponding turbine rotor speed are proportional to wind velocity. Hence the wind turbine generation system could be controlled by changing the rotor speed proportional to wind speed to obtain maximum power. Therefore, the wind velocity has an important role in the MPPT algorithm. The dynamics of wind turbine generation system is described as Equation (7).

$$\frac{dP_e}{d\omega_r} = \frac{dP_m}{d\omega_r} - J\frac{d\omega_r}{dt} - J\omega_r\frac{\frac{d^2\omega_r}{dt^2}}{\frac{d\omega_r}{dt}} \tag{7}$$

Where J is the system inertia and P_e is generator power.

Figure 3 presents the proposed wind turbine driven PMSG and its controller. This system includes a PMSG driven by a wind turbine, an AC/DC rectifier, an artificial neural network estimator, boost converter and its predictive controller. Firstly, the ANN estimator predicts the wind speed. Then, based on the obtained wind speed, the wind turbine drives the PMSG. Finally, the predictive controller controls the duty cycle boost converter to obtain the maximum efficiency.

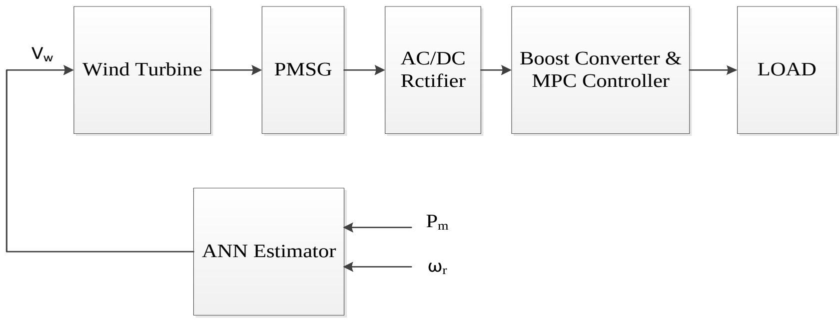

Figure 3. The proposed wind generation system and its controller

3.1. Wind Velocity Estimation by ANN

The proposed neural network is used to estimate the fast and accurate velocity of wind to avoid using the mechanical sensor (anemometer). In this method, P_m and ω_r are inputs of the neural network which is obtained from mechanical characteristic of turbine according to equation (4) and neural network is configured with 2 linear neurons as input layer, 5 sigmoid neurons in hidden layer and 1 neuron in output layer.

In order to train the neural network, the method of back propagation with Levenberg-Marquardt back propagation training function and mean square error (MSE) with 1000 samples of rotor speed and output power are used. Also, wind velocity samples are used as target of the ANN training as shown in Figure 4.

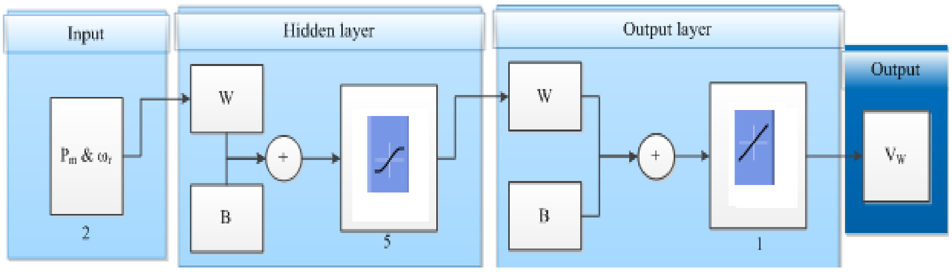

Figure 4. The proposed artificial neural network

3.2. Predictive Controller Design for Boost Converter

The predictive model of controller is implemented to estimate the future behavior of the controlled variables so that proper control actions could be determined [18] and [19]. A DC/DC boost converter is used to control the V_{dc} in order to extract the maximum power from the system. In predictive controller, output voltage of converter is compared with reference value and is used to obtain the maximum power point based on the slope method. Then, control voltage is produced for PWM controller and control of duty cycle. One of the most interesting advantages of this controller is simplicity of control and implementation that is leads to fast response and exact tracking as shown in Equation (8). As it can be seen from the Figure 5, the operation of the converter can be described as follows when the switch is closed (S=1).

$$\begin{aligned} \frac{di_L}{dt} &= \frac{v_{dc}}{L} \\ \frac{dv_{dc}}{dt} &= -\frac{i_L}{C_1} + \frac{i_{dc}}{C_1} \\ \frac{dv_o}{dt} &= -\frac{v_o}{RC_2} \end{aligned} \tag{8}$$

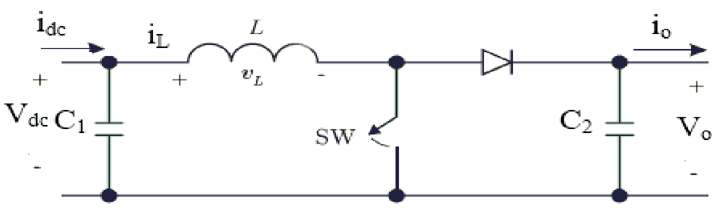

Figure 5. Boost converter [20]

When the switch is opened (S=0) as shown in Equation (9), we have:

$$\frac{di_L}{dt} = \frac{v_{dc}}{L} - \frac{v_o}{L}$$
$$\frac{dv_{dc}}{dt} = -\frac{i_L}{C_1} + \frac{i_{dc}}{C_1} \quad (9)$$
$$\frac{dv_o}{dt} = \frac{i_L}{C_2} - \frac{v_o}{RC_2}$$

Discrete form of the system can be written as shown in Equation (10).

$$i_L(k+1) = i_L(k) + \frac{T_S}{L} v_{dc}(k) - \frac{T_S}{L} v_o$$
$$v_{dc}(k+1) = -\frac{T_S}{C_1} i_L(k) + v_{dc}(k) + \frac{T_S}{C_1} i_{dc}(k)$$
$$v_o(k+1) = -\frac{T_S}{C_2} i_L(k) + (1 - \frac{T_S}{RC_2}) v_o(k)$$
$$i_L(k+1) = i_L(k) + \frac{T_S}{L} v_{dc}(k) \quad (10)$$
$$v_{dc}(k+1) = -\frac{T_S}{C_1} i_L(k) + v_{dc}(k) + \frac{T_S}{C_1} i_{dc}(k)$$
$$v_o(k+1) = (1 - \frac{T_S}{RC_2}) v_o(k)$$

The cost function for states of open and close switch is defined in Equation (11).

$$J^1_{S=0,1} = w_A \cdot \left| v_o(k+1)_S v^* \right|^2 + w_B \cdot \left| i_L(k+1)_S - i^* \right|^2 \quad (11)$$

The cost function will be calculated for all the switching states; for the next step the proper control action will be applied.

4. SIMULATION RESULTS

The proposed wind generation system is simulated by using MATLAB/SIMULINK. The parameters of wind turbine are: Nominal power 12KW, Nominal wind velocity 12 m/s, turbine radius r_m=3m, C_{pmax}=0.665, λ_{opt}=10.97 and pitch angle=0 deg. Generator parameters are: Nominal power 13.7 KW, three-phase, Phase resistance R_s=0.0495 Ω, phase inductance L_s=0.831 mH, flux linkage ψ = 0.435 V.s., number of poles P=5, total inertia of turbine and generator: J = 0.032 kg*m^2.

As it has been explained in pervious section, firstly the ANN estimates the wind velocity. The performance of the neural network is shown in Figure 6. We have run the ANN network and the estimated wind velocity of 14.6 m/s is obtained. This figure show that desired performance of ANN estimator. After training and running the ANN estimator, as it is shown in Figure 7, the proposed wind generation system and its controller is implemented in SIMULINK.

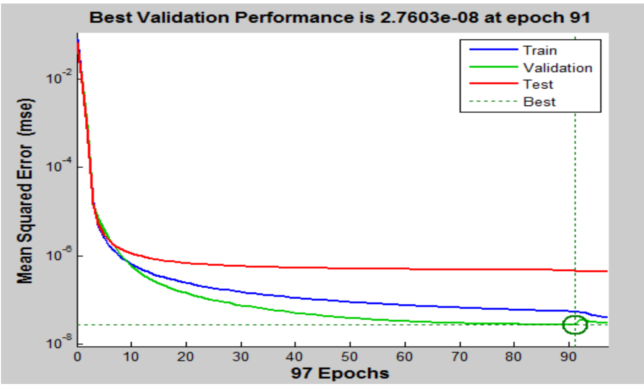

Figure 6.Performance of the ANN

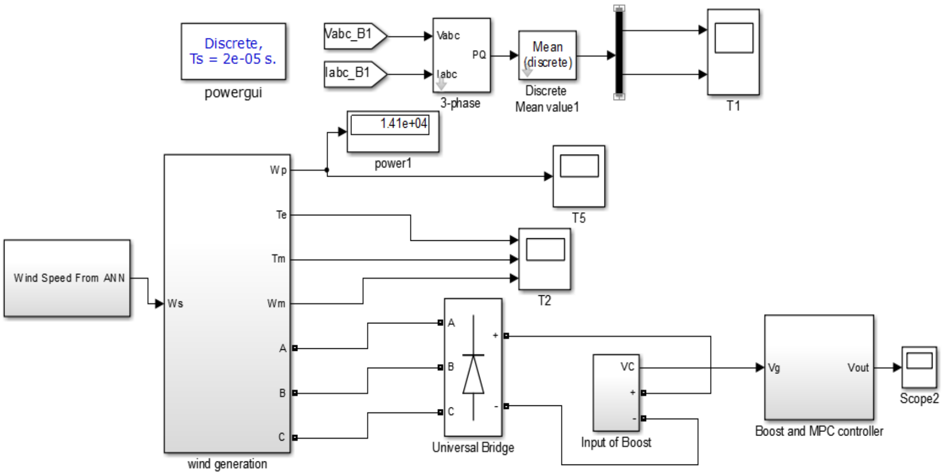

Figure 7. View of implemented system in MATLAB/Simulink

The simulation results are shown in Figures 8 to 10. Figure 8 shows the output of the wind generation system for 0.1 T. Figure 8(a) is the electrical torque of the turbine and the Figure 8(b) is the mechanical torque and Figure 8(c) is the rotor speed. As it could be seen the torque follows the rotor speed. Moreover Figure 9 shows the Wind speed, Rotor speed, Pitch angle, Electrical torque, and mechanical Torque of the turbine generation system. Figure 10 show the output of the generator includes output voltage (rms), line current (rms) and output power P_{ac}. Hence, by analyzing these figures, it can be observed that the turbine operates with a C_p close to the optimal value. Moreover the duty cycle of the boost converter is optimized. The simulation results show that the proposed system can track the maximum power point exactly.

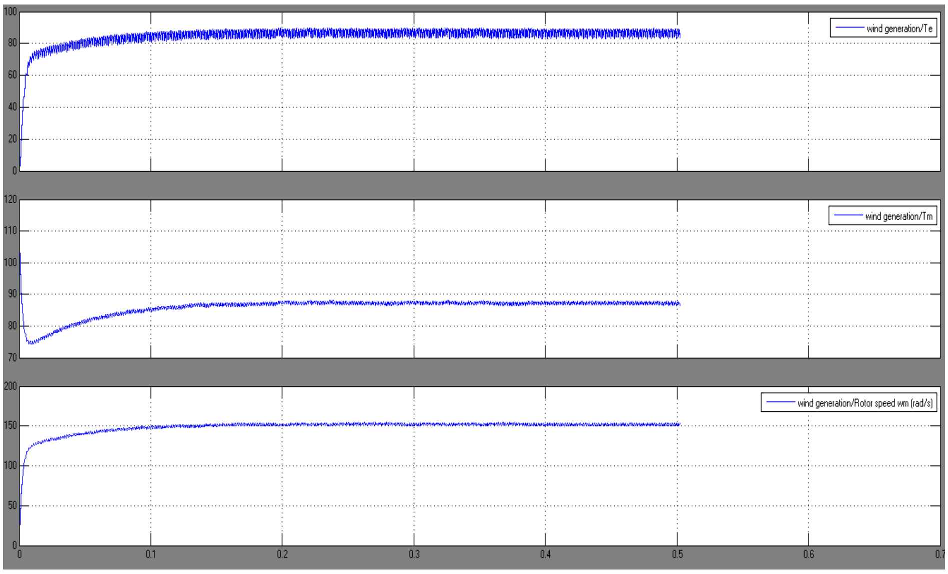

Figure 8. Output of the wind generation system (a) T_e: electrical Torque, (b) T_m: Mechanical Torque and (c) rotor speed

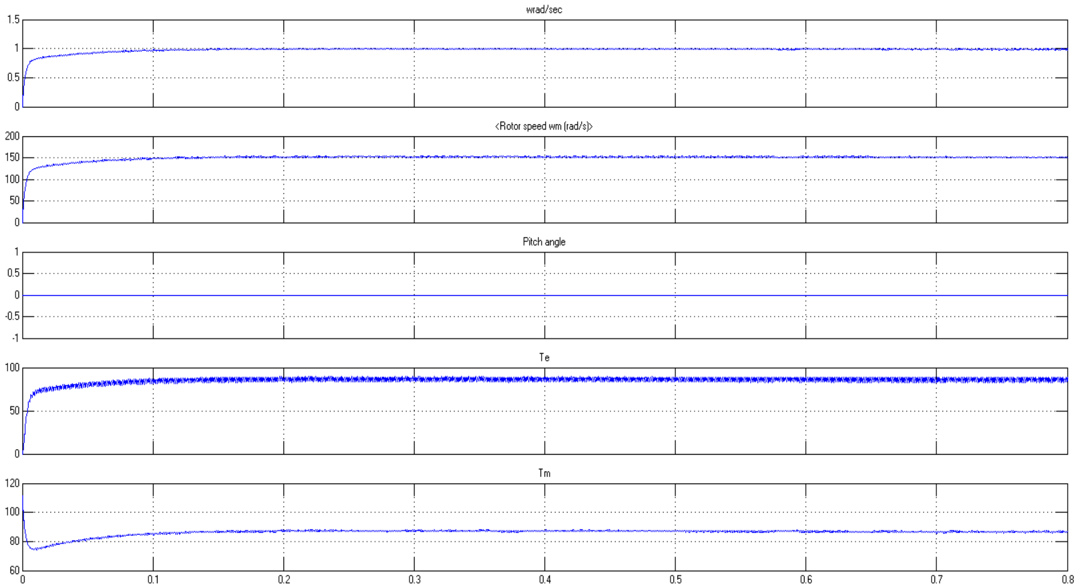

Figure 9. (a) Wind speed (rad/s), (b) Rotor speed (rad/s), (c) Pitch angle (deg), (d) Electrical torque T_e and (e) mechanical Torque T_m

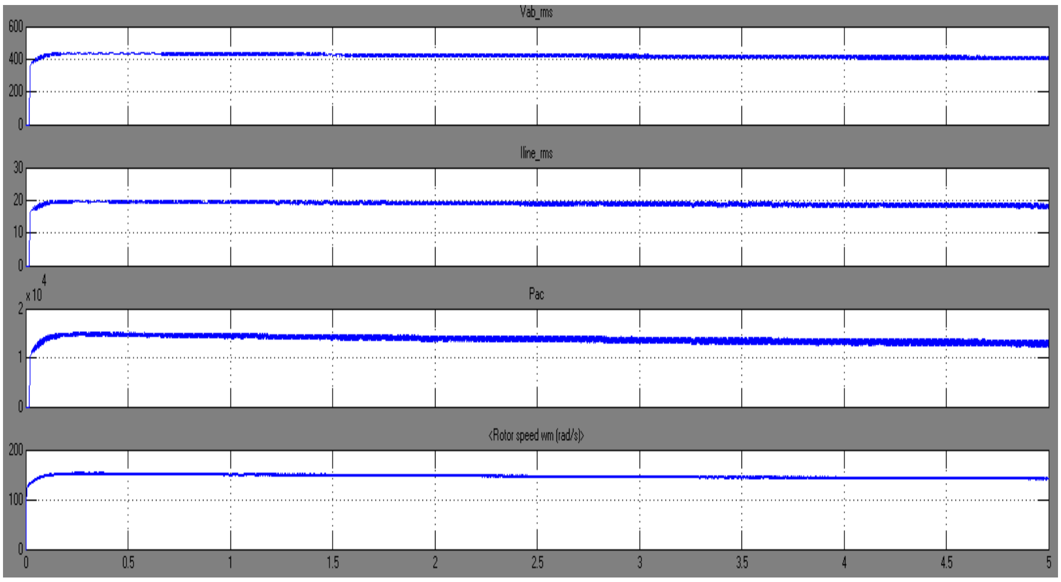

Figure 10. Output of the generator (a) Output voltage (rms), (b) Line current (rms), (c) output power P_{ac} and (d) rotor speed

5. CONCLUSION

In this paper, the ANN estimator and the predictive controller of the boost converter is presented together. A neural network is used to estimation of wind velocity. The neural networks inputs are rotor speed and the output power. The estimated wind speed is the output of the ANN that is used in the wind generation system. Moreover, predictive controller is used to maximize the efficiency of the boost converter. The simulation results proved the performance of the proposed method. Compared to the traditional control strategies, the proposed method has a higher performance for extraction of mechanical power and is comparatively easy and high practical value with easy hardware implementation.

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