Considerations above modeling and control of windmills

Iosif Szeidert, Octavian Prostean, Ioan Filip, Nicolae Budisan, Vasar Cristian

Department of Automation and Industrial Informatics, Faculty of Automation and Computer Sciences, “Politehnica” University from Timisoara, Av. V. Parvan, No.2, 300223, Timisoara, Romania, Phone: (0040) 256 403237, Fax: (0040) 256 403214, siosif@aut.utt.ro

Abstract: The paper presents issues regarding the modeling, control (using conventional PD/neural network controller) and simulation of windmills. There are considered several applications study cases based on asynchronous generator usage, by using the MATLAB-PSB (Power System Blockset) implementations for different specific functioning regimes.

Keywords: Windmills, modeling, simulation, control, asynchronous generator, neural networks, MATLAB-Simulink environment, functioning regimes

1 INTRODUCTION

The paper describes a windmill structure implemented in the MATLAB-Simulink simulation environment by using the specialized PSB toolbox, designed for modeling and simulation of energetic and electrical components. In figure 1 there is presented the MATLAB - Simulink diagram of the considered windmill, which contains the following main components: asynchronous machine, synchronous machine, wind turbine, frequency regulator and dump load. The practical problems in the grid integration of windmill represent special cases of design and analysis of energetic power systems. [1], [5]

2 WINDMILL MODELLING AND CONTROL ISSUES

The asynchronous machine model is based on the Park dq equations (detailed in appendix). In this paper, the asynchronous machine operates in the generating regime. In this regime, the input into the machine is represented by the mechanical energy (torque) and the output is represented by the electrical energy (voltages, currents, frequency). There occurs the necessity to adjust the rotor speed in relation to the changing wind speed in order to maintain the aerodynamic efficiency at a maximum possible value. The considered wind turbine is modeled as a controlled mechanical torque source that supplies the asynchronous generator. The frequency regulator input is represented by the voltage’s frequency. There is used a three-phase Phase Locked Loop (PLL) system to measure the frequency of the 3-phase voltage of the network. Therefore, the measured frequency is compared to the reference frequency (60 Hz) in order to obtain the frequency error. Afterwards, this error is integrated in order to obtain the phase. A PD type controller derives the error phase.

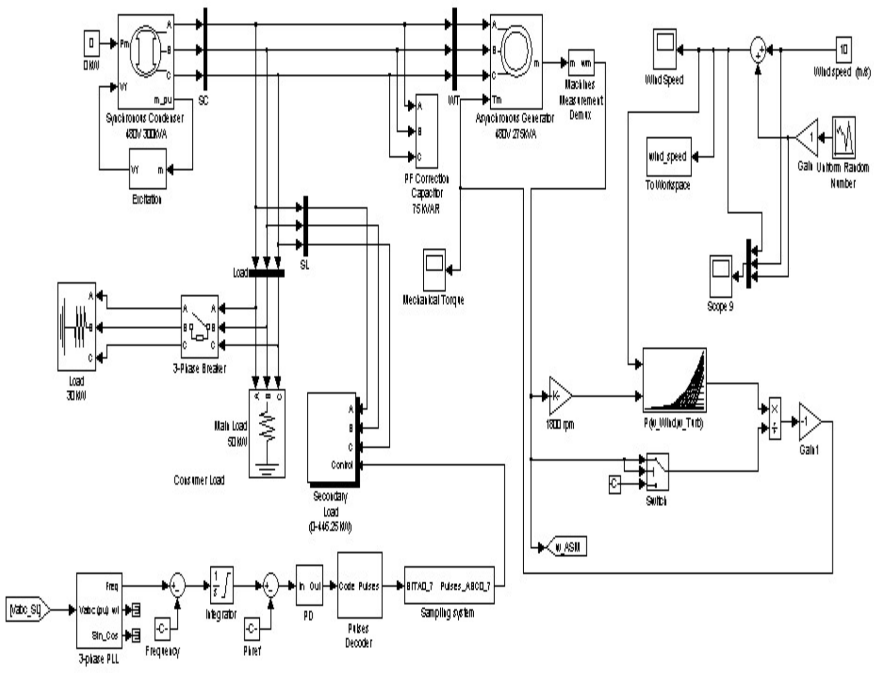

Figure 1. The MATLAB-Simulink Windmill Diagram.

The analog signal is afterwards converted to an 8–bit signal that commands the switching elements from the dump load. The regulator's output is the desired power of the dump load. The dump load is used to dissipate the excess power produced by the windmill and simultaneously to maintain constant the frequency. The dump load consists of eight three-phase resistors connected in series with GTO (Gate Turn-Off) type based switches. The dump load uses an 8-bit binary command so that it results that the load can be varied in the range of 0 to the maximum power in 256 steps. [3]

In the considered windmill control structure, the synchronous machine presents only the role of a synchronous compensator. In figure 2 there is detailed the structure of the considered frequency regulator. This structure has been used in the first two study cases (A and B).

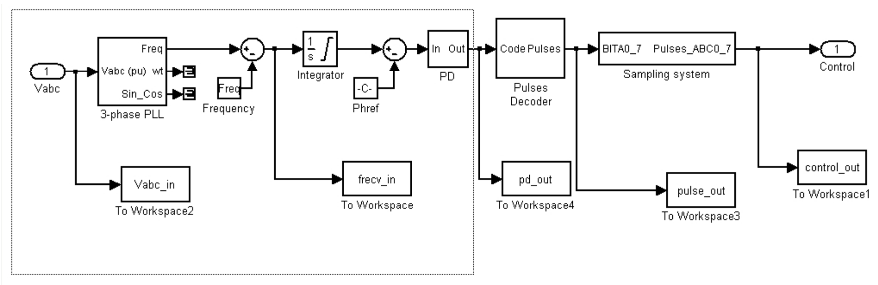

Figure 2. The frequency regulator.

Another study case (case C) was developed using a modified control structure. The marked area from figure 2 (containing the PLL block and conventional PD controller) has been replaced with a recurrent neural network structure. The neural network was trained considering the prescribed frequency and phase reference values constant. We considered several neural networks. The best performances were obtained by using a 4 layers neural network. The modified structure is presented in figure 3.

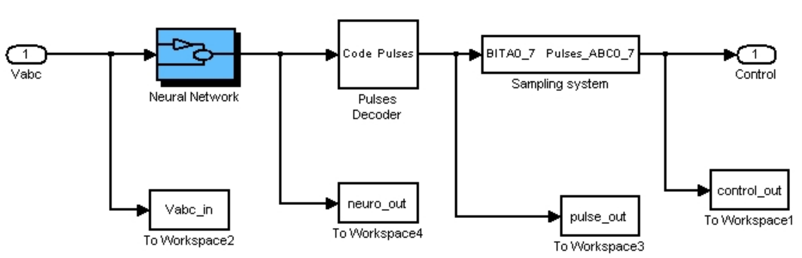

Figure 3. The frequency regulator based on a neural network.

3 WINDMILL STUDY CASES – SIMULATION RESULTS

Study case – A

The asynchronous generator's short-circuit regime transients

This specific regime can occur in the case of an autonomous or grid connected windmill. The short-circuit regimes can be total or partial (1,2,3-phase short-circuit). The study of these transients reveals the mechanic stress of the energy conversion line. These regimes can lead to severe system failures. The study of this specific transients are important in order to implement safety procedures that prevent the malfunction of the energy conversion line or of the grid connected consumers. In this study case, there is considered the case of a partial short-circuit (one-phase short-circuit) that occurred at 1,00 seconds. The short-circuit acts for 0,50 seconds. Afterwards, at 1,50 seconds the short-circuit is removed. The simulation interval is set to 0 … 3 seconds (using the variable step solver, ode23tb). The wind speed is considered constant and preset to 10 (m/s). In figure 4 is represented the evolution of the 3-phase voltage system. There can be spotted that on the phase where the short-circuit occurred the voltage is obviously zero, but on the other two phases there occurs an over voltage effect, that drops to the nominal value after the short-circuit removal, due to the control system action. Similarly, in figure 5 there can be also noticed that after the short-circuit removal the frequency advances towards the nominal value. There can be noticed that in this highly stressing regimes (short-circuit regimes) the power energy parameters cannot be maintained in compliance with the electrical energy delivery parameter standards/regulations (STAS 930/1989, RENEL - PE 143/1994). Thus, there can be concluded that in the case of a short-term short-circuit the windmill's control structure succeeds to stabilize and to operate the energy conversion in the range of nominal operating conditions. [2],[4]

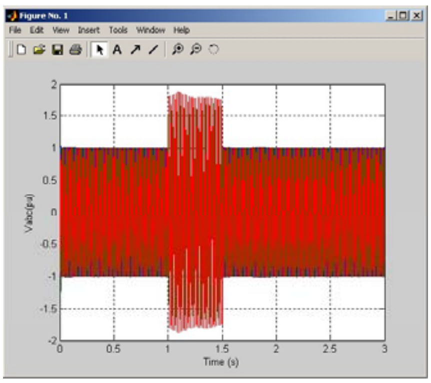

Figure 4.Vabc 3-phase voltage (pu).

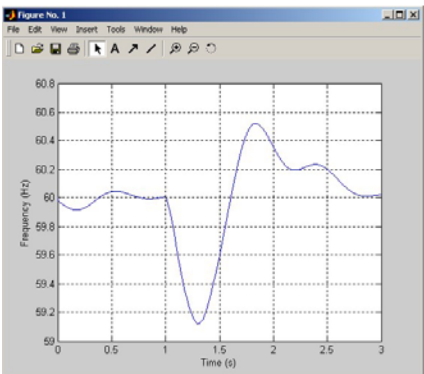

Figure 5. Frequency (Hz).

Study case – B

The asynchronous generator's nominal functioning regime at rated power

The second study case is conducted considering the normal functioning regime at rated power and rated wind speed.

The wind speed is considered having the average value of 10 (m/s) during the entire simulation time period. The wind speed presents a random variation. In figure 6 is represented the considered wind speed evolution. The simulation interval is set to 0 … 3 seconds. Initially, there is connected only a main consumer of 50 kW. At 1,00 seconds there is also connected a secondary consumer with nominal power of 40 kW. At 2,00 seconds the secondary consumer is disconnected. This fact can be noticed in the figure 9, which represents the evolution of the considered load power.

In the figure 7, is represented the evolution of the electrical energy frequency. It can be noticed the fact that in the spite of a continuous wind speed variation and of a variable load power (consumer) the entire windmill control structure succeeds to control the network voltage's frequency. There can be noticed that the frequency varies between 59,5 Hz and 60,6 Hz. In figure 8, is represented the asynchronous machine speed (rpm) in pu (per unit) units. There can be noticed that the rotation speed is slightly over the synchronous speed because the machine operates in generating mode. The wind turbine's power evolution (kW) is represented in pu units (figure 10).

It can be concluded that the considered windmill's control structure presents good overall control performances.

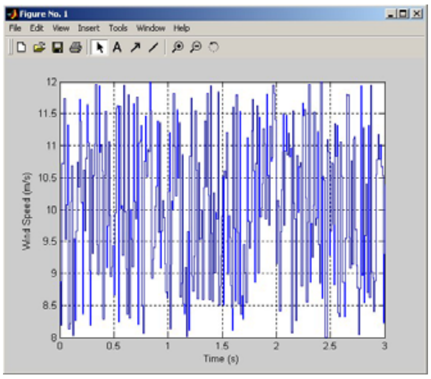

Figure 6. Wind speed evolution (m/s)

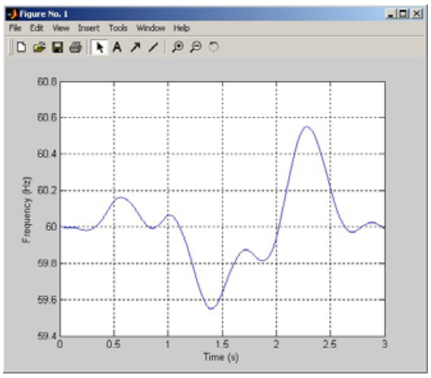

Figure 7. Frequency (Hz).

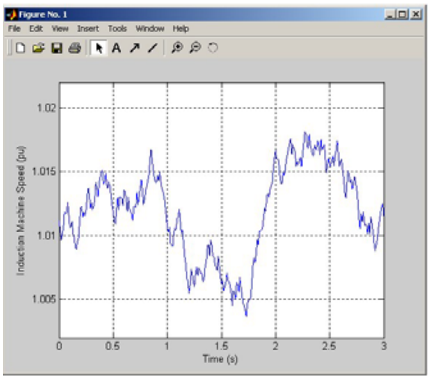

Figure 8. Asynchronous machine's speed (pu).

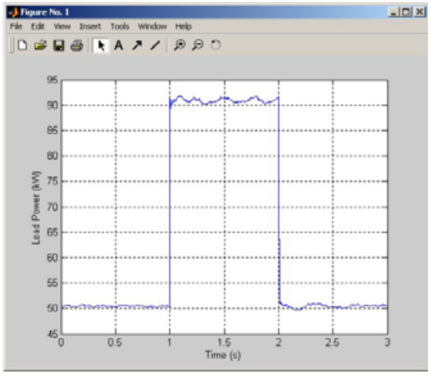

Figure 9. Load power (kW).

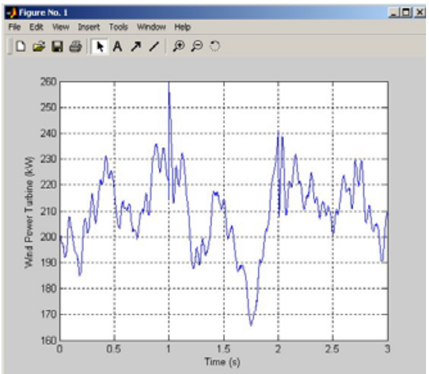

Figure 10. Wind turbine power (kW).

Study case – C

The asynchronous generator's nominal functioning regime at rated power (considering the neural network based control structure)

In this study case there were considered the same simulation conditions as in the previous case (case B), but using the modified control structure based on a recurrent neural network. The obtained results are presented in figures 11, 12 and 13, the frequency, the asynchronous machine's speed and respectively the load power evolution. As it can be remarked the control structure presents a lower performance level, but which still satisfies the imposed goal of the windmill control. However, the modified control structure represents a viable control solution.

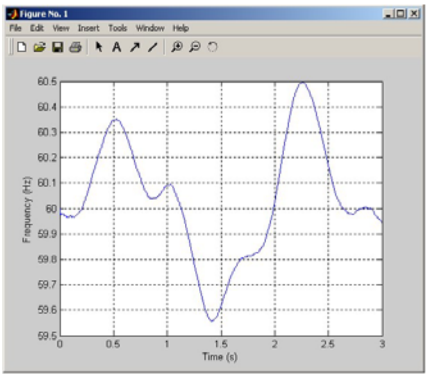

Figure 11. Frequency (Hz).

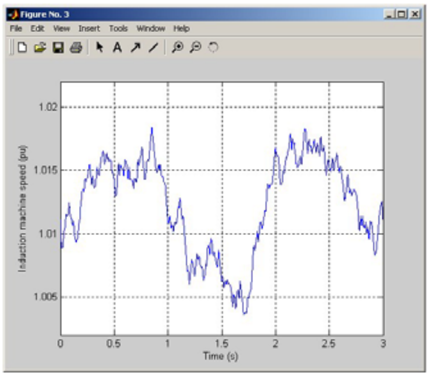

Figure 12. Asynchronous machine's speed (pu).

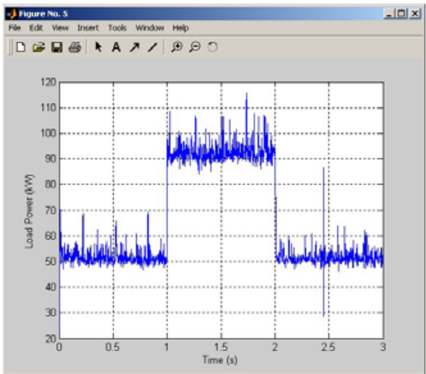

Figure 13. Load power (kW).

Conclusions

There can be concluded that both controller structures (conventional PD/neural network) present similar control performances. The usage of the neural network controller presents the advantage of an easier implementation on specialized computational structures, such as the case of control algorithms implemented on DSP (digital signal processors).

The above exposed study cases present a great significance in the actual trend of the global renewal energies usage and development such as the particular case of windmills. In order to study the windmills performances there is mandatory detailed analysis of the dynamic behavior of all main components of the wind energy conversion line: wind turbine, electrical generator, converter, grid and other additional elements).

It can be concluded that in the considered functioning regimes the modeled windmill structure presents an overall good performance regarding the specified energy power parameters in the context of the integration in a distributed power energy system (wind farms connected to the power grid).

References

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Appendix

Wind turbine model

The wind turbine is mainly characterized by the power speed characteristics. In the case of a horizontal axis wind turbine, operating in a steady state regime, the mechanical power P_{MEC} is expressed in (1):

$$P_{MEC} = \frac{1}{2}\rho\pi R^2 u^3 C_p(\theta,\lambda) \tag{1}$$

$$\lambda = \omega_{rot} R / u \tag{2}$$

where: ρ - represents the air density, R - is the turbine’s radius, u - the wind speed, $C_p(\theta,\lambda)$ - is the aerodynamic efficiency (power coefficient), θ - is the pitch angle, λ is the tip speed ratio (2) and ω_{rot} - is the rotor turbine speed.

Asynchronous machine model

The mathematical model of the asynchronous generator presents two subcomponents: the electrical system and the mechanical system. The equations (3)-(11) represent the Park dq - asynchronous machine model:

Electrical system equations:

$$U_{qs} = R_S i_{qs} + \frac{d}{dt}(L_s i_{qs} + L_m i_{qr}) + \omega(L_s i_{ds} + L_m i_{dr}) \tag{3}$$

$$U_{ds} = R_S i_{ds} + \frac{d}{dt}(L_s i_{ds} + L_m i_{dr}) - \omega(L_s i_{qs} + L_m i_{qr}) \tag{4}$$

$$U_{qr} = R_r i_{qr} + \frac{d}{dt}(L_r i_{qr} + L_m i_{qs}) + (\omega - \omega_r)(L_r i_{dr} + L_m i_{ds}) \tag{5}$$

$$U_{dr} = R_r i_{dr} + \frac{d}{dt}(L_r i_{dr} + L_m i_{ds}) - (\omega - \omega_r)(L_r i_{qr} + L_m i_{qs}) \tag{6}$$

$$T_e = \frac{3}{2} p\left((L_s i_{ds} + L_m i_{dr}) i_{qs} - (L_s i_{qs} + L_m i_{qr}) i_{ds}\right) \tag{7}$$

Where:

$$L_s = L_{ls} + L_m \text{ and } L_r = L_{lr} + L_m \tag{8)-(9}$$

Mechanical system equations:

$$\frac{d}{dt}\omega_m = \frac{1}{2J}(T_e - T_m) \text{ and } \frac{d}{dt}\theta_m = \omega_m \tag{10)-(11}$$

Where: R_s, L_{ls} - stator resistance and leakage inductance, R_r, L_{lr} - rotor resistance and leakage inductance, L_m - magnetizing inductance, L_s, L_r - total stator and rotor inductances, U_{qs}, i_{qs} - q axis stator voltage and current, U_{qr}, i_{qr} - q axis rotor voltage and current, U_{ds}, i_{ds} - d axis stator voltage and current, U_{dr}, i_{dr} - d axis rotor voltage and current, ω_m - angular velocity of the rotor, θ_m - rotor angular position, p - number of pole pairs, ω_r - electrical angular velocity ($\omega_m \times p$), θ_r - electrical rotor angular position ($\theta_m \times p$), T_e - electromagnetic torque, T_m - shaft mechanical torque, J - combined rotor and load inertia constant.