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SEBASTIAN SZKOLNY, OLGIERD MAŁYSZKO*

HARDWARE-IN-THE-LOOP SIMULATOR FOR TESTING WIND TURBINE GENERATORS

SYMULATOR TYPU *HARDWARE-IN-THE-LOOP* DO TESTOWANIA GENERATORÓW TURBIN WIATROWYCH

A b s t r a c t

This paper presents research issues of electric generators using systems of the Hardware-in-the-Loop (HIL) type. Using the HIL system, it is possible to reproduce the actual operating conditions of wind turbines working with different types of generators in a laboratory environment. This approach easily and economically allows analyzing the hardware and software controlling the operation of the generator. This system has been implemented on the sbRIO National Instruments controller cooperating with regenerative frequency converter with DTC control of ABB. The paper presents all the components of this system and discusses their operation.

Keywords: *generator*, *wind turbine*, *simulator*, *test stand*

S t r e s z c z e n i e

W niniejszym artykule przedstawiono problematykę badań generatorów elektrycznych z wykorzystaniem systemów typu *Hardware-in-the-Loop* (HIL). Za pomocą systemu HIL możliwe jest odzwierciedlenie w środowisku laboratoryjnym rzeczywistych warunków działania turbin wiatrowych współpracujących z różnymi typami generatorów. Takie podejście pozwala na szybkie i ekonomiczne przygotowanie stanowiska badawczego do analizy działania sprzętu, jak i oprogramowania sterującego pracą generatora w warunkach zbliżonych do rzeczywistych. System ten został zaimplementowany na sterowniku sbRIO firmy National Instruments współpracującym z przemiennikiem częstotliwości ze sterowaniem DTC firmy ABB. W pracy przedstawiono ważniejsze składniki tego systemu i omówiono ich działanie.

Słowa kluczowe: *generator*, *turbina wiatrowa*, *symulator*, *stanowisko badawcze*

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* Ph.D. Eng. Sebastian Szkolny, Ph.D. Eng. Olgierd Małyszko, Department of Power Systems and Electrical Drives, Faculty of Electrical Engineering, West Pomeranian University of Technology, Szczecin.

1. Introduction

Electric power produced by wind turbines is strongly dependent on wind speed. As a result, the amount of production is rather unpredictable [5]. This behavior of wind turbines connected to the power system affects its stability.

In addition, modern wind turbines include such devices as voltage and frequency converters. As a result, the generated power contains a lot of harmonic current and voltage.

In order to determine parameters such as the characteristics of the generated active and reactive power, flickers or harmonics are necessary to carry out the relevant tests. The tests must be performed in a wide range of parameter changes. Such research can take months, and generate significant cost.

An interesting solution to this problem is to conduct research using HIL (Hardware-in--the-Loop) simulation methods [7, 8, 11, 13–15].

The idea of a HIL simulation system is to replace real systems with a simulation platform. This simulation platform is equipped with an interface for connecting the simulator with real devices. In the proposed solution, the wind turbine and its control systems are simulated by the HIL system. The simulation platform is connected with a real generator by an asynchronous motor. The torque of the asynchronous motor is controlled by the simulation platform. The simulated process must be described by the relevant mathematical models. The model is described in this paper.

Using the HIL system, it is possible to reproduce the actual operating conditions of wind turbines working with different types of generators in the laboratory environment. This approach easily and economically allows analysis of the hardware and software controlling the operation of the generator.

2. The test stand

In 2008, at the Faculty of Electrical Engineering of West Pomeranian University of Technology in Szczecin, the Research Group for Power Transmission Lines and Unconventional Power Plants Analysis was set up (the authors of this paper are its members). The team deals with an analysis of the possibilities of connecting renewable energy sources to the power system, as well as the technical aspects of the decentralized power generation [2–4]. Team experience gained in this field led to the start of a new research topic and led to a decision to build the test stand for simulating the operation of the wind turbine. For this purpose, the dynamometric stand built in the parent department of the authors within the framework of a research project [1] was used.

This test stand is equipped with a driving system consisting of a high speed asynchronous motor type CM-5-7 (Fig. 1) and inverter with direct torque control (DTC) type ACS 800 (Fig. 2) both devices are manufactured by ABB.

Using this set, it is possible to get a torque on the shaft of the generator of about 100 Nm. The limitation is caused only by the torque sensor DataFlex 32/100. The maximum instantaneous torque equals 300 Nm (Fig. 3). It can be obtained up to its rated speed of 4000 rpm.

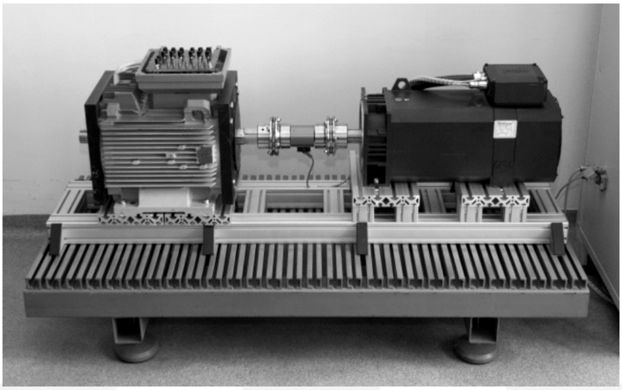

Fig. 1. The dynamometer used to build a wind turbine emulator

Fig. 2. The inverter ACS 800 and the controller NI sbRIO 9606

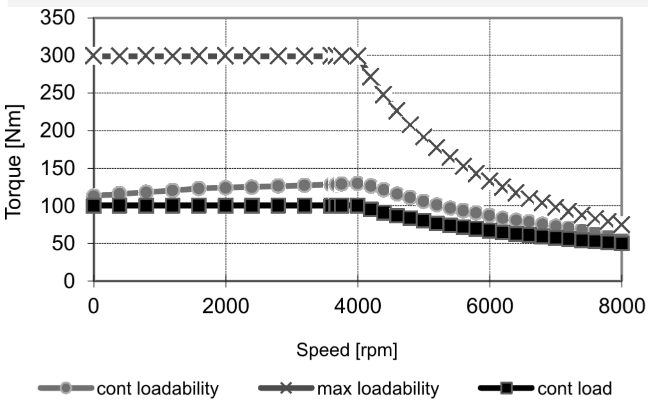

Fig. 3. Mechanical characteristics of the drive used for the construction of the dynamometer

Rated power of the motor equals 54 kW, maximum speed of 8000 rpm and the moment of inertia of 0.15 kgm^2.

The NI sbRIO-9606 controller is used as a master control system. It is joined with the NI 9683 card by RMC connector. The NI 9683 card is used for the transmission of both analog and digital signals. The main task of the NI sbRIO-9606 controller is to control the dynamometer according to the given operation algorithm. In this case, it is the wind turbine simulator.

3. The control algorithm

The most important issue concerning the construction of the wind turbine simulator is modelling the wind speed variability in a virtual environment. This is necessary because the amount of electrical energy produced by wind turbine depends on wind speed.

3.1. Model Wind

In the analysis of a wind turbine operation in the power system, it is assumed that the variability of the wind speed can be modeled using the following methods: the method of the sum of harmonics; the method of step changes or incremental changes; the method of stochastic variables [5]. For the construction of the test stand, the first method was used (i.e. the sum of harmonics). In addition, wind gusts are also included. Such a model of wind can be described by the following relationships [5]:

$$V(t) = V_0\left(1 + \sum_k A_k \sin(\omega_k t)\right) + V_g(t) \tag{1}$$

where:
V_0 – the average value of the wind speed [m/s] (assumed 9 m/s),
A_k, ω_k – amplitude [m/s] and pulsation [rad/s] of the k-th harmonic of wind speed,
$V_g(t)$ – wind gusts, which are described by the following equation [5] [m/s],

$$V_g(t) = \frac{2V_{g\max}}{1 + e^{-4(\sin(\omega_g t) - 1)}} \tag{2}$$

where:
V_{gmax} – amplitude of wind gusts [m/s],
ω_g – speed of wind gusts [rad/s].

In practice, it is assumed that the frequency of wind speed harmonics is in the range 0,1, …, 10 Hz while the amplitude of wind gusts can be up to 10 m/s with a period in the range of 10–50 sec. An example of these relationships implemented in LabView is shown in Fig. 4 and an example of wind speed variability for sample parameters is shown in Fig. 5.

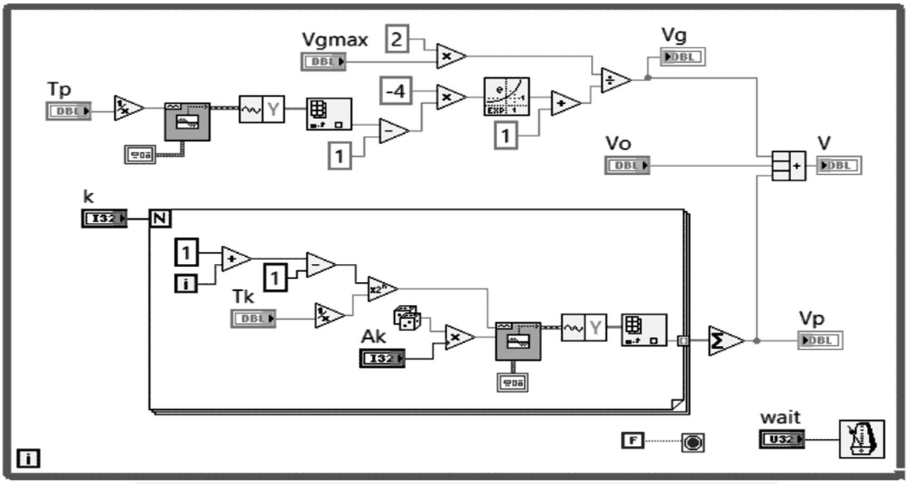

Fig. 4. A subprogram (subVI) generating the wind speed variability

3.2. Power of the wind turbine

The value of the power produced by the wind turbine can be described by the following mathematical model [9, 10, 12]:

$$P_w(V) = \begin{cases} 0 & V < V_{ci} \\ aV^3 - bP_r & V_{ci} \le V < V_r \\ P_r & V_r \le V < V_{co} \\ 0 & V_{co} \le V \end{cases} \tag{3}$$

where:

P_w – electric power generated by the wind turbine [W],
P_r – rated power of wind turbine [W],
V_{ci}, V_r, V_{co} – cut-in, nominal and cut-out wind speed [m/s],
a, b – coefficients which depend on construction of the turbine.

This model determines the average value of the power produced by the wind turbine depending on wind speed. However, at a given wind speed, the real wind turbine may produce different values of electrical power. This is shown in Fig. 6.

Furthermore, in the case of the flicker analysis or the quality parameters of electric power, the model described by the equations (3) is insufficient. This is because it does not take into account a number of phenomena affecting these parameters – e.g. wind turbine power changes caused by a mechanical vibrations associated with moving blades of the wind wheel in front of the tower of wind turbine, the asymmetry of the wind wheel or vibration of blades [5]. Therefore, it is necessary to accurately model these phenomena.

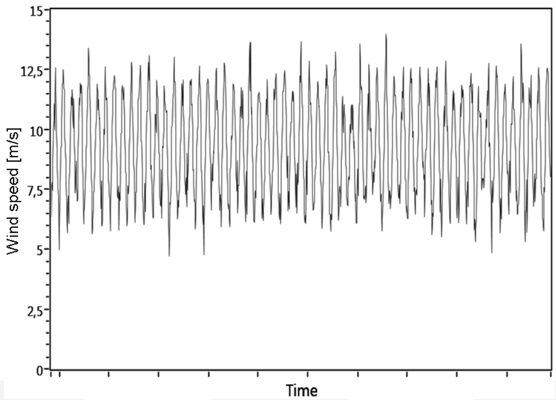

Fig. 5. An example of the variability of wind speed

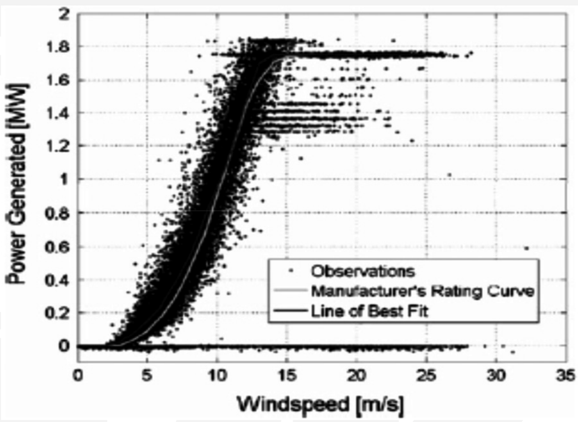

Fig. 6. The actual value of the power generated by the real wind turbine [6]

The mutual relationships between the mathematical descriptions of individual phenomena can be presented in the form of a diagram, this is shown in Fig. 7. Each of the blocks shown in this diagram describes one of the phenomena and is described by a separate subprogram (subVI). A set of these subprograms creates the structure of a program written in LabView environment.

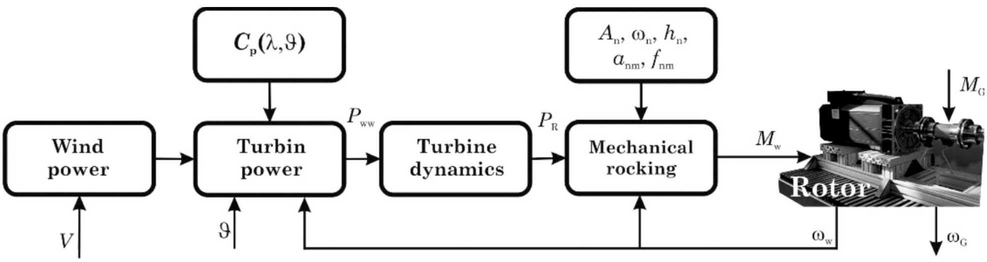

Fig. 7. Structure of wind turbine model

The first block (defined as the mechanical power of the wind turbine obtained from the wind flow) can be described by the following equation [5, 10]:

$$P_{WW} = 0,5 \cdot c_P(\lambda, \vartheta) \cdot \rho A V^3 \tag{4}$$

where:

$\rho = \rho_0 - 1.194 \cdot 10^{-4} H$	–	air density [kg/m^3],
$\rho_0 = 1,225$ kg/m^3	–	the air density at sea level at $T = 288$ K,
H	–	height of the location of a wind turbine above sea level [m],
A	–	swept area [m^2],
V	–	wind speed [m/s],
$c_P(\lambda, \vartheta)$	–	a coefficient which describes the characteristic of the turbine for the coefficient of blade pitch ϑ and specific speed λ.

Implementation of this relationship in the LabView environment is shown in Fig. 8

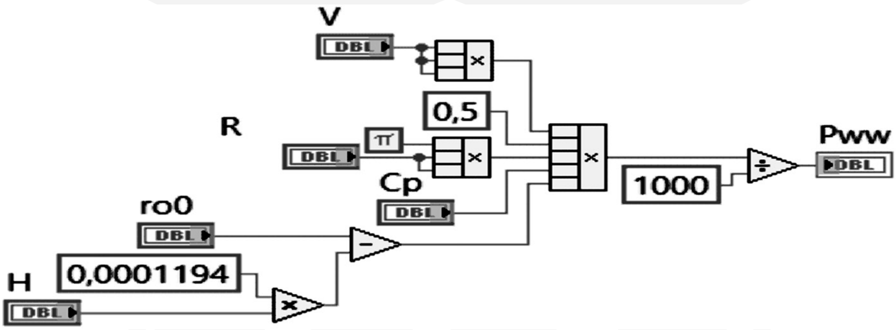

Fig. 8. A subprogram (subVI) defining the value of the power produced by the wind turbine

The coefficient c_p identifying the characteristics of the turbine can be described by the following relationship [5, 10]:

$$c_P(\lambda, \vartheta) = c_1\left(\frac{c_2}{\Lambda} - c_3\vartheta - c_4\vartheta^x - c_5\right)e^{-\frac{c_6}{\Lambda}} \tag{5}$$

where:

c_1–c_6 – coefficients (sample values taken from [5, 16]: $c_1 = 0.5$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 0$, $c_5 = 5$, $c_6 = 21$),

Λ – parameter which is described by the following formula:

$$\frac{1}{\Lambda} = \frac{1}{\lambda + 0.08\vartheta} - \frac{0.035}{1 + \vartheta^3} \tag{6}$$

where:

ϑ – blade pitch angle [rad],

$\lambda = \frac{\omega R}{V}$ – specific speed,

ω – angular velocity of the turbine rotor [rad/s],

R – radius of the rotor [m].

The code calculating the value of the coefficient c_p written in G-language is shown in Fig. 9.

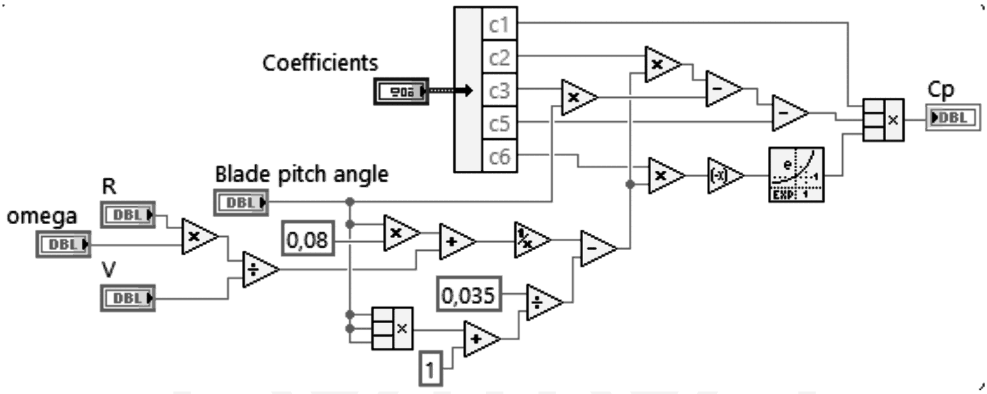

Fig. 9. The subprogram (SubVI) defining the coefficient C_p

3.3. Dynamics of the wind turbine

In real operating conditions, there are a number of phenomena associated with the impact of wind on the turbine blades. For this reason, it is necessary to take into account the dynamics of the wind turbine. The dynamics can be described by the following transmittance [5, 10]:

$$\frac{P_R}{P_{WW}} = K_W \frac{1 + sT_{W1}}{1 + sT_{W2}} \tag{7}$$

Typical values of these parameters for medium power wind turbines with a power control system using a drag effect are as follows [5]: $K_W = 1$, $T_{W1} = 3.3$ s, $T_{W2} = 0.9$ s.

3.4. Mechanical vibration

The quality of the produced electrical energy is mainly influenced by the variability of the wind speed. However, for better accuracy, the mechanical vibration of wind turbines must be also taken into account. These torsional oscillations are transmitted to the shaft, and then to the generator. As a result, electrical energy generated by the wind turbine and transmitted to the power system contains a number of harmonic current and voltage.

The most important factors which affect the mechanical vibration of wind turbines are as follows: the asymmetry of the wind wheel; change of power of wind turbine caused by mechanical vibrations associated with moving blades of the wind wheel in front of the tower of wind turbine; vibrations of the blades which are dependent on their structure and size [5, 17].

Taking into account the mechanical vibration of wind turbines, the mechanical power on the shaft of the wind turbine can be described by the following equation [5]:

$$P_W = P_R\left(1+\sum_{k=1}^{3} A_k\left(\sum_{m=1}^{2} a_{km} g_{km}(t)\right)h_k(t)\right) \tag{8}$$

$$g_{km}(t) = \sin\left(\int_0^t m\omega_k(\tau)d\tau + \phi_{km}\right) \tag{9}$$

where:

A_k, ω_k, $h_k(t)$, g_{km}, φ_{km} – value, pulsation, modulation, distribution and phase of the k-th type of power swings,

m – number of harmonics,

a_{km} – normalized value of g_{km}.

3.5. Model of gear

The next element taking part in the conversion of wind energy into electric energy is the gear. This consists of: pitch control; wind wheel; shaft; generator rotor; gear (not included in wind turbines with low-speed generators). The dynamics of this system can be described by the following differential equations [5]:

$$\begin{cases} \dfrac{\mathrm{d}\delta_W}{\mathrm{d}t} = \omega_W - \omega_{W0} = \Delta\omega_W \\ \dfrac{\mathrm{d}\delta_G}{\mathrm{d}t} = \omega_G - \omega_{G0} = \Delta\omega_G \\ J_W \dfrac{\mathrm{d}\Delta\omega_W}{dt} = M_W - K\left(\delta_W - \dfrac{\delta_G}{\upsilon}\right) - D\left(\Delta\omega_W - \dfrac{\Delta\omega_G}{\upsilon}\right) \\ J_G \dfrac{\mathrm{d}\Delta\omega_G}{\mathrm{d}t} = M_G + \dfrac{K\left(\delta_W - \dfrac{\delta_G}{\upsilon}\right) + D\left(\Delta\omega_W - \dfrac{\Delta\omega_G}{\upsilon}\right)}{\upsilon} \end{cases} \tag{10}$$

where:

ω_{W0}, ω_{G0} – the wind wheel speed and the generator rotor speed in a steady state [rad/s],

J – moment of inertia [kg·m^2],

M – mechanical moment [kg·m^2/s^2],

D – damping coefficient [kg·m^2/s],

K – stiffness coefficient [kg·m^2/s],

δ – angle [rad],

υ – gear ratio [–].

The index *W* refers to the wind wheel side, and the index *G* refers to the gear side of the generator rotor.

All of these elements of the wind turbine model may affect the quality of the produced electrical energy.

The proposed model of wind turbine allows analyzing the influence of individual parameters of the used mathematical model on the quality parameters of the generated electrical energy. This test stand can be also used in every stage of the wind turbine design and optimization.

4. Conclusions

This paper presents a Hardware-in-the-Loop type simulator used for the laboratory testing of wind turbine generators. Using this simulator, it is possible to reproduce the actual operating conditions of wind turbines with different types of generators in the laboratory. This approach allows an easy, economical and rapid analysis of both devices and their control software. This system has been implemented at sbRIO controller manufactured by National Instruments. This controller cooperates with the inverter with DTC control (manufactured by ABB). Furthermore, the use of the LabView graphical programming environment creates enormous opportunities for research prototype generators and converters of electric energy cooperating with wind turbines.

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