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LABORATORY STAND FOR SMALL WIND TURBINE SIMULATION

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Abstract. *The article presents a concept of the laboratory stand for wind turbine simulation, built on the basis of cage induction motor, supplied from a frequency converter. The model assumes control of the engine torque, using simple constant Volt/Hertz control with slip regulation, taking into account the moment of inertia of the simulated turbine. Performance of the system for different wind and generator load conditions has been shown. Test results proved, that the turbine torque is well tracked by the wind motor emulator.*

Keywords: induction motors, wind energy, simulation

STANOWISKO LABORATORYJNE DO SYMULACJI MAŁEJ TURBINY WIATROWEJ

Streszczenie. *W artykule przedstawiono koncepcję stanowiska do symulacji turbiny wiatrowej, zbudowanego na bazie silnika indukcyjnego klatkowego zasilanego z przetwornicy częstotliwości. Opracowany model zakłada sterowanie momentem silnika, przy wykorzystaniu prostego algorytmu u/f = const. z kompensacją poślizgu, przy uwzględnieniu momentu bezwładności odtwarzanej turbiny. Przedstawiono zachowanie się układu symulatora dla różnych warunków wietrznych i różnych wartości obciążenia generatora. Moment obrotowy turbiny jest wiernie odwzorowany pracą silnika.*

Słowa kluczowe: silniki indukcyjne, energia wiatru, symulacja

Introduction

In order to reduce the pollution and degradation of our environment, renewable sources of energy become more and more popular. Among them, wind power is said to be the most promising non fossil fuel, as its share of global energy production grows with the fastest pace [1, 2].

Current research is conducted towards increasing the efficiency of the process of extraction and conversion of wind power into electricity, and reducing the price per generated kilowatt hour. Depending on the adopted wind turbine control strategy and generator technology, power electronic converters can play different roles in wind turbine systems (WTSs). Such devices, like two or three level back-to-back converters, require sophisticated control algorithms, enabling generator torque control and synchronization of the output WTS voltage with the electricity grid.

Future trends assume that WTSs act like completely controllable power sources and enable support for the work of the electricity grid and better integration of the power generated from the wind [1, 2].

In development of such power converters wind turbine simulators may become very useful. Field tests using real wind turbines are usually troublesome and expensive. A laboratory stand in form of a wind turbine simulator can make the development process independent from wind conditions, which makes it faster and therefore can cut the costs.

The article presents a concept of the laboratory stand for wind turbine simulation, built on the basis of a cage induction motor, supplied from a frequency converter. The model assumes control of the engine torque, using simple constant *Volt*/*Hertz* control with slip regulation. This solution enables the reproduction of the steady state characteristics of an actual wind turbine. Such a concept was described in [6]. In the presented new approach the moment of inertia of the simulated turbine is taken into account and thus, in terms of varying wind speed, some aspects of the dynamic response of the turbine are reproduced by work of the simulator. In work [4] the computer simulation model was described. This article contains laboratory research results obtained from tests performed on the constructed simulator.

1. Power of the wind

The theoretically available power, that could be generated from the wind, can be expressed by [5]:

$$P_{\mathrm{w}} = \frac{\rho A V^3}{2} = \frac{\rho \pi R^2 V^3}{2} \tag{1}$$

where: A – swept area of blades [m^2], R – turbine blade radius [m], V – wind speed [m/s], ρ – density of air [kg/m^3]. According to Betz's law, an ideal turbine in theory would extract 16/27 of this power [6]. In practice the actual power generated by a wind turbine is even lower and is characterized by the wind power coefficient defined as:

$$C_{\mathrm{p}} = \frac{P_{\mathrm{t}}}{P_{\mathrm{w}}} \tag{2}$$

where: P_{t} – mechanical power generated by the turbine [W]. This value depends from the tip speed ratio [5, 6, 7]:

$$\lambda = \frac{\omega_{\mathrm{t}} R}{V} \tag{3}$$

where: ω_{t} – angular speed of blades [rad/s]. Equations (1) – (3) describe the Betz's law, which can be well illustrated by $C_{\mathrm{p}} - \lambda$ curves. An example of such a curve, characterizing a specific wind turbine, is presented in Fig. 1 [3]. The value of C_{p} resembles the performance of a wind turbine, and is also a function of the pitch angle β. For the curve presented in Fig. 1 β remained constant.

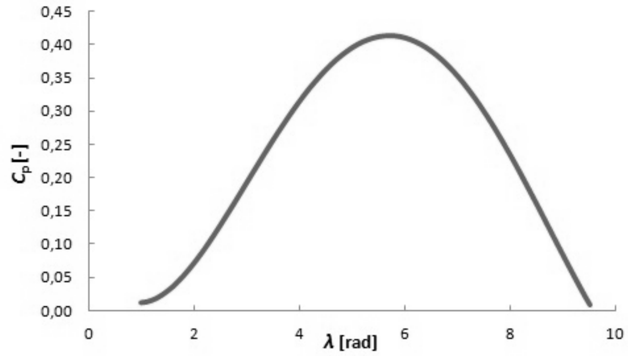

Fig. 1. $C_p(\lambda)$ wind turbine characteristic

The curve presented in Fig. 1 can be described by a fourth order polynomial [3]:

$$C_{\mathrm{p}}(\lambda) = A_0 + A_1\lambda + A_2\lambda^2 + A_3\lambda^3 + A_4\lambda^4 \tag{4}$$

where: A_0 = 0,093368, A_1 = -0,1838, A_2 = 0,118605, A_3 =-0,01773, A_4 = 0,000756.

The power generated by the wind turbine can also be calculated from:

$$P_{\mathrm{t}} = \omega_{\mathrm{t}} T_{\mathrm{t}} \tag{5}$$

where: T_{t} – wind turbine aerodynamic torque [N·m].

2. Wind turbine model

In order to emulate the work of a wind turbine a proper mathematical model, implemented in the system controller memory, is needed. The model used for the purpose of this work is presented in form of a block scheme in Fig. 2.

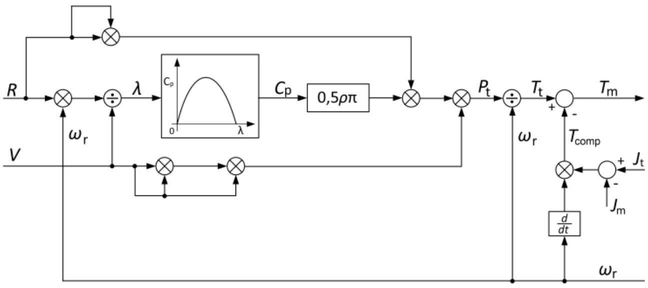

Fig. 2. Mathematical wind turbine simulator model block scheme

From equations (1) – (5) the wind turbine torque T_t can be derived. This value is considered as the steady state aerodynamic torque produced by a constant wind speed V. For dynamic system response emulation an additional torque component T_{comp} has to be taken into account. The wind turbine and wind turbine simulator drive trains are presented in Fig. 3.

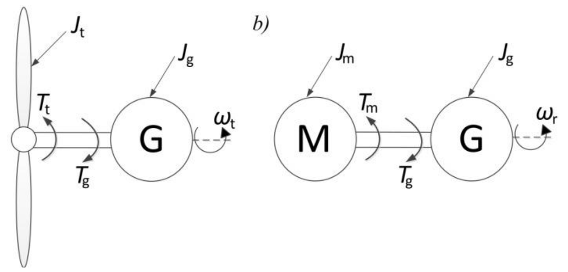

Fig. 3. Block scheme: a) wind turbine, b) wind turbine simulator drive train

The system presented in Fig. 3a can be described with equation [6]:

$$T_t = (J_t + J_g)\frac{d\omega_t}{dt} + T_g \tag{6}$$

where: J_t – wind turbine moment of inertia [kg·m^2], J_g – generator moment of inertia [kg·m^2], T_g – generator load torque [N·m], ω_t – turbine shaft angular speed [rad/s].

After replacing the wind turbine by the cage induction motor the system has the form presented in Fig. 3b, and can be described by equation [6]:

$$T_m = (J_m + J_g)\frac{d\omega_r}{dt} + T_g \tag{7}$$

where: J_m – motor moment of inertia [kgm^2], T_m – motor drive torque [N·m], ω_r – motor shaft rotational speed [rad/s].

Through determination of T_g from (7) and placing that term to (6), with the assumption that $\omega_t = \omega_r$, after reorganization, the motor drive torque T_m can be calculated from (8):

$$T_m = T_t - (J_t - J_m)\frac{d\omega_r}{dt} = T_t - T_{comp} \tag{8}$$

where: T_{comp} – torque compensation component [N·m].

The torque component T_{comp} is an additional value compensating the generally large difference in moment of inertia between the wind turbine blades and the rotor of the squirrel cage induction motor.

To obtain the value of T_{comp} the derivative of the rotor speed signal ω_r is necessary. Laboratory tests have shown critical influence of the speed derivative value on the stability of the simulator control system. A digital low pass filter is needed. The order and cut off frequency of this filter have to be carefully selected, to make real time calculations possible.

3. Control system

In the proposed model the effect of a rotating wind turbine, caused by the blowing wind, is simulated by the work of the cage induction motor supplied from a frequency converter. A simplified block scheme of the simulator is presented in Fig. 4. The system operates with simple closed loop constant *Volt*/*Hertz* control scheme with slip regulation. The generated mechanical power of the system corresponds to the power of the simulated turbine.

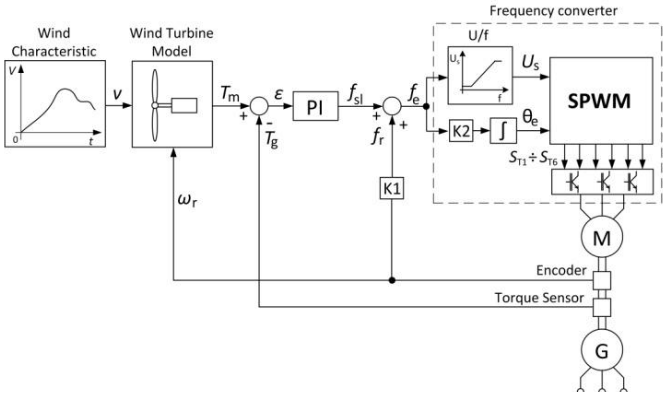

Fig. 4. Simplified block scheme of wind turbine simulator control system

With respect to the given wind speed V, the simulated turbine parameters (R, $C_p(\lambda)$ curve, turbine moment of inertia J_t) and the measured motor shaft rotational speed ω_r, the necessary motor torque T_m reference value is calculated. The mathematical wind turbine model from Fig. 2 has been incorporated in the *Wind Turbine Model* block. After subtracting the measured load torque T_g from the reference value T_m, the error signal ε is generated and delivered to the input of the PI controller. As a result the slip frequency f_{sl} is obtained. The sum of f_{sl} and f_r gives the stator voltage frequency f_e. This value is sent to the frequency converter, where, according to the *u*/*f* control scheme, the gate drive signals $S_{T1} - S_{T6}$ of the power switches are generated.

4. Laboratory stand

Fig. 5 shows the configuration of the developed laboratory stand. A 3 kW motor is used as the drive, which enables the simulation of turbines of about 2 m of maximum blade radius. The system incorporates a torque sensor and an incremental encoder. The control algorithm is implemented as software in TMS320F2812 DSP unit, controlling the output voltage frequency f_e of the converter. The laboratory stand is presented in Fig. 6. The system includes a 3 kVA directly coupled (no gearbox) permanent magnet synchronous generator PMSG. The system parameters have been listed in Table 1.

The converter responsible for the regulation of the generator speed (and realization of maximum power point tacking MPPT) is not a part of this system. The simulator is suited to reproduce the emulated wind turbine torque. The generator side converter is an external device meant to be tested with the help of the laboratory stand. Thus, it has to be stated clear, that the presented laboratory stand is not an emulator of a whole wind power plant.

Table 1. Laboratory setup system parameters

System component	Parametrs
Squirrel cage induction motor	3 kW, 400 V, 720 rpm
Permanent magnet synchronous generator	3 kVA, 400 V, 450 rpm
Rotary incremental encoder	1024 ips
Torque meter	+/- 75 Nm
Frequency converter	5.5 kW, 400 V
Couplings	torsionally stiff servo couplings
Controller	TMS320F2812

The simulated turbine parameters, as well as the reference wind speed, are entered using a dedicated program implemented on a personal computer, communicated with the system controller via an USB port. The application is called RejDiag and has been developed at the Electrotechnical Institute. During the simulation process it enables user supervision, parameter registration and manual control over the system.

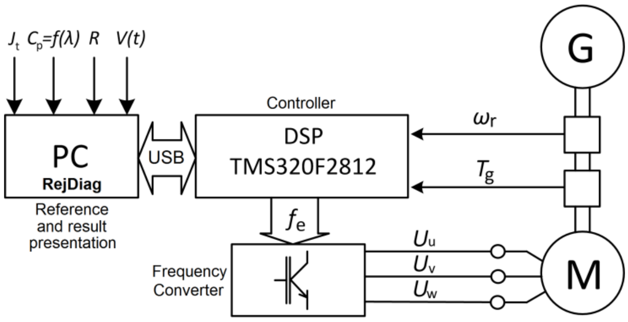

Fig. 5. Block scheme of laboratory stand for small wind turbine simulation

5. Experimental results

The work of the simulator has been examined through emulating the rotation of a small wind turbine. The blade radius R was set to 1,5 m. The power curve C_p = f(λ) of the simulated turbine corresponds to the curve presented in Fig. 1 and is described by equation (4). The parameters of the simulated wind turbine are presented in Table 2. During the tests no additional generator control was implemented. The PMSG terminals were connected to three phase symmetrical loading resistance R_{load}. Two cases were considered.

Fig. 6. Laboratory stand for small wind turbine simulation

Firstly, the dynamic response of the system to varying wind speed conditions has been tested. The results in form of waveforms are presented in Fig. 8. During the test the generator load resistance R_{load} remained constant. The reference wind speed V is shown in Fig. 8a. The measured motor angular speed ω_r and generator load torque T_g are depicted in Fig. 8b and Fig. 8c respectively.

The wind turbine emulation process starts after about 2,8 s, when the motor starting procedure is over, and the reference wind speed is greater than 0. It can be seen, that the measured mechanical values ω_r and T_g change according to the given wind speed V. Closer examination of the waveforms indicates the flattened shape of the torque and speed response in comparison with the reference wind speed signal. This is the effect of the emulation of the turbine moment of inertia J_t. During the emulation process J_t was set almost ten times higher than the actual induction motor moment of inertia.

Table 2. Emulated wind turbine parameters

Turbine parameter	Value
Rotor blade radius R	1.5 m
Rotation axis	horizontal
Number of blades	3
Moment of inertia	0.3 kgm^2
Rated rotational speed	500 rpm
Rated wind speed	10 m/s
Rated power	1.6 kW
Maximum power coefficient	0.42

Secondly, system response to generator load changes has been examined. For given constant wind speed V, step changes of the generator load resistance R_{load} were forced. The values equalled (per generator phase): 150 Ω, 133 Ω, 100 Ω, 83 Ω, 67 Ω. In this way, the system operational point moved. For each R_{load} change, the rotational speed n_R and the mechanical power P_m on the shaft have been recorded. The tests have been conducted for three different wind speed V values: 6 m/s, 8 m/s, 10 m/s. The results, in form of a chart, are presented in Fig. 7.

From Fig. 7 it can be seen, that the operating points of the wind turbine simulator, recorded for a given wind speed V, form curves, resembling the shape of the power curve depicted in Fig. 1. The maximum power point can be observed at different rotational speeds. However the calculated tip speed ratio λ in the maximum power points for all the three curves from Fig. 7 is the same, and approximately equals 5,8.

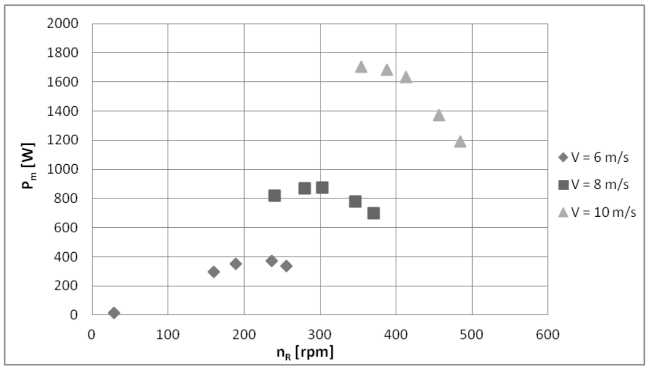

Fig. 7. Laboratory results for tests under V = const. and R_{load} = var. conditions: (150 Ω, 133 Ω, 100 Ω, 83 Ω, 67 Ω – per generator phase).

6. Conclusion

In the article a laboratory stand for small wind turbine simulation was presented. The system is designed to speed up the development process of power electronic converters for wind turbine applications. It enables laboratory research on WTS independently from wind conditions. The power electronic converter meant to be connected to the generator terminals and enable continuous speed regulation to perform MPPT, is not a part of the described wind turbine simulator. The presented laboratory stand is suited to study the performance of such converters.

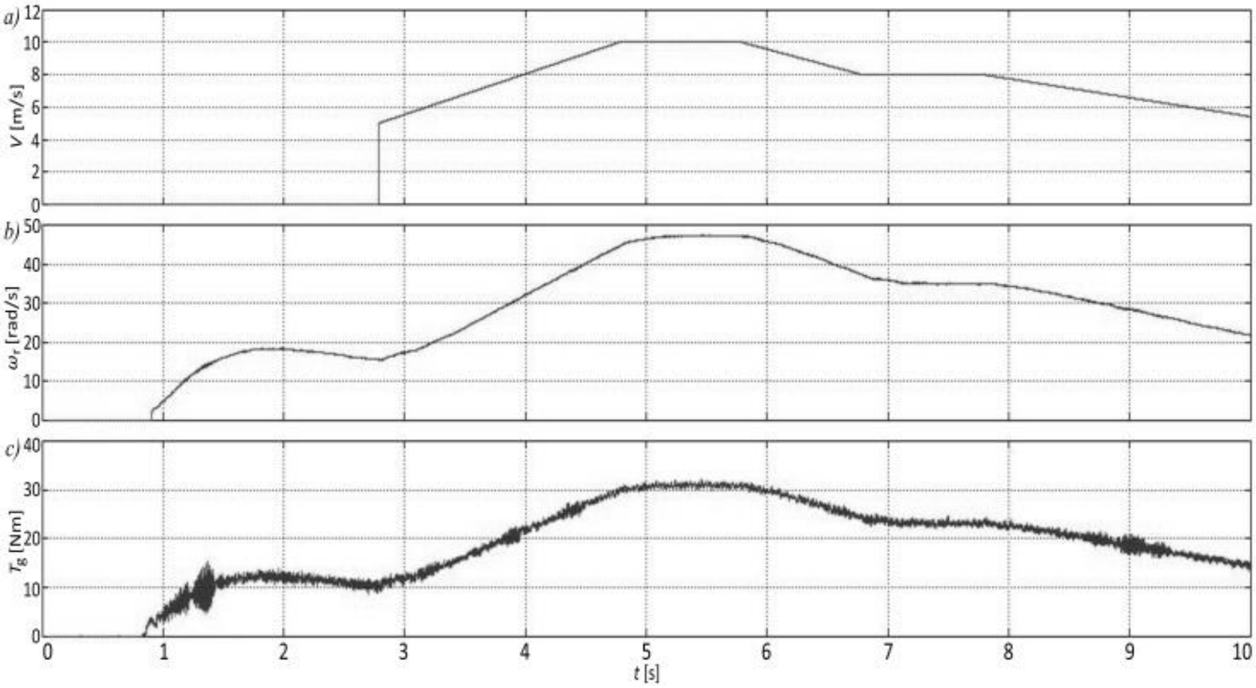

Fig. 8. Experimental results waveforms: a) wind speed reference; b) measured angular motor speed; c) measured torque

The proposed structure, in form of a squirrel cage induction motor supplied from a frequency converter, emulates steady state characteristics of a wind turbine. The system operates with simple constant *Volt*/*Hertz* control scheme, with slip regulation, where the motor torque is the control variable.

The system enables the simulation of small wind turbines with different parameters and in various wind conditions. The simulated turbine power and torque are well tracked. In states of varying wind speed, the engine rotational speed changes proportionally, but also with respect to the value of the simulated moment of inertia. The presented experimental results show proper work of the wind turbine simulator. The need of performing a motor starting procedure before the actual start of the simulation process can be considered a drawback and future research will be conducted in order to mitigate this problem.

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