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REAL-TIME HYBRID MODEL OF A WIND TURBINE WITH DOUBLY FED INDUCTION GENERATOR

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Abstract—In recent years renewable sources have been dominating power system. The share of wind power in energy production increases year by year, which meets the need to protect the environment. Possibility of conducting, not only computer simulation, but also laboratory studies of wind turbine operation and impact on the power system and other power devices in laboratory conditions would be very useful.

This article presents a method of performing real-time hybrid model of a wind turbine. The advantage of a hybrid model is the combination of the possibilities and flexibility of simulation of aerodynamic and mechanical phenomena with the electric machine, which is seen from the point of view of the grid as a real wind turbine. The originality of the presented approach is using a real-time digital model to control a power device connected to the grid. Real-time simulation is performed of aerodynamic phenomena and conversion of wind energy for a mechanical moment on the shaft, which controls via a converter of asynchronous motor driving a doubly-fed induction generator.

The hybrid model allows testing wind turbines in transient conditions after disturbances not feasible with physical wind. The paper describes the concept and the structure of a wind turbine hybrid model. Components of a wind turbine hybrid model are described. The results of laboratory studies of the real-time hybrid model of a wind turbine are presented.

Keywords—wind turbine model; real-time hybrid model; real-time simulation; Simulink Real-Time; wind turbine laboratory studies; LINTE^2.

I. INTRODUCTION

Testing of the wind turbine (WT) connected to the power system is associated with the problem of forcing interesting operation states, some of which may be related to the disturbances of the system's operation, which is unacceptable during normal operation. On the other hand in simulation studies on the impact of WT operation on grid and power devices connected to the grid, it is necessary to use simulation models, which limit the research possibilities.

There are few descriptions of hybrid wind farm models in the specialist literature. One of example of hybrid modeling has been used in research of floating wind turbines, in which the model is a turbine tower in scale of 1:30 floating in the wave basin [1]. Wind loads on the turbine are simulated and applied in real time, via strings on the substructure by a set of actuators. An analogous idea was in basis of the concept of modeling a wind power plant with use of a 2.5 kW doubly-fed asynchronous generator (DFIG) driven by a DC motor in the Massachusetts Institute of Technology. Only the control description of the generator converter was found [2]. Despite the authors' effort, finding a description the implementation of the physical model of a wind power plant with the use of an electric machine come to nought.

During research work on determining the impact of WT operation on electrical power equipment require generation of proper waveforms of electrical signals, the idea arose to build a WT model which properties and behavior from the point of view of the power grid are the same as in the real turbine, what is evaluated in basis of active and reactive power and rotational speed measurement. Proposed concept of the hybrid model combines the modeling capabilities of a real wind turbine connected to the grid in a laboratory scale using a properly controlled doubly-fed induction generator with the flexible simulation possibilities of control systems, turbine properties, wind and phenomena related to the mechanical generation of mechanical torque from wind energy. Simulation part of the hybrid model interacts in real time through I/O conditioning modules with power devices that are part of hybrid model.

The advantage of the hybrid model is that it allows to identify real problems that do not occur in the simulation model (external interference, e.g. harmonic influence, other than the modeled correlation between individual elements of the model). The hybrid model makes allowance for the impact on the WT operation of such elements as measuring transducers, filters, communication interfaces. In typical computer modeling not all of the mentioned aspects are taken into account or are taken into account in a simplified way and this leads to both quantitative and qualitative changes in the proposed control algorithms. The use of a hybrid model allows for better testing and preparation of algorithms and control systems for operation in a real device.

The hybrid model is perfectly suited for laboratory tests of a network model (microgrid), where real power devices are modeled by power devices with the same properties but scaled to power of 30÷100 kVA, operating in a three-phase 400 V grid.

The results presented in this article are the result of research conducted as part of the doctoral dissertation entitled "Scalable physical models of selected types of wind farms in hardware-in-the-loop technology". The article presents selected results showing the research capabilities of the hybrid model of a wind turbine with doubly fed induction generator. The real-time hybrid model of a WT with DFIG was developed by the author and realized by Institute of Power Engineering in the

LINTE^2 Laboratory at Gdańsk University of Technology. The main goal of the research is to develop a method of building a hybrid model, which consists of hardware - asynchronous motor driving a doubly-fed induction generator with suitable control using signals of current, voltage, power and rotational speed of the motor and generator and an elaborated software model of wind and phenomena related to the conversion of wind energy for a mechanical moment on the shaft driving the generator, which simulates behavior of a real wind turbine.

II. HYBRID MODEL - THE CONCEPT OF A TEST STAND

A. The concept

The presented concept of the wind turbine hybrid model (WTHM) is depicted in Fig. 1. The basis for the concept of the hybrid model is the implementation of a test stand, which includes a computer with I/O cards and power devices.

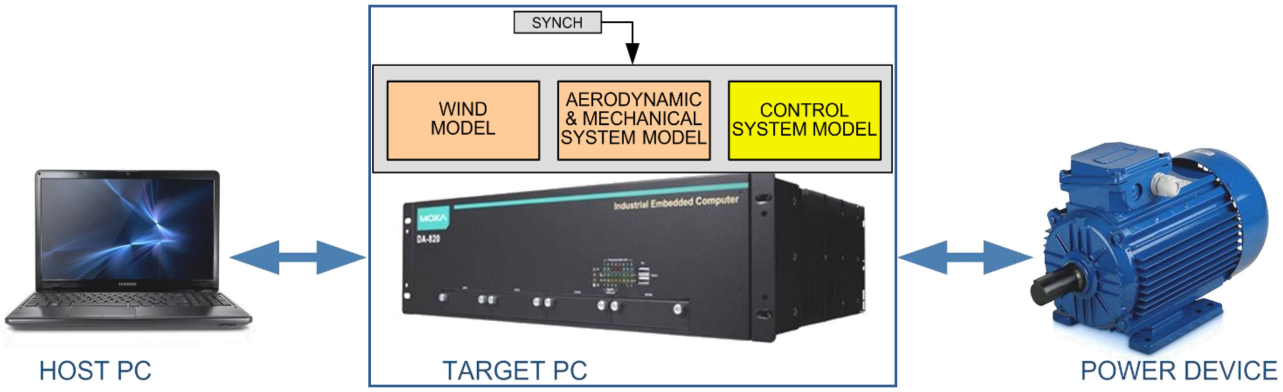

Fig. 1. The concept of a wind turbine hybrid model.

The power devices include:

- An asynchronous motor with an inverter drive.
- Doubly-fed induction generator with field converter.

The computer, called Target PC, is equipped with I/O cards, along with cards for separating input and output signals, and software enabling real-time running of applications of:

- Wind model.
- Phenomena related to the conversion of wind energy for a mechanical moment on the shaft driving the generator.
- Algorithms of the wind turbine mechanical and electrical control system.

Target PC uses the Simulink Real-Time platform from Mathworks. Target PC is able to operate standalone, but it can be controlled via a host computer (Host PC). The modeled mechanical and electrical behavior of the wind turbine is realized in real time from the point of view of phenomena occurring both in the turbine and in the environment. The WTHM of the 50kVA turbine is connected to the 400 V grid.

B. Simulink Real-Time

Simulink Real-Time (SLRT) allows to compile a Simulink model to a real-time application and run it on dedicated target computer hardware connected to physical devices [3]. SLRT allows real-time testing and simulation of algorithms of control systems modeled in Simulink. SLRT is used for rapid control prototyping or DSP systems prototyping. SLRT enables testing of prototype control systems in a loop in the simulated work environment to which they are designed - hardware-in-the-loop (HIL) [4]. Simulation is managed with use of a Host PC.

C. Research test stand in the LINTE^2 laboratory

The real-time hybrid model of a WT with doubly-fed induction generator marked WG2 was realized in the LINTE^2 Laboratory at Gdańsk University of Technology [5]. The LINTE^2 laboratory was built to conduct research on physical models of power network elements in a configurable system. There are 30 physical models of power devices with power from 50 to 150 kVA in it, including OLTC transformers, HVDC, UPFC [6], BESS [7], Supercapacitor [8], Flywheel [8][9] and Load model [10]. There are four modeled rotating power generation units, two turbogenerators and two wind turbines. All unit operation in LINTE^2 is synchronized externally with 1 kHz signal. For that reason I/O cards had been adapted for external synchronization of initialization A/D conversion.

III. STRUCTURE OF THE WIND TURBINE HYBRID MODEL

Wind turbine models are well described e.g. in: [11][12][13]. In the wind turbine real-time hybrid model groups of main components can be distinguished (Fig 2):

1. HOST PC – computer with Matlab Simulink, from which models are loaded and can be controlled and monitored.
2. TARGET PC – computer on which Simulink Real-Time Model (SLRTM) application is running in real time and controling power devices via conditioning modules (I/O). Main functional components of SLRTM:
   - **Wind model**, wherein wind changes and gusts are generated, additionally disturbance of the air flow by the tower are modeled.
   - **ECSM**: Electrical control systems model, which consists of the active power controller and reactive power controller.
   - **MCSM**: Mechanical control systems model consisting of the pitch controller, rotational speed controller and maximum power point tracking system (MPPT).
   - **A&MM**: Aerodynamic and mechanical system model, which consists of the rotor model and inertia model.
3. POWER DEVICES – where the key element is connected to the grid generator of the same type as in modeled WT:
   - **GEN**: Doubly-fed induction generator with field converter, which simulates generator of the modeled WT. DFIG power rating is 55 kW.
   - **DRV**: Converter of asynchronous motor driving the DFIG controlled by A&MM. A&MM and DRV make that the rotational speed of the DFIG is identical to the speed of the generator of the modeled WT.

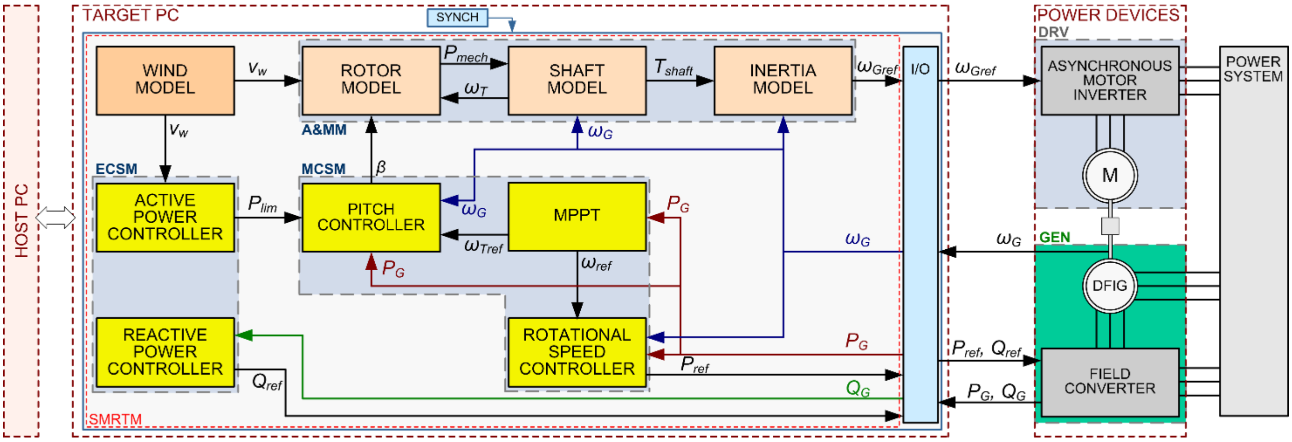

Fig. 2. The block diagram of the structure of a wind turbine hybrid model. When: v_w - wind speed, P_{mech} - the power from the wind on the shaft, T_{shaft} - torque on the shaft (at the generator side), ω_G - rotational speed of the wind turbine generator, ω_T - rotational speed of the turbine rotor, β - pitch angle; P_G, Q_G - active and reactive generator power

A&MM consists of:

- Rotor model. This is a model of aerodynamic properties of a wind turbine and it is the link between the wind and the mechanical system. It describes the dependence of the mechanical power of the turbine on the wind speed v_w, rotational speed of the turbine rotor ω_T and the pitch angle of the blades β (1).

$$P_{mech} = f(v_w, \omega_T, \beta) \tag{1}$$

- Shaft model. The turbine rotor and the induction generator rotor are connected through a shaft system with a relatively low stiffness, therefore, the two-mass model is usually used, in which the two masses represent the turbine rotor and the generator rotor [14].
- Inertia model. The generator of the WTHM has its own moment of inertia which is c.a. 10 times smaller than a generator of a real wind turbine. Hence rotational speed of generator simulated in real time in two-mass model is the setpoint of the controller of inverter drive of asynchronous motor driving the generator of the WTHM.

MCSM consists of:

- MPPT. There is an optimal value of rotational speed of the turbine for which the wind power transmitted to the turbine reaches its maximum value. Regulating the optimum rotational speed of the turbine will ensure the most efficient use of wind, which can be achieved by the appropriate beta angle controlling. When the nominal power is reached, even if the wind speed increases, the nominal power is maintained by regulating the beta angle. [11][12][13][14].
- Rotational speed controller, which regulates optimal ω_G by electrical torque, i.e. changing the generated power.
- The pitch controller, which limits rotor rotational speed for $v_w \geq 11$ m/s, when wind speed WT reaches nominal power, then rotor speed cannot be controlled by electrical torque. Increasing the pitch angle results in lowering aerodynamic efficiency of the rotor.

ECSM consists of:

- Active power controller, which can operate in maximum active power mode, delta power control mode or limited power mode.

- Reactive power controller, which regulates voltage, reactive power or power factor mode. It keeps reactive power within the permissible operating range.

Typically, simulations assume that the wind direction is perpendicular to the swept area of blades, however, the power reduction and flicker due to yaw angle can be also modeled. The yaw control system sets the turbine to the wind direction. A yaw angle of 10^o reduces the power below 5% [15].

IV. LABORATORY STUDIES

The real-time hybrid model of a wind turbine with doubly-fed induction generator (WG2) was tested in the LINTE^2 Laboratory. Tests included operation at different wind speeds, in different regulation modes and the impact of phenomena related to the wind turbine on turbine operation.

Fig. 3 presents waveforms of selected signals illustrating the behavior of the described WTHM during wind changes and gusts in the full range of wind speeds (a typical range 3,5÷25 m/s was assumed).

After start-up procedure, which lasted 110 s, WG2 is controlled by virtual wind. Three types of wind changes can be distinguished. In the first stage (120 s÷200 s), a steady increase of wind speed was emulated, which allows observing the effect of operation of the pitch controller. From 120 s the wind grows by small steps from 5 m/s and in 145 s exceeds speed (11 m/s) at which the turbine reaches its rated power. In this time WT power transferred to the grid (P_{grid}) increases from c.a. 0,1 pu to nominal value and the rotational speed increases from 0.7 pu to 1.2 pu (which is the entire scope of operation). Further increase of the wind speed does not cause any increase of the grid power nor rotational speeds, what is the result of pitch control. The recorded waveforms confirmed the correct operation of the pitch controller.

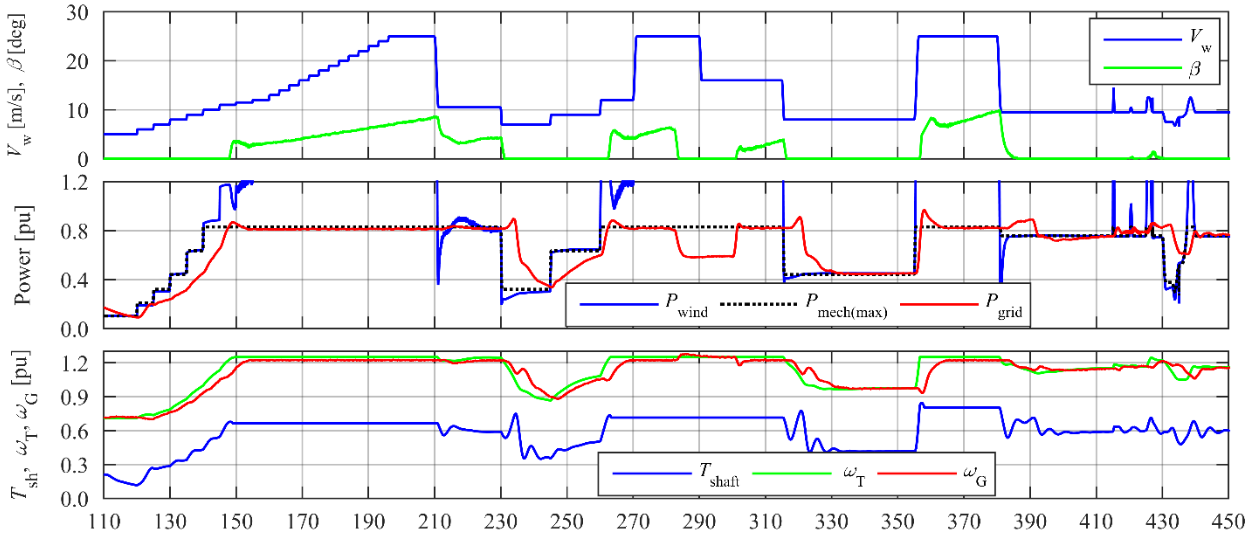

Fig. 3. Oscillograms from laboratory tests of the hybrid model working in maximum active power mode. The upper window: wind speed (v_w), pitch angle (β); the middle window: the power of the wind stream blowing at a constant speed perpendicular to the surface swayed by the turbine blades (P_{wind}), estimated power of the wind stream that can be transferred to the rotor of a wind turbine with active pitch control ($P_{mechmax}$), the power of the wind turbine transferred to the grid (P_{grid}); the lower window: torque on the wind turbine shaft (T_{shaft}), rotational speed of the turbine rotor (ω_T), rotational speed of the wind turbine generator (ω_G). Wind operation range: v_w = 3,5÷25m/s; Nominal values: for v_w = 11 m/s P_{wind} = 1,0 pu, P_{grid} = 0,827 pu, $\omega_T = \omega_G$ = 1,2 pu, T_{shaft} = 0,667 pu.

In the second stage (210 s÷380 s) the response of the WTHM for step changes of wind speed was tested. This experiment perfectly shows the dynamics of phenomena. Since the shaft and the generator are modeled as the two-mass-spring-damper system we can observed different dynamics of generator and turbine speed changes. The interaction between the power of the wind and part of it converted to electrical power transferred to the grid, mechanical limitations and pitch control can be seen.

In the last stage (415 s÷440 s) realistic wind changes and gusts are simulated, the resulting impact on power, torque rotational speed signals can be seen. The obtained signals waveforms are consistent with waveforms of signals in real wind turbines.

V. CONCLUSIONS

A real-time hybrid model of a wind turbine which combines the computer modeling capabilities with a real doubly-fed induction generator has been presented.

Results of laboratory studies show that from the point of view of the power grid the tested real-time hybrid model of a WT is seen as the modeled real WT. The real-time hybrid model is able to simulate any real WT in any wind condition.

In addition to presented capabilities, the developed WTHM allows simulation of other phenomena related to the wind turbine, including:

- Turbine tower shadow (3P effect).
- Dependence of wind on height (1P effect)
- Non-coaxiality of the gear elements.
- Resistance of movement related to viscosity friction.
- Mechanical gear teeth broken effect.

Tests of the scope of applicability of the model are underway. The results achieved so far are promising and the developed utter method will be published after the research and laboratory tests are completed. A real-time hybrid model of a wind turbine is a very useful tool for laboratory studies of impact of WT on the grid and other power devices in laboratory conditions.

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