VERTICAL AXIS WIND TURBINE WITH PERMANENT MAGNET SYNCHRONOUS GENERATOR SIMULATION IN MATHLAB SIMULINK

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Abstract. The research paper discusses the dynamic process simulation of the vertical axis wind turbine with a permanent magnet synchronous generator. Experimental and analytical investigations show that the real aerodynamic model, which is based on the wind speed, generator rotation angle and angular speed and the dimensions of the wind turbine in virtual model, provides more accurate simulated wind turbine real torque output than theoretical equation simulations that are based only on the wind speed or generator angular speed. MATLAB SIMULINK simulated virtual model shows the importance of the moment of inertia in vertical axis wind turbine system, where by finding the best moment of inertia for the vertical axis wind turbine it becomes possible to achieve a more stable real torque output.

Key words: wind speed, transfer function, simulation, torque, moment of inertia.

Introduction

Renewable energy nowadays is one of the most widely discussed topics around the world. Wind energy as the part of the renewable energy sources and its usage in Latvian territory is most frequently researched and discussed. It takes lot of time and financial costs to find a new generation wind turbine. Designing of the turbine is an important process but in order to see how the real turbine operates in the wind area the turbine should be built and tested in air tunnels or good weather conditions with stable wind [1].

Computer software and the applications today help conduct research in many areas. Wind industry can be one of the industries where the simulation of the virtual models is helping to test turbines by making use of the virtual turbine model [2; 3]. Around the world virtual models are built to fully reflect all the turbine components and the control process, however, the main problem that researchers come across when building virtual models is related to actual parameters of the turbine aerodynamic process and the data about the aerodynamic process.

The main tasks of this work are design and study of the virtual turbine model, simulation of the virtual model operation with the help of the virtual model in MATLAB SIMULINK application as well as evaluation of the possible turbine operation as a stand-alone turbine in the wind fields.

Materials and Methods

The first parameter for the wind turbine simulation is the wind speed v_w simulator (Fig. 1). The wind speed in this simulation is artificially simulated and, unfortunately, fails to correspond to what occurs in real life. The real wind is very unstable, which makes it difficult to analyse the aerodynamic and transfer processes. In order to demonstrate how the aerodynamic model of the turbine operates, it is important to build the cyclical wind speed simulator. The average value of simulated wind speed v_w is 4 $m \cdot s^{-1}$. The wind speed varies ±1 $m \cdot s^{-1}$ with the frequency 0.1 Hz (Fig. 1).

The research object is the vertical axis wind turbine. Aerodynamic design for the turbine is based on the patent [4]. The blades are fabricated as subsonic aerodynamic wind turbine blades arranged in arrays, wherein the aerodynamic blades are disposed at the periphery of the rotor, and are spaced apart at substantially equal spatial intervals (Fig. 2). Typically, the aerodynamic blades are positioned in such a way that the outward concave surface of the aerodynamic blade is facing the rotational axis.

From the information provided in the patent [4] the torque obtained from the wind in the rotor blades is calculated by the MATLAB SIMULINK. Theoretical torque calculation in absolute time makes the vertical axis wind turbine (VAWT) simulation model more close to the real standing turbine. Theoretical torque T_t calculation is set up as a subsystem VAWT (Fig. 3). This subsystem calculates the total theoretical torque T_t obtained from the wind imposed on the generator. According to the experimental results the efficiency of the wind turbine is $\eta = 0.4$.

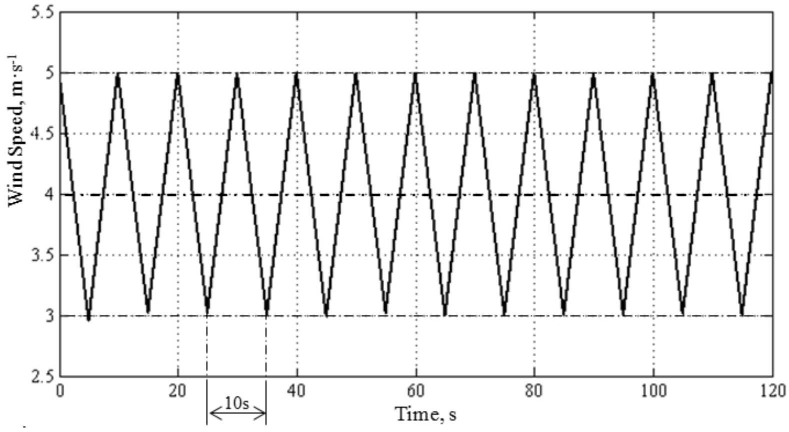

Fig. 1. **Simulated wind speed v_w**

The main inputs of VAWT internal components are as follows: generator rotation speed ω (rad·s^{-1}); angle of the turbine θ (rad); wind speed v_w (m·s^{-1}). The calculation results are compared with the aerodynamic turbine calculation. VAWT direct outputs: total wind turbine theoretical torque T_t (Nm), each turbine blade block theoretical torque T_{bli} (Nm) and the turbine specific speed ratio λ.

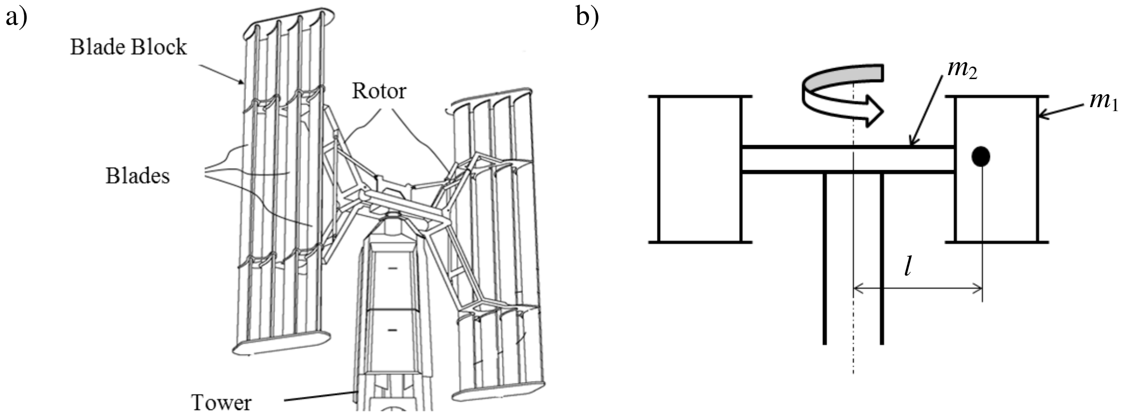

Fig. 2. **Wind turbine mechanical design according to the patent:** a – full structure; b – simplified structure for calculation of the moment of inertia (m_1 – blade block mass, kg; m_2 – rotor mass, kg; l – radius of the mass centre)

The theoretical torque calculation subsystem VAWT contains mechanical parameters and dimensions for each blade in the blade block. One blade block consists of four blades. For each blade the theoretical torque is calculated at the angle θ. Then the theoretical torques calculated for all the four blades are summed up. When the total theoretical torque is calculated for both blade blocks the final T_t is the sum of the blade block theoretical torques. In the position of rotation each blade has the torque line as a function depending on θ. The torque value varies from positive to negative. The shape of the blades allows the turbine to work more on the positive torque with less negative torque effect. The theoretical T_t and the average T_{av} wind turbine torque are calculated according to the formulas:

$$T_t = k \cdot \sum_{i=1}^{n} T_{bli}\ ,\ T_{av} = k_\lambda \cdot \omega_t^{\ 2} = \frac{\pi \cdot \rho \cdot R^5 \cdot \eta \cdot i^3}{2 \cdot \lambda^3}\omega_t^{\ 2}, \tag{1}$$

where T_{bli} – theoretical torque for one blade, Nm;
ω_t – wind turbine shaft angular speed, rad·s^{-1};
$k = 2$ – number of wind turbine blocks;
$n = 4$ – number of blades in one block;
$R = 3.75$ m – wind turbine rotor radius;
$i = 1:6$ – gear ratio (multiplier);
$\eta = 0.4$ – wind turbine efficiency;
$k_\lambda = 7.5$ kg·m^2 –specific constant for designed wind turbine;

λ – wind turbine linear speed and wind speed specific ratio.

The theoretical torque is an instantaneous value. To achieve more accurate wind turbine simulator the transient torque should be transferred to the generator through the transfer function with the delay of the transient torque connection to the generator shaft. The turbine torque transient process is described as the first order inertial function. The transfer function $W_t(s)$ of the wind turbine real torque T_r to the PMSG shaft is as follows:

$$W_t(s) = \frac{\omega_g(s)}{v_w(s)} = \frac{K_t}{\tau \cdot s + 1} = \frac{2.28}{\tau \cdot s + 1}, \tag{2}$$

where $\omega_g(s)$ – Laplace transform of generator shaft angular speed, rad·s^{-1};
$v_w(s)$ – Laplace transform of wind speed, m·s^{-1};
τ – time constant of wind turbine inertia, s;
K_t = 2.28 rad·m^{-1} – transfer coefficient of wind turbine system.

The time constant τ is calculated in accordance with the inertia of the wind turbine system [5]. For calculation of the turbine whole moment of inertia in the virtual model the following elements are included: wind turbine blade blocks, wind turbine rotor, which fixes the blocks and the permanent magnet synchronise generator (PMSG). From the technical specification of the generator it is known that the moment of inertia of the generator is J_g = 7.8 kg·m^2, however, the moment of inertia of the wind turbine blade blocks and the rotor needs to be calculated. The wind turbine system for the purpose of inertia calculation consists of the two masses m_1 and m_2 with the radius of the mass centre (Fig. 2, b). The moment of inertia of the wind turbine is calculated as follows:

$$J_t = 2 \cdot \frac{m_1 \cdot \frac{m_2}{2}}{m_1 + \frac{m_2}{2}} \cdot l^2 = 2 \cdot \frac{320 \cdot \frac{1100}{2}}{320 + \frac{1100}{2}} \cdot 2.5^2 = 2528 \text{ kg·m}^2, \tag{3}$$

where m_1 = 320 kg – block mass of wind turbine blades;
m_2 = 1100 kg– wind turbine rotor mass;
l = 2.5 m – radius of mass centre.

The virtual model of the wind turbine transient process is structured as an open transfer function, which makes it possible to recalculate the variable parameters K_t and τ during simulation. For example, if the turbine is in a steady state or the torque from the wind is low then the wind turbine time constant τ is high. If the time constant τ is high, then the start process is slow. When the rotating speed is higher and the torque from the wind is greater, the transient process goes on rapidly. VAWT simulation system includes the subsystem Torque Transfer *f.* that simulates the transient process of the wind turbine torque reduced to the generator shaft (Fig. 3). The transfer function $W_t(s)$ is included into the subsystem Torque Transfer *f.* The time constant τ under the rated wind station load 56 kW is calculated as follows:

$$\tau = \frac{(\frac{J_t}{i^2} + J_g) \cdot \omega}{T_{rav}} = \frac{(2528 \cdot 36 + 7.8) \cdot 3}{20742} = 13.2s, \tag{4}$$

where J_g = 7.8 kg·m^2 – generator moment of inertia;
ω = 3 rad·s^{-1} – wind turbine rated rotation speed;
T_{tav} = 20742 Nm – wind turbine rated torque.

For PMSG simulation the standard block from SimPowerSystems library is used (Fig. 3). The block name in the virtual model is 56 kW PMSG. To provide more effective simulation results the real data according to the specification of PMSG type "M3BJ-315LKB-12" is used. It is important to take into account the fact that PMSG is represented by a second-order state-space model. The model assumes that the flux established by the permanent magnets in the stator is sinusoidal, which implies that the electromotive forces are sinusoidal [6].

The load is imported from SIMULINK library SimPowerSystems connected directly to the PMSG (Fig. 3) [7]. The block name in the virtual model is Load. The load electrical active power P_{load} = 56 kW.

According to technical and theoretical explanations the virtual model is performed in MATLAB SIMULINK. The model consists of 3 subsystems and 9 standard library blocks. The wind speed is simulated with the block Wind Builder. The constant and sawtooth wind components are summarised and linked to the subsystem VAWT. In the subsystem VAWT the theoretical torque calculations are performed (Fig. 3).

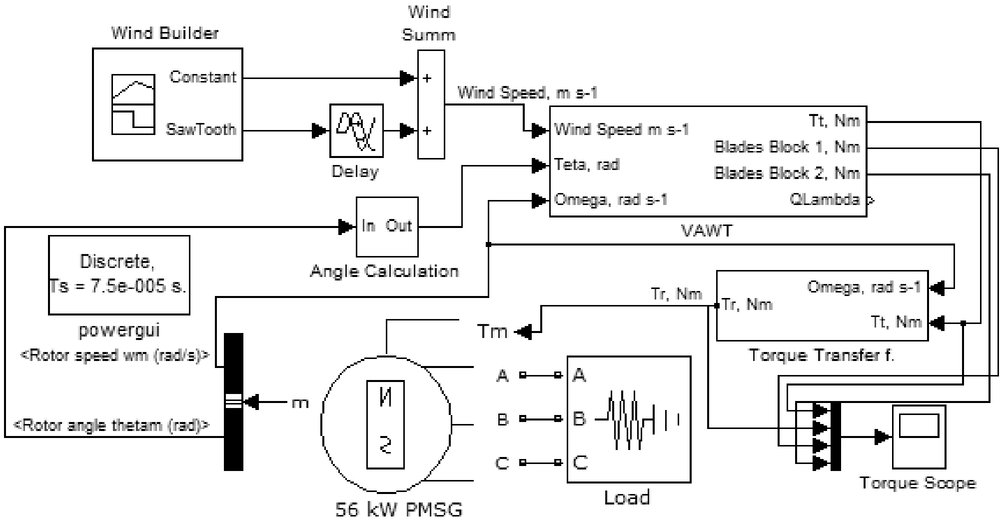

Fig. 3. **Wind turbine virtual model in MATLAB SIMULINK**

One output of the block “56kW PMSG” is the rotor angle. To provide simulation of the wind turbine with the required angle θ the subsystem Angle calculation is used, which makes it possible to calculate the relative angle in the range from 0 to 2π rad from the absolute generator shaft rotation angle (Fig. 3).

Results and discussions

The back way (backward run) of the blade is a serious problem for vertical axis wind turbines without pitch control. (Fig. 4). The theoretical torque provided by the wind speed at the angle θ is individual for each designed wind turbine. The blade profile should be designed to achieve higher theoretical torques at each angle θ. The theoretical torque of the whole turbine is shown as separate trends of each blade and the sum of all theoretical torques (Fig. 4).

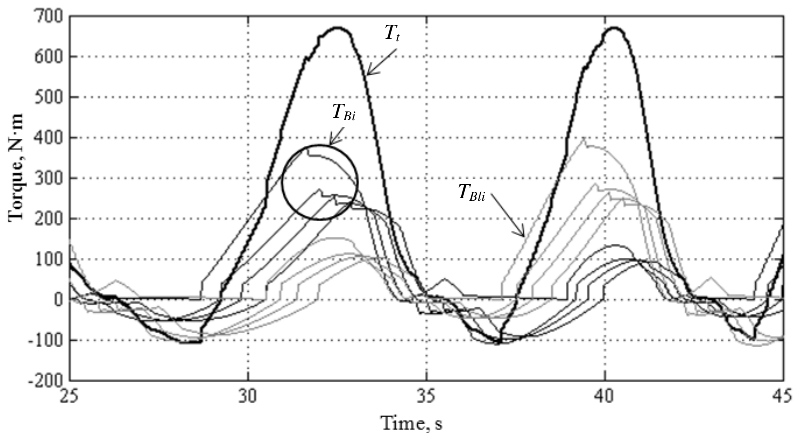

Fig. 4. **Wind turbine simulation with constant wind speed 4 m·s^{-1}**

The full wind system virtual model is ready for operation. For the purpose of simulation of the virtual model the two key simulation conditions have been created. For both attempts the simulation time is 120 s and the start condition parameters are: ω_g = 0 rad·s^{-1}, θ = 0 rad.

For the first simulation the wind speed is constant – $v_w = 4$ m·s^{-1}. The results of simulation show that at constant speed the wind turbine theoretical torque demonstrates high deviation of up to ± 136% from the average value – T_t = 260 ± 360 Nm. The simulated real torque T_r on the generator shaft is T_r = 260 ± 10 Nm. T_r deviation around the average value is about ± 5 %, which stresses the importance of the moment of inertia in the wind turbine torque stabilisation and process performance. The T_r transient time in simulation is 120 s.

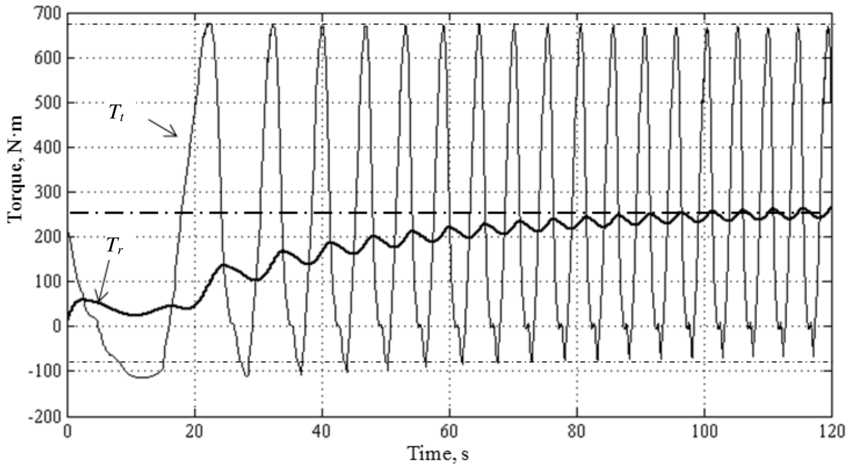

Fig. 5. **Wind turbine torque simulation with constant wind speed 4 m·s^{-1}**

If the wind turbine had less inertia, the system would be very unstable, which would give bad results on the PMSG output power. Increasing the inertia of the VAWT is the frequently used solution for stabilisation of the wind turbine T_r performance.

The second simulation is made for the variable wind speed $v_w = 4 \pm 1$ m·s^{-1} (Fig. 1). The simulation results show that the wind turbine real torque T_t = 260 ± 360Nm. Deviation of the T_t is ±136 % from the average T_t. The maximum amplitude of T_t varies from the 500Nm to 850Nm.The T_t negative braking torque maximum value is -100 Nm. The simulation shows that T_r on the generator shaft is more stable T_r = 260 ± 10Nm. The deviation from the average is about ± 5 %, because of stabilisation of the moment of inertia in the wind turbine torque. The T_r transient time in simulation is 90 s (Fig. 6).

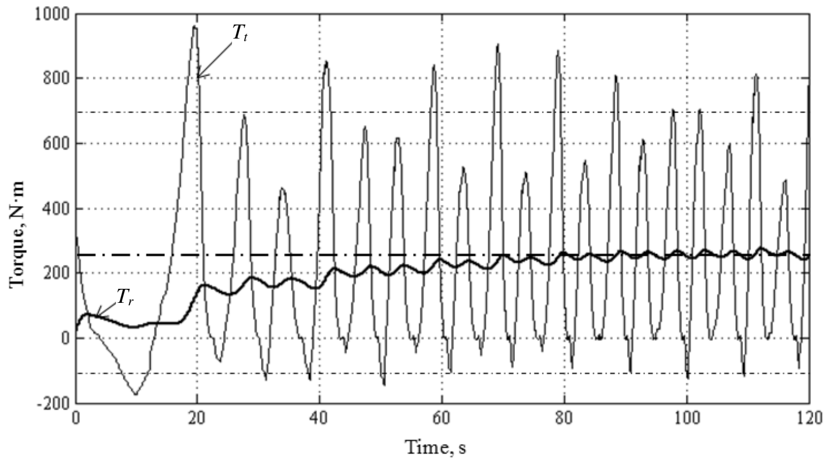

Fig. 6. **Wind turbine torque simulation with variable wind speed**

Conclusions

1. The vertical axis wind turbine without pitch control with the blades produced as subsonic aerodynamic wind turbine blades arranged in arrays simulated as a virtual model in MATLAB SIMULINK shows the wind turbine process performance and wind generated rapid torque impact on the wind turbine and provides an opportunity to analyse the wind turbine dependence on the moment of inertia for the system.

2. The wind generated rapid torque depends on the wind turbine rotation angle, which makes the torque to change within the range of T_t = 260 ± 360 Nm with the deviation of T_t is ±136 % from average T_t. The generated theoretical torque can be with a negative impact on the turbine T_t = -100 Nm.
3. The wind generated theoretical rapid torque in the wind turbine wings is transferred and smoothed due to the moment of the wind turbine inertia in the turbine, where the moment of inertia is large enough to produce the rapid theoretical torque with the deviation ± 136 % from the average T_t in the range ± 5 %. This shows high importance of the moment of inertia in the vertical axis wind turbine process performance.

Acknowledgement

The author is very grateful for support to thesis supervisor Andris Sniders.

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