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Robust Control Design Solution for a Permanent Magnet Synchronous Generator of a Wind Turbine Model

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Abstract: The paper addresses the development of a perturb and observe algorithm implemented for maximum power point tracking control of a permanent magnet synchronous generator. It is shown that this algorithm tracks the optimum operation point and provides fast response even in the presence of faults. The strategy implements the tracking algorithm by using real—time measurements, while providing maximum power to the grid without using online data training. The solution is simulated in the Matlab and Simulink to verify the effectiveness of the proposed approach when fault–free and faulty conditions are considered. The simulation results highlight efficient, intrinsic and passive fault tolerant performances of the algorithm for electric generators and converters with low inertia.

Keywords: Robust control design, passive fault tolerant control, maximum power point tracking, perturb and observe algorithm, permanent magnet synchronous generator, wind turbine model.

1. INTRODUCTION

Wind energy is produced by wind forces that usually are transformed into electricity due to the movement of turbine blades. This energy is captured and transmitted to an electric generator. The whole system represents the wind turbine that can vary in size depending on the location wind conditions Pramod (2010); Heier (2014b). This renewable source of energy allows to generate electric power as long as wind is present. There are two types of electric generators exloited in these installations, *e.g.* synchronous and asynchronous machines. The former requires external DC power supply for the rotor or permanent magnets. The latter relies on induction principle where the rotational magnetic field from the rotor induces the voltage in the stator winding. Nowadays, wind turbine can rely on several solutions depending on the generator type Manwell et al. (2002); Garcia-Sanz and Houpis (2012). One of the most common implementation is the Permanent Magnet Synchronous Generator (PMSG) because of the operation simplicity and low cost. Induction machines are selected depending on their wounded rotor, which characterises the Doubly Fed Induction Generator (DFIG), and the Squirrel Cage Induction Generator (SCIG), including single or double cage Gasch and Twele (2012).

One of the wind turbine most important parameter is Power Coefficient (C_p), which indicates the efficiency of the system in terms of energy transformation. It considers all possible losses that may affect the wind turbine performance including mechanical and electrical characteristics. This parameter is usually provided by the manufacturer on the basis of laboratory tests and mathematical model simulations. The generator is able to produce a certain amount of power if the torque and speed can reach its electrical design characteristics. Consequently, the length of the blades is important for achieving the required torque and rotational speed.

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From the mechanical point of view, C_p depends mainly on the relation between the rotational speed ω_r, the length of the blades, *i.e.* the rotor radius R, and the wind speed V_w. This parameter is known as tip speed ratio λ described by Eq. (1):

$$\lambda = \frac{\omega_r R}{V_w} \tag{1}$$

In order to understand how the function C_p can be described, it is important to recall the basic concepts of wind energy and power. These concepts are used in order to explain the so–called Betz Limit, which represents the turbine efficiency in terms of mass conservation. This law states that it is possible to capture up to 59.5% from total available wind Castellani et al. (2014). The tip speed ratio is calculated using Eq. (1), where λ is the tip speed ratio, V_w is the wind speed, R is the length of the blade, and ω_r the wind turbine rotor rotational speed.

Moreover, the analysis of a Wind Energy Conversion System (WECS) requires the following considerations:

- wind is a renewable energy source and it is necessary to measure its speed and direction for proper wind turbine operation;
- the nacelle rotation angle also known as *yaw*, which needs to be regulated on the basis of the wind direction;

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- for variable speed wind turbines, the blades may change their inclination angles. This allows to create resistance, thus leaving the turbine to accelerate or stop. The angle of the blade is known as *pitch* angle;
- once the energy is transmitted to the generator, its design allows to generate a certain amount of electric power. However, the voltage, frequency and phase of the signals are to be coupled with respect to the grid levels. For standalone systems, these parameters must match the load requirements. In order to achieve the electric connection, power electronic converters are incorporated.

Maximum Power Point Tracking (MPPT) control allows the system to provide most of the available active power by controlling the power electronic converter. For example, the most common converter is the back to back (AC/DC/AC) configuration. Since power electronic devices can reach high speed frequency response, it is easier to command the voltage signal that leads a MPPT control. First, a fully controlled rectifier sets the optimum voltage for maximising the extractable power from the generator. Then, this maximum power point is constantly tracked to guarantee ideal operation. Finally, a fully controlled inverter produces the output voltage signal that needs to be synchronised with respect to the load or the grid requirements. It allows the system to work continually, while the yaw and pitch controllers work simultaneously for finding the best direction and pitch angle Heier (2014a).

MPPT control is performed by different methods Muhammad (2014): maximum power control, optimum torque control, and optimum tip–speed control. Maximum generated power control requires wind speed sensors to generate a power reference signal, which is used for controlling the digital controller block. It is important to note that those sensors cannot provide an accurate measurement of the wind speed, as the wind field changes when the blades are rotating. Moreover, the measured generated power (P_m), the grid voltage and current (v_g, i_g), as well as the reference power estimated on the basis of the actual wind speed (P_{m^*}) are used as auxiliary control signals, as shown in Fig. 1.

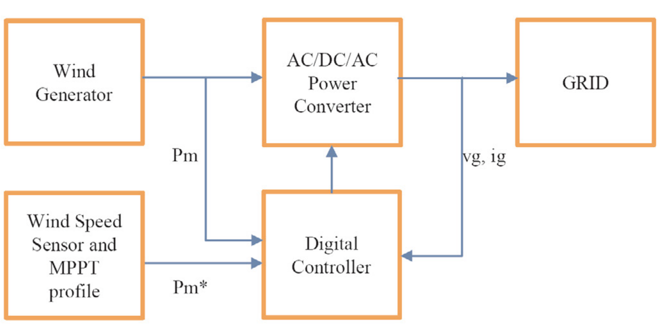

Fig. 1. Diagram of the maximum power control scheme.

A variation of this method results in the Power Signal Feedback (PSF) control, which uses records of output power from the grid. The values of the maximum power curves are stored and computed for creating a reference. This signal and the output measured power command feed the digital controller.

Optimum generated torque control uses torque measurements from the generator, which is transformed into a torque reference. Similarly, in the maximum generated power control system depicted in Fig. 2, the grid voltage and current are measured and used by the digital controller in order to command the power converter.

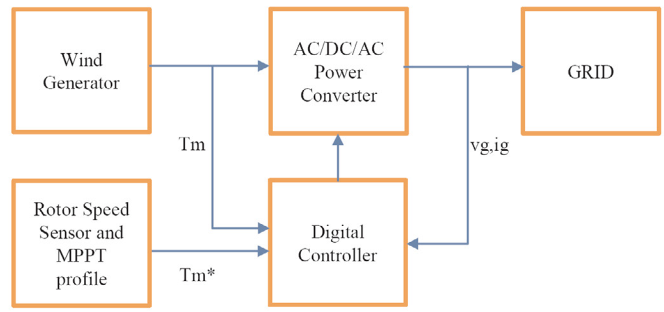

Fig. 2. Diagram of the optimum generated control scheme.

Optimum tip–speed control is probably the less accurate method, which relies only on the wind speed measurement and the rotor speed. Since the system requires wind speed sensor and rotor speedometer, it needs specific design requirements.

Multiple algorithms can be applied for maximum power control to produce a stable and constant C_p at the output of the generator, as shown in Fig. 3. The model input considers all the variables related to the rotor speed and pitch angle, whilst the output is the pitch angle command Khouloud et al. (2015).

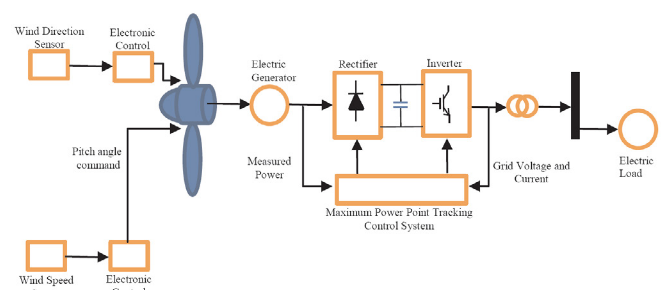

Fig. 3. PID regulation scheme for C_p control.

The key point of the paper relies on the development of a control solution that is robust with respect to faults affecting the system. In general, Fault Tolerant Control (FTC) solutions are divided into two types of schemes, *i.e.* Passive Fault Tolerant Control (PFTC) and Active Fault Tolerant Control (AFTC) systems. On one hand, PFTC does not need for Fault Detection and Diagnosis (FDD) or Fault Detection and Isolation (FDI) task, or even controller re–design, but it has quite limited FTC features. On the other hand, AFTC is able to manage the fault on the system component in an active way and it rearrange the control laws such that the stability is maintained and acceptable performances of the entire process are kept. Therefore, a successful strategy of AFTC exploits real–time FDD/FDI modules in order to provide the updated information regarding the health status of the dynamic process. Over the last decades, the increasing demand for safety, stability, reliability, and availability in power plants has motivated important research activities in the FTC area, as described *e.g.* in (Mahmoud et al. (2003)).

In particular, with special attention to wind turbine systems, they represent complex nonlinear dynamic processes, with aerodynamics that are nonlinear, partially unknown, and unsteady. Moreover, their rotors, generators and components are affected by complex turbulent wind inflow field effects that generate fatigue loading and disturbance torques. To this end, the need of condition monitoring, diagnosis and robust control of wind turbine systems motivates these fundamental and challenging task activities, as addressed *e.g.* in (Odgaard and Stoustrup (2013)). Wind turbines actually installed in offshore conditions may implement complex control methodologies and techniques in order to obtain the prescribed achievements and performances.

A fundamental control task that explains the interest of this paper, and in particular regards the intrinsic fault tolerance capabilities of the designed control solution. In fact, the *passive* fault tolerance features of the control module must take into account the management of the possible faults affecting the process under investigation. Considering this particular issue, the FTC problem applied to a wind turbine benchmark was analysed *e.g.* in (Odgaard et al. (2013)), which considered a simple but, at the same time, realistic, general and high–fidelity simulator of a typical and industrial wind turbine system.

Finally, the paper will show that the control solution implemented via a perturb and observe approach together with a MPPT scheme is able to exhibit passive fault tolerant features when applied to the considered wind turbine simulator.

2. WIND TURBINE MODEL AND CONTROL SCHEME

The wind turbine model consists of all mechanical and electrical components. The main modules are represented by the blades that capture wind forces, the nacelle housing the generator and the gear–box, the tower supporting the wind turbine, and the connection to the grid or load. This model is simulated in the Matlab and Simulink environments.

First, it is necessary to define the type of generator. Once selected, the WECS can produce energy reducing mechanical fatigue and possible faults. Note that the occurrence of faults is also considered in this work, as analysed for example in Simani and Farsoni (2018). The MPPT represents the strategy that is able to extract the higher amount of power on the basis of the wind conditions. The C_p curve as a function λ is used to represent this concept on the basis of the manufacturer information. The mathematical relation can be described as parametric model that includes the C_p curve. In particular, Fig. 4 depicts the general C_p coefficient with respect to the λ parameter, using the simulation data provided in MathWorks (2019) with the following parameters: $c_1 = 0.5176$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$ and $c_6 = 0.0068$.

As shown in Fig. 4, these parameters lead to $C_{p_{max}} = 0.48$ and $\lambda_{opt} = 8.1$.

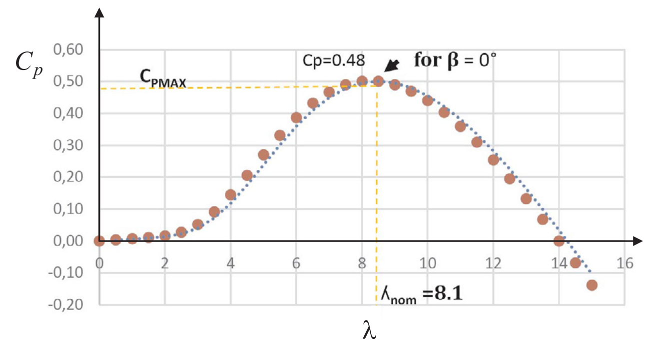

Fig. 4. Power coefficient C_p as function of λ at $\beta = 0^o$.

According to Wang and Chang (2004), there are mainly three algorithms for determining the MPPT:

- the Power Signal Feedback (PSF), based on the optimum torque control;
- the Hill Climb Search (HCS), based on the maximum power control;
- the tip–speed ratio (TSR), based on the optimum tip speed control.

In particular, the PSF technique provides a power reference based on the load or grid side electric characteristics, and then the inverter is configured to maximize the power extraction.

The HCS method applies an intelligent memory method using the techniques relying on the 'search-remember-reuse' algorithm, which finds the maximum wind power extraction without the need of knowing the parameters of the wind turbine or the electrical load/grid connection.

Finally, the TSR strategy allows to produce the maximum power by measuring or estimating the wind speed and the generator rotational speed. Additionally, it is required knowledge of the optimum TSR operational point. However, there are different aspects to be considered in order to calculate C_p: this work has selected the C_p expression of Eq. (2) taken from Thongam and Ouhrouche (2014):

$$C_p(\beta,\lambda) = 0.5176\left(\frac{116}{\lambda_i} - 0.4\,\beta - 5\right)e^{-\frac{21}{\lambda_i}} + \\ +0.0006795\,\lambda \qquad (2)$$

where:

$$\lambda_i = \left(\frac{1}{\lambda + 0.08\,\beta} - \frac{0.035}{\beta^3+1}\right)^{-1} \qquad (3)$$

and β is the collective pitch angle. Note that each specific wind turbine model can be described by different expressions of the C_p function of Eq. (2).

Knowing the for of the C_p expression, it is possible to calculate every point of its curve in real time during the power generation. Moreover, using this relation it is possible to determine the variable inputs and outputs in the controller design and to define the C_p at a desired working point.

Considering that the variations of the pitch angle β modify the wind turbine speed, it is important to control this variable by stablishing a relationship between the wind speed and the pitch angle.

Therefore, a general pitch angle expression can be obtained using a trigonometric expression taken from the general blade design procedure addressed in Kulunk (2014), which has the form of Eq. (4):

$$\frac{\partial}{\partial \beta}\left(\sin^2\beta\,(\cos\beta-\lambda\sin\beta)\,(\sin\beta+\lambda\cos\beta)\right)=0 \qquad (4)$$

After some simplifications, the optimum relative wind angle β, also known as pitch angle for a local tip–speed ratio, has the form of Eq. (5):

$$\beta=\frac{2}{3}\tan^{-1}\left(\frac{V_w}{\omega_r\,R}\right) \qquad (5)$$

Usually, the generator speed ω_r has to be constant in order to maintain constant voltage and power. However, when the TSR method is applied, also ω_r may change. This means that the frequency may vary. However, standalone loads do not affect the DC link, but the total amount of delivered power must be set constant. On the other hand, if this method is used when the system is connected to a grid, the output power must be connected thought a converter.

Some considerations regarding inertial forces at the generator are addressed *e.g.* in Wang and Chang (2004). The main input for this algorithm is the measured power P_m of Eq. (6) depending on the applied torque T_f, the wind turbine angular speed ω, and the overall electrical efficiency η of the system from the generator input to the inverter output, which represents one key factor:

$$\begin{aligned} P_m &= P_{LOAD}+T_f\,\omega+\omega\,J\frac{d\,\omega}{d\,t} \\ &= \frac{1}{\eta}\,P_{OUT}+T_f\,\omega+\omega\,J\frac{d\,\omega}{d\,t} \end{aligned} \qquad (6)$$

Eq. (6) indicates the amount of power that is produced in terms of angular speed, and how the inertial forces $J\frac{d\,\omega}{d\,t}$ can produce extra power to the system.

3. PERTURB AND OBSERVE ALGORITHM

The MPPT using the Perturb and Observe (PO) algorithm represents a technique based on the derivative of the output power curve. The results presented in this paper have been achieved by selecting PMSG. This approach is similar to the hill climb algorithm proposed *e.g.* in Wang and Chang (2004).

The PO method is implemented using a state machine, whose block diagram is shown Fig. 5, where the initial values are updated each cycle.

In the first stage, the algorithm verifies if the MPPT algorithm is activated or not by confirming a bit that is set to 1 or 0. Then, in the second step, the initial voltage parameters are defined to perform the initialisation of the controller. In the next stage, the algorithm proceeds to calculate the power P by multiplying the measured voltage V and current I.

The differences of the power and voltage are thus calculated, ΔP and ΔV, whilst the algorithm verifies if the actual values need to be increased or decreased based on the reference value of the voltage V_{ref}. These values are stored for establishing the maximum and minimum limits of reference voltage, $V_{ref}Min$ and $V_{ref}Max$ that the controller can generate MathWorks (2019).

The converter power system is then configured using the vector space control considering the voltage grid level. The system also allows to synchronise the generator frequency and the grid.

Fig. 6 depicts the generator power output based on the wind speed, whose profile is reported in Fig. 7. This profile was selected for providing a better understanding of inertial forces at the generator.

It is worth noting that constant wind speeds produce a more stable power coefficient C_p since the algorithm does not require to multiple iterations. In other words, the more stable the wind speed is delivered to the blades, the more power can be obtained from the generator and extracted from the wind source. Under these conditions, possible faults are also tolerated and thus compensated in a passive way.

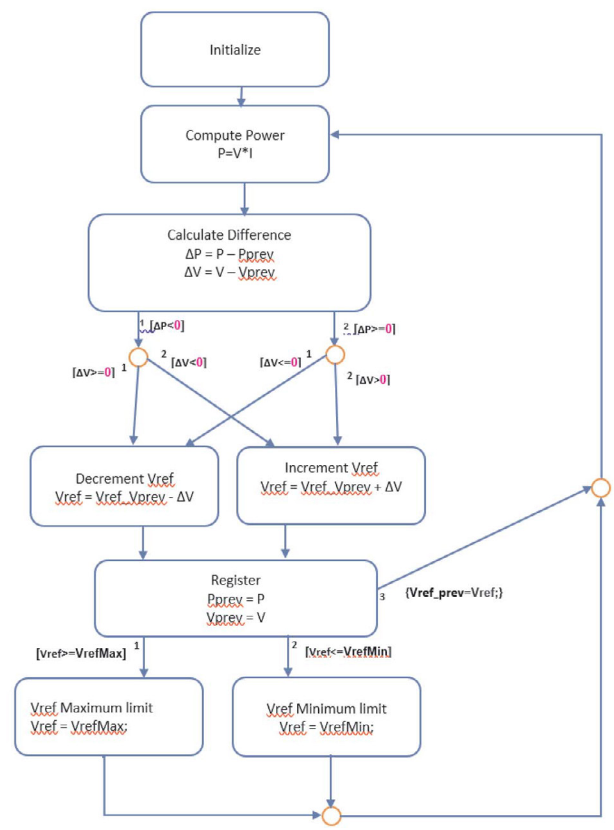

Fig. 5. Diagram of the perturb and observe state machine algorithm.

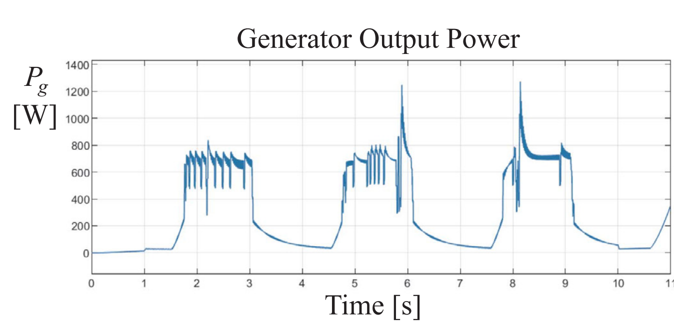

Fig. 6. Generator output power.

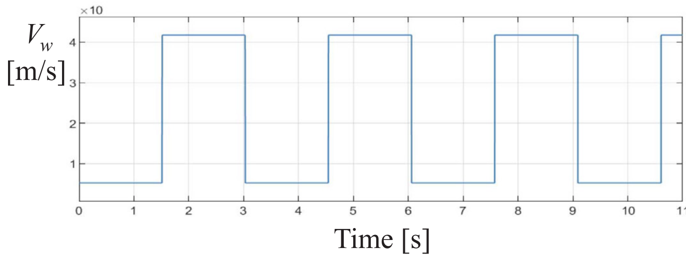

Fig. 7. Wind speed V_w profile.

The power coefficient C_p as a function of time is depicted in Fig. 8. In particular, Fig. 8 (a) shows the C_p response with PO control in the presence of faults. It can be noted how the C_p function increases when the wind flows fasters across the blades. On the other hand, C_p decreases progressively when the wind speed is reduced abruptly Mohammadi et al. (2014). This effect is due to inertial forces.

Fig. 8 (b) shows the presence of multiple oscillations due to the faults affecting the system that are not mitigated by the PO algorithm corrections over the time. It is worth noting that the initial power and voltage values, ΔV and ΔP, are considered null. However, when the system starts to compute these values, the data are recorded and updated continuously every sampling time. This method is widely applied also for solar applications. As an example, a similar algorithm can be found in Banu and Istrate (2012) for solar panels MPPT control.

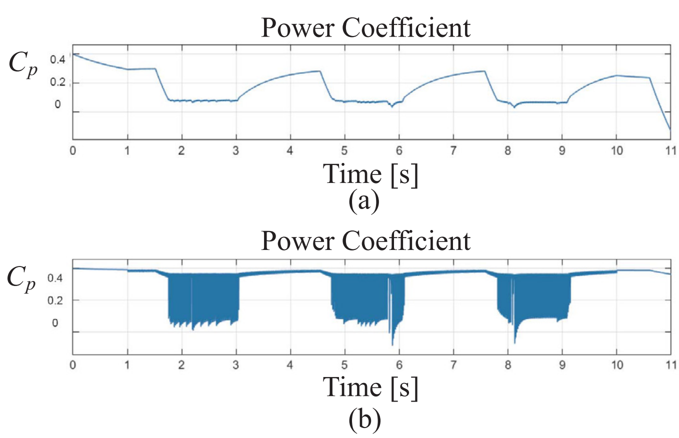

Fig. 8. Power coefficient C_p (a) for PO control with faults and (b) MPPT method without PO.

Therefore, the comparison of Figs. 8 (a) and (b) serve to highlight the passive fault tolerance features acquired by the developed control approach relying on a MPPT scheme with a PO algorithm.

Finally, Fig. 9 sketches the Simulink implementation of the algorithm proposed in this paper.

4. CONCLUSION

The perturb and observe method addressed in this paper can be considered as a reliable technique for wind turbine systems implementations for low inertia generators. The algorithm iteration speed allowed the controller to correct the actuated signal feeding the power converter. The main advantage of the proposed approach relies on the fact that it can be easily implemented by using conventional programmable devices and can achieve even faster responses using embedded systems. The simplicity of the algorithm could allow to work simultaneously using complementary techniques such as artificial neural networks, deep learning or similar. The simulation tests highlighted that this technique can be implemented for real scenarios where the wind and rotor speed sensors are not available. Future investigations will address a more accurate analysis of the design of the proposed fault tolerant control scheme, which will include also real implementations and the online training for application to generators with high intertia.

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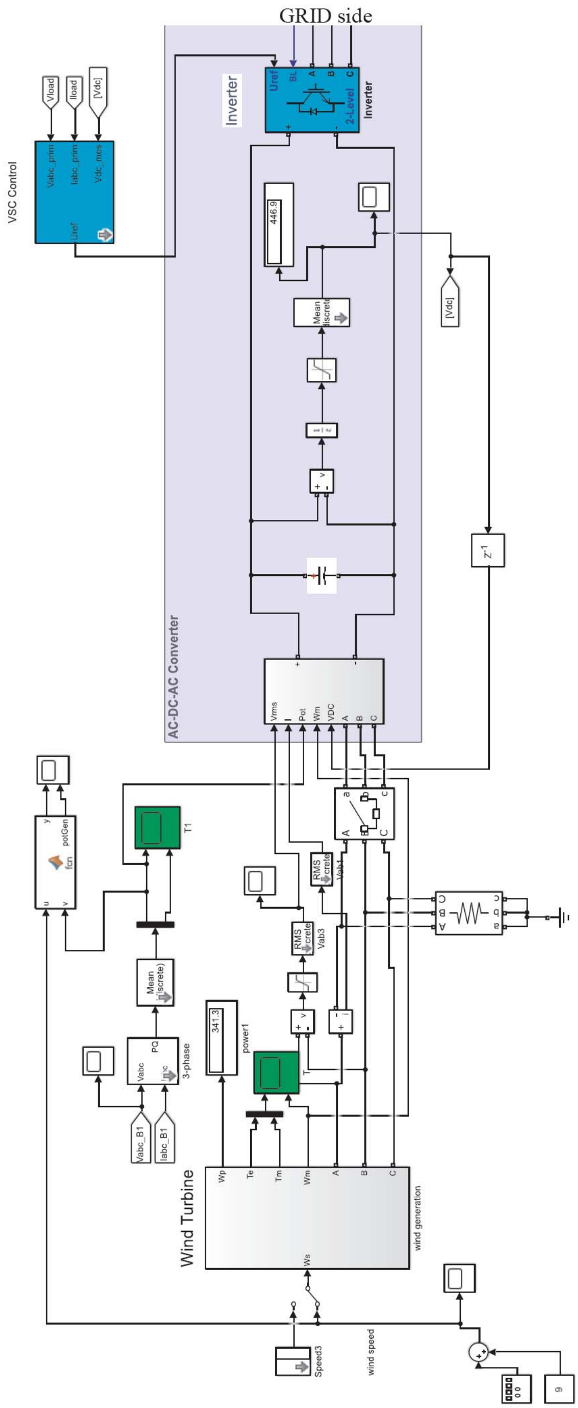

Fig. 9. Simulink scheme of the developed wind turbine system.

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