

UPRAVLJANJE PRETVARAČIMA U VETROTURBINAMA

CONTROL OF CONVERTERS IN WIND TURBINES

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U ovom radu predstavljen je algoritam upravljanja pretvaračem koji se koristi u vetroturbinama. Zbog stohastičkog karaktera brzine i smera vetra potrebno je izvršiti konstantnu kontrolu kako bi se obezbedio maksimalni koeficijent iskorišćenja vetroturbine, a samim tim i maksimalna snaga koja se prenosi konvertorom. Mašina koja se koristi za ovu svrhu je asinhroni generator. On je povezan preko ispravljača na DC link koji je dalje preko invertora i izlaznog filtra povezan na mrežu. Ova simulacija je odrađena za proizvoljni profil brzine vetra i to u Simulink simulacionom paketu.

Ključne reči: *vetar, turbine, pretvarači, kontrola, ispravljač, inverter, DC link*

In this paper, the control algorithm of converters used in wind turbines is presented. It is necessary to perform a constant control of the stochastic character of the wind speed and direction in order to ensure the maximum efficiency of wind turbines, and thus the maximum power transmitted by the converter. The machine used for this type of turbine is an induction generator. It is connected via a rectifier to a DC link which is connected to the grid via an inverter and an output filter. This simulation is done for a random profile of wind speed in the Simulink simulation package.

Key words: *wind, turbines, converters, control, rectifier, inverter, DC link*

1 Introduction

With the increased fear of climate change, there is an increased use and application of energy sources that have reduced emissions of carbon dioxide and other greenhouse gases into the atmosphere during their use. First of all, there is an expansion of the use of machines that convert wind energy into electricity. The process itself must be carefully designed because wind is a rather unpredictable source of energy. Namely, the wind speed and its direction are constantly changing. When connecting such sources to the grid, several parameters must be observed. Namely, parameters such as frequency, power and torque must be fully adjusted in order to successfully connect to the network. Also, the network itself is characterized by three important parameters: the frequency of the grid voltage, the electrical angle of the grid and its amplitude value. Therefore, before the advancement in power electronics, connecting such sources to the grid was practically impossible. Today, power converters are so advanced that they perform all the necessary functions with minimal response time and energy consumption. The converter itself consists of several parts. On the machine-turbine side, we use a rectifier based on IGBT transistors, which we control using pulse-width modulation. The machine we use in this simulation is an induction generator, primarily because it is often used in the real case because as it is easiest to place in a wind turbine. It is connected to the wind turbine via a gearbox. Further, the converter contains a single capacitor (DC link) which has the role of maintaining the power supply in the event of sudden voltage drops. Finally, we use an inverter based on IGBT transistors, which we also control by pulse-width modulation. The layout of the entire simulation is given in Figure 1. Figure 2 shows the subsystem of the wind turbine itself.

2 Wind model

For winds of arbitrary density and speed, the effective wind speed can be calculated, which gives the same wind power but respects its standard density of $1,225 \text{ kg/m}^3$. The model for calculating the effective wind speed is given in Figure 3. The inputs to the model are wind speed and density, while the output is the effective wind speed.

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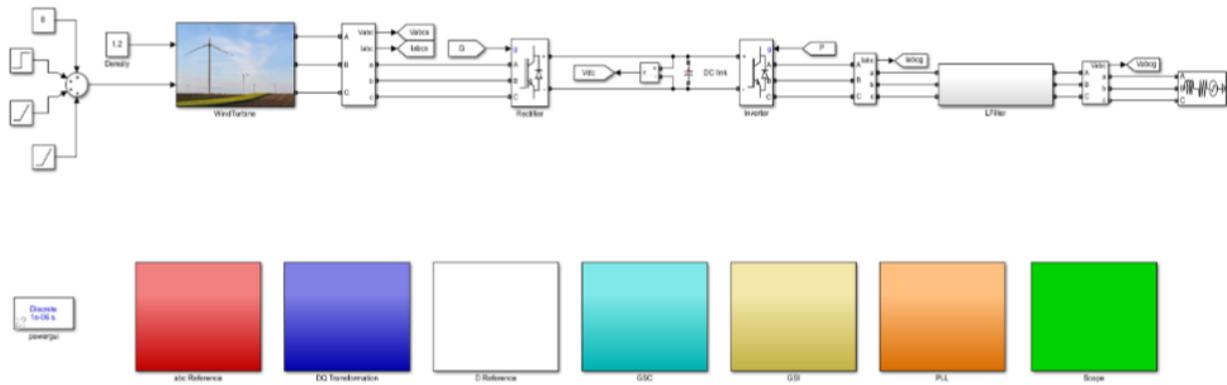


Figure 1 Simulation layout

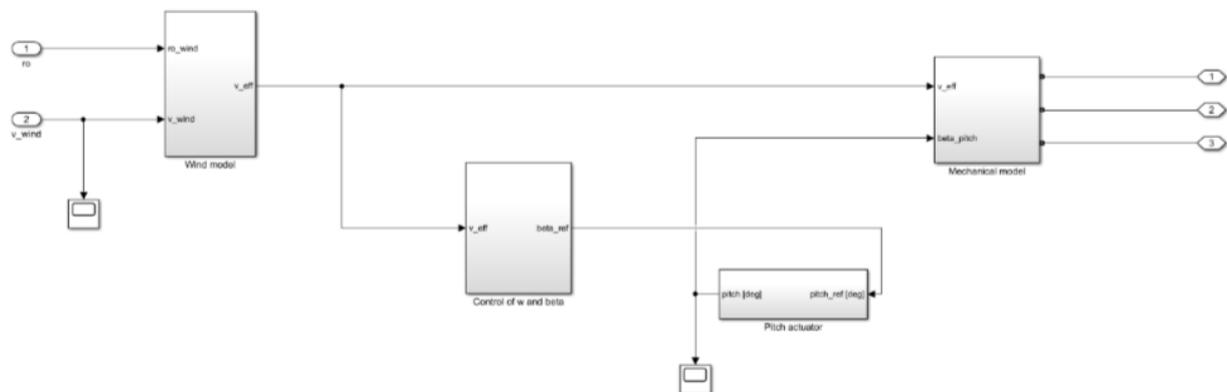


Figure 2 Windturbine subsystem

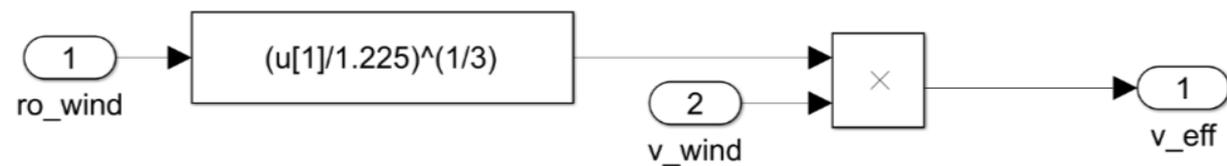


Figure 3 Wind speed model

Figure 4 shows the algorithm for calculating the turbine output power.

The mechanical power extracted from the wind can be expressed as follows [5]:

$$P_m = 0.5 * C_p(\lambda, \beta) * \rho * A * v^3$$

where P_m is the mechanical power output of the wind turbine, $C_p(\lambda, \beta)$ is the power coefficient, λ is the tip-speed ratio (TSR) of the turbine blade, while β is the pitch angle of the blade. The constant ρ represents the density of air, A is the area covered by the wind turbine blades, and v is the wind speed. The gearbox transfers power from the rotating part of the wind turbine shaft to the rotating shaft of the generator. The angular velocity of the generator ω_m is related to the angular velocity of the wind generator ω_t through the following equation:

$$\omega_m = G * \omega_t$$

where G is the gearbox ratio. The ratio of the line speed of the blade tip is related to the angular speed of the wind generator ω_t and the angular speed of the generator ω_m through the following equation:

$$\lambda = \frac{R * \omega_t}{v}$$

where R is the radius of the turbine blades. The power coefficient C_p is a nonlinear function of λ ; several nonlinear C_p models can be found in the literature. In this paper, the power coefficient model is adopted [5]:

$$C_p(\lambda, \beta) = a_1 * \left(\frac{a_2}{\lambda} - a_3 * \beta - a_4 \right) * e^{\frac{-a_5}{\lambda}} + a_6 * \lambda$$

with $a_1 = 0,5109$, $a_2 = 116$, $a_3 = 0,4$, $a_4 = 5$, $a_5 = 21$, $a_6 = 0,0068$, $a_7 = 0,08$ and $a_8 = 0,035$.

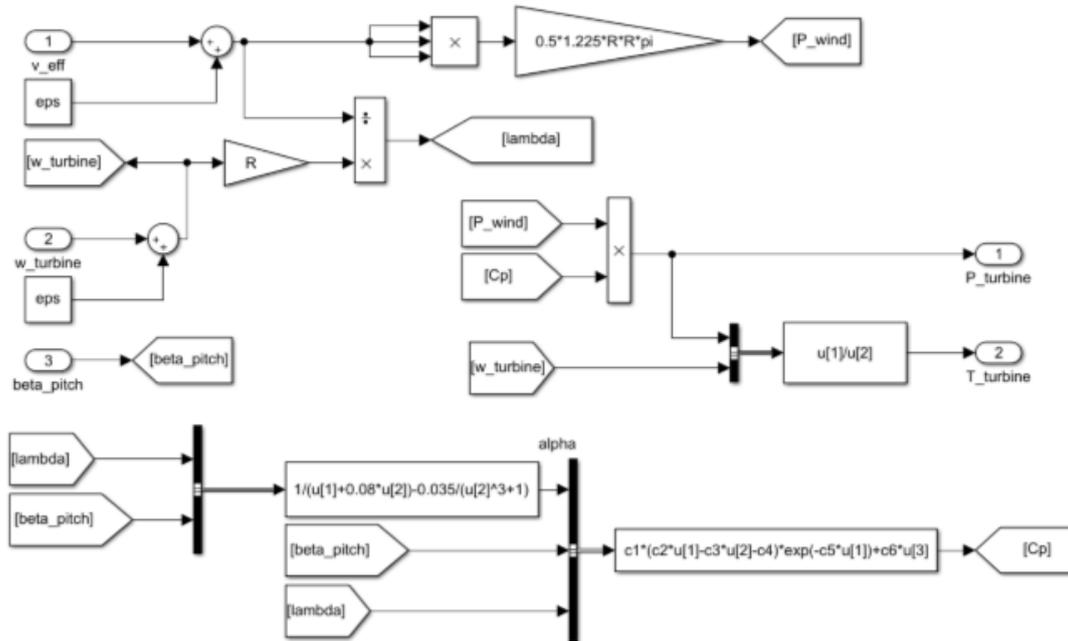


Figure 4 Calculating turbine power

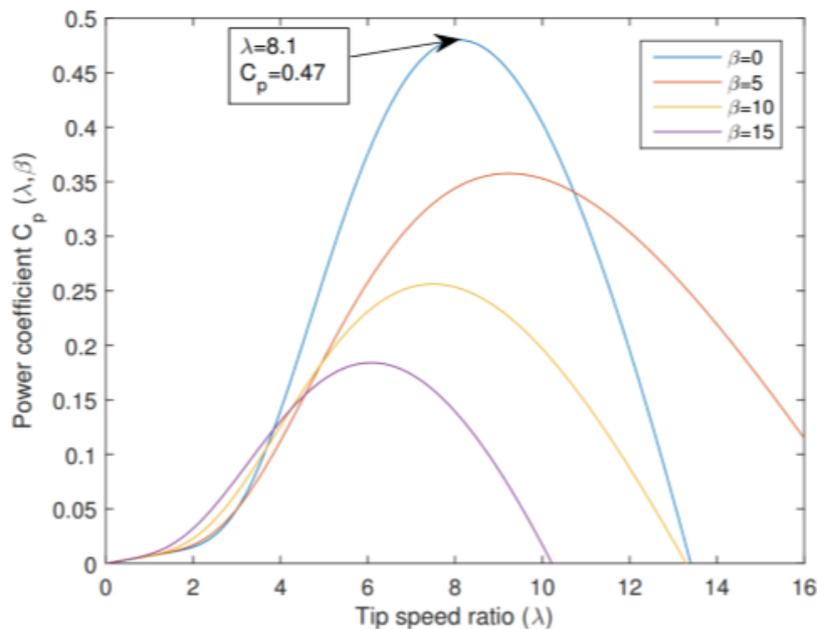


Figure 5 Power coefficient as a function of a tip speed ratio

From Figure 5, which shows the dependence of the power factor on the TSR, can be seen that the maximum value of the power factor C_p is $C_{pmax} = 0.47$. This value is obtained when the angle of inclination β is equal to zero degrees and the corresponding optimal peak velocity ratio is $\lambda_{opt} = 8.1$. In Figure 6 we see the dependence of mechanical power on rotor speed for different wind speeds.

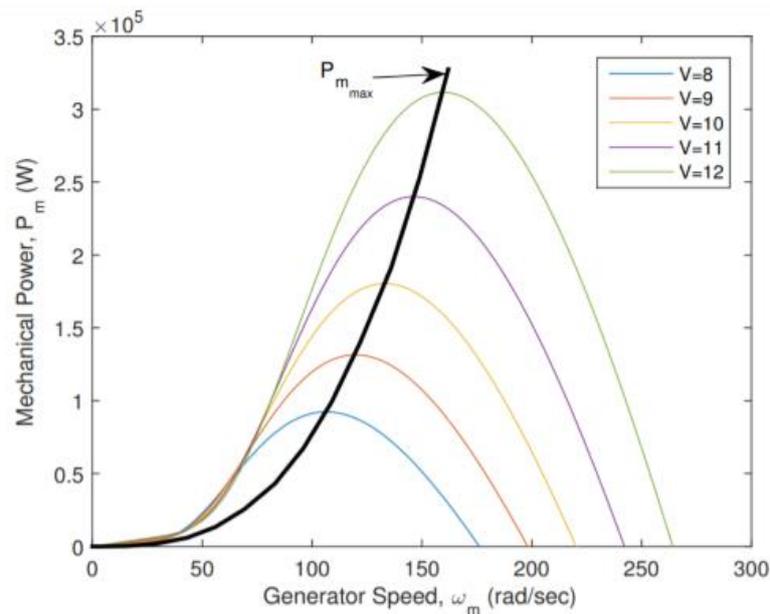


Figure 6 Mechanical power extracted as a function of generator speed

3 Mechanical model of turbine

Figure 7 shows the mechanical part of the turbine, with the following inputs: effective speed, blade angle while the output is the rotor speed. The picture shows that there is a conversion of torque and speed (due to the existence of a reducer).

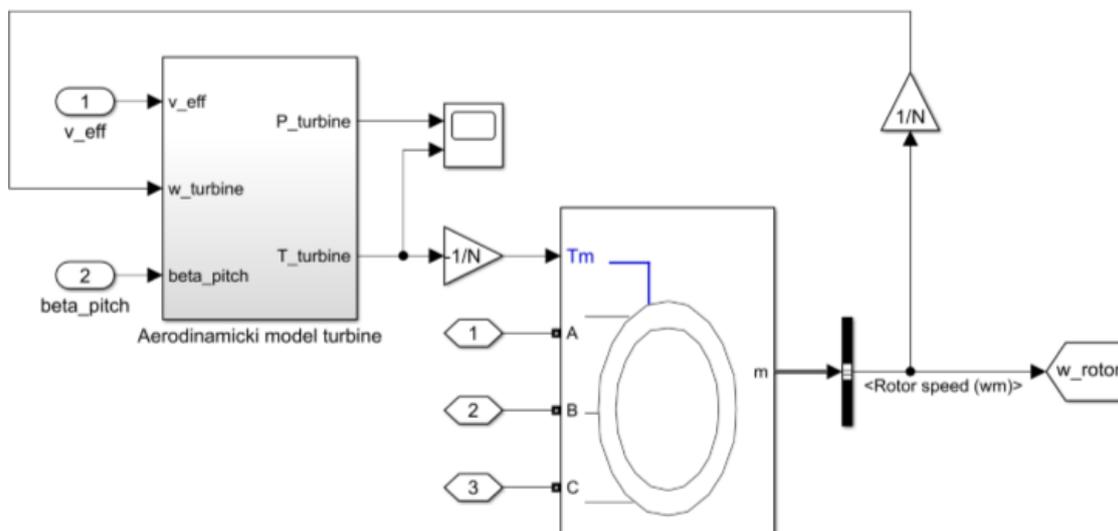


Figure 7 Mechanical part of turbine

Control of induction generator

One of the biggest challenges in designing such converters is to control an induction generator. In this simulation, the method of indirect vector control was used.

The very concept of indirect vector control appeared in the late 1960s, when K. Hasse in his doctoral dissertation explained the method of uncoupled flux and torque control of an induction motor, thus practically reducing asynchronous motor control to DC motor control. The essence of this approach is based on a complex mathematical model of an asynchronous machine and the existence of an energy converter with which we can achieve the necessary phase voltages on it. The mathematical model of a real three-phase asynchronous machine would be very complex and impractical for application, therefore by successive application of Clarke's, three-phase-two-phase, and Park, rotational, transformations from real three-phase machine we make a mathematically equivalent,

imaginary, two-phase machine whose windings rotate synchronously (the so-called Blondel transformation).

By setting the reference dq system so that the entire flux of the rotor is in the axis d ([Equation]), we achieve the set goal, i.e. unbundled control of the flux and torque of the induction machine.

Thus, by setting the value of the stator current in the d axis, we control the flux in the machine, and by using the value of the stator current in the q axis, we control the torque of the machine. The realization of the set values of the stator currents is achieved by means of 2 PI current regulators. If we want the generator to work in speed control mode, we need to add another PI controller which will be superior to the current regulator in the q axis. In order to achieve the regulation described in this way, it is necessary to measure the stator currents as well as the rotor speed. It is necessary to mention that the regulation performed in this way requires double application of Blondel's transformation, in which the frequency of rotor currents is performed by estimation based on reference values of stator currents in the d and q axes, which follows from the equations mentioned above. In Figure 8 we can see the implementation of determining the rotor reference speed at which there is a maximum turbine efficiency.

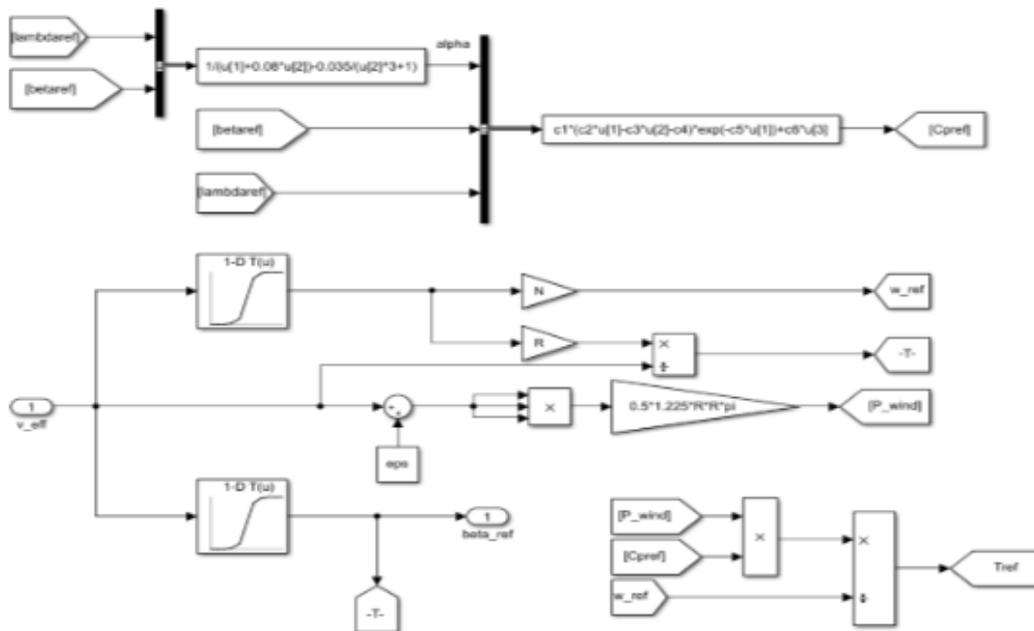


Figure 8 Calculating reference speed of rotor

Figure 9 shows how to control the pitch of the blade (pitch angle).

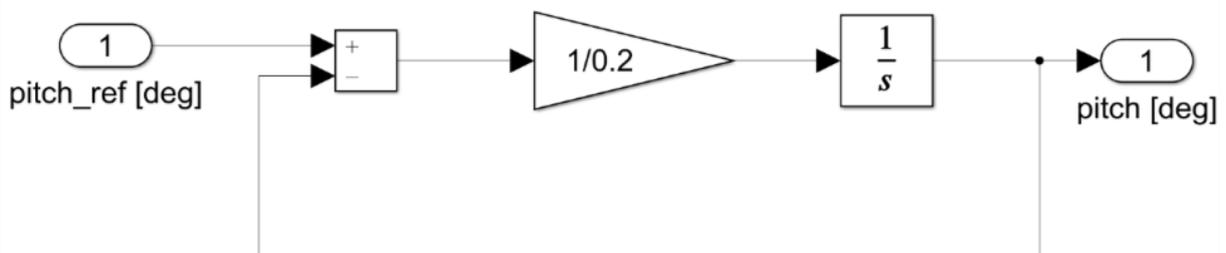


Figure 9 Pitch angle control

Figure 10 shows the control of the converter connected to the generator.

4 Calculating of PI parameters in d and q axis

The parameters of the current regulators in the d and q axes are determined by the principle of optimization of the amplitude characteristic, using the modular optimum, where the parameters of both regulators are the same. We represent a three-phase inverter bridge through its gain and delay,

which is determined on the basis of the carrier frequency, by means of which the pulse width is modulated. The connection between the voltage and the stator current is described via gain and delay, which are obtained from the RL circuit of an equivalent replacement circuit of an induction motor that is in short circuit (ignoring the rotor resistance). The current regulation loop is given in Figure 11 [4].

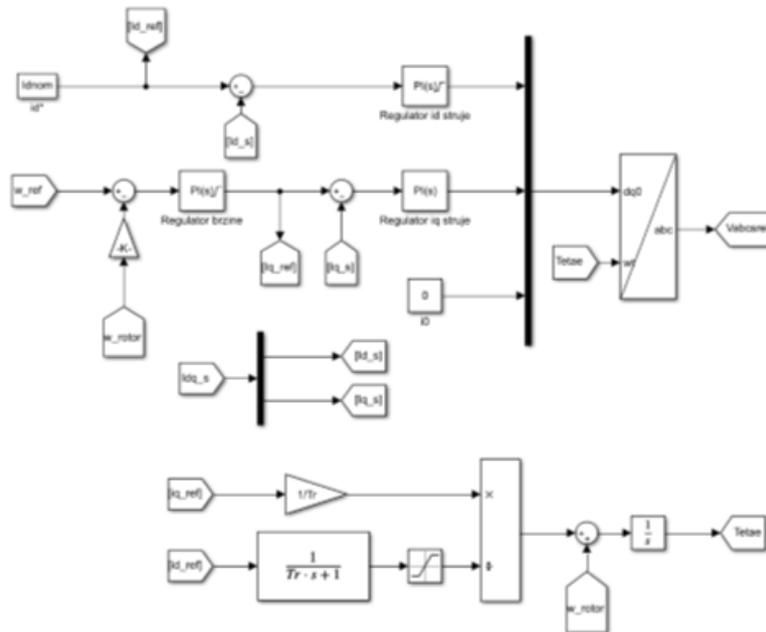


Figure 10 Control of GSC

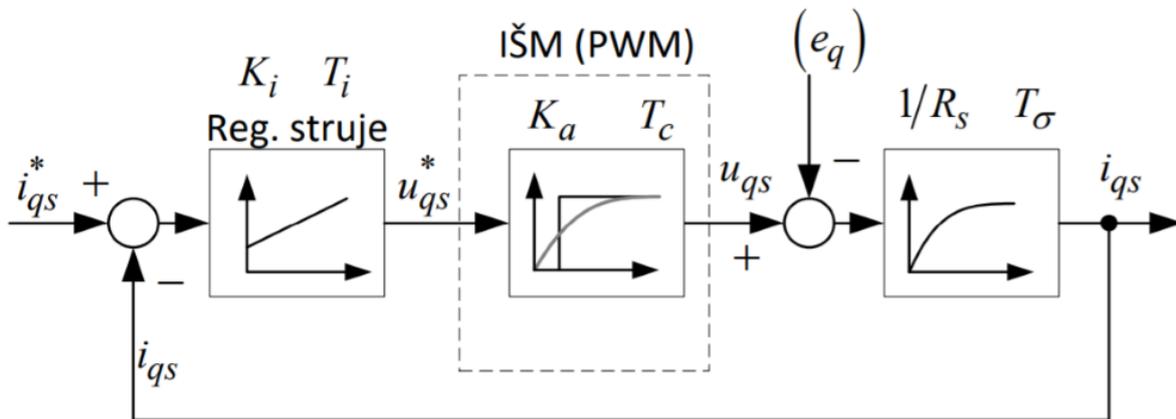


Figure 11 q axis current control

5 Calculating of PI parameters of speed

The parameters of the speed regulator are determined according to the principle of optimization of the amplitude characteristic, applying a symmetrical optimum. The previously solved current loop is equivalent using one transfer function. In the speed feedback, there is a filter whose role is to suppress the noise in the measured speed signal, which has a dominant component at a frequency of 30 Hz at 10% of its value. The gain in the filter branch is determined by the type of speed sensor used. The speed control loop is given in Figure 12 [4].

6 Control of inverter

To convert DC voltage to mains voltage we need an inverter. It consists of 3 branches with 2 switches each. In this analysis, the voltage of the capacitor (DC link) was considered to be constant and can be equivalent to a battery. Each branch is controlled independently.

Inverter control (GSC block) is performed by pulse-width modulation. It was performed in a dq synchronously rotating system because of the reasons presented in the previous part of the paper. Within this control, voltage control with a DC link has been implemented, in order to ensure the transmission of complete active power.

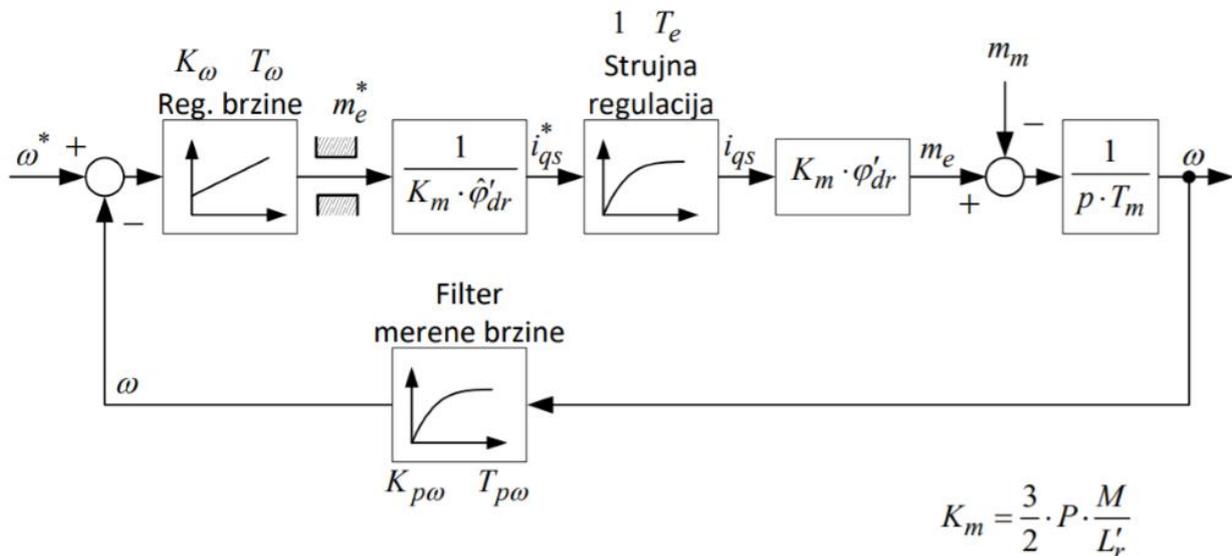


Figure 12 Control of rotor speed

0 The corresponding active and reactive power in a synchronously rotating system are:

$$P = 1.5 * (vd * id + vq * iq)$$

$$Q = 1.5 * (vq * id - vd * iq)$$

By setting the voltage along the q axis to zero, we obtain a completely uncoupled control. Due to the nature of the output provided by the inverter (the current has a saw shape), it is necessary to install an additional filter, which will reduce these ripples. That is why it is necessary to calculate the voltage drops on it in order to perform synchronization (for a given reference of active and reactive power). The equations that apply in this case can be expressed by the following connections:

$$\begin{pmatrix} \frac{dia}{dt} \\ \frac{dib}{dt} \\ \frac{dic}{dt} \end{pmatrix} = \begin{pmatrix} \frac{-R}{L} & 0 & 0 \\ 0 & \frac{-R}{L} & 0 \\ 0 & 0 & \frac{-R}{L} \end{pmatrix} \begin{pmatrix} ia \\ ib \\ ic \end{pmatrix} + \frac{1}{L} * \begin{pmatrix} ua - va \\ ub - vb \\ uc - vc \end{pmatrix}$$

$$\begin{pmatrix} \frac{did}{dt} \\ \frac{diq}{dt} \end{pmatrix} = \begin{pmatrix} -R & \omega L \\ -\omega L & -R \end{pmatrix} \begin{pmatrix} id \\ iq \end{pmatrix} - \frac{1}{L} * \begin{pmatrix} vd \\ vq \end{pmatrix} + \frac{1}{L} * \begin{pmatrix} ud \\ uq \end{pmatrix}$$

$$ud = \left(Kp + \frac{Ki}{s} \right) * (id^* - id) - \omega * L * iq + vd$$

$$uq = \left(Kp + \frac{Ki}{s} \right) * (iq^* - iq) + \omega * L * id + vq$$

The layout of the corresponding block diagram is given in the figure below. The input is represented by the current values of the currents in the d and q axes as well as the voltage value on the capacitor. They are controlled by appropriate PI controllers. This control is shown in Figure 13.

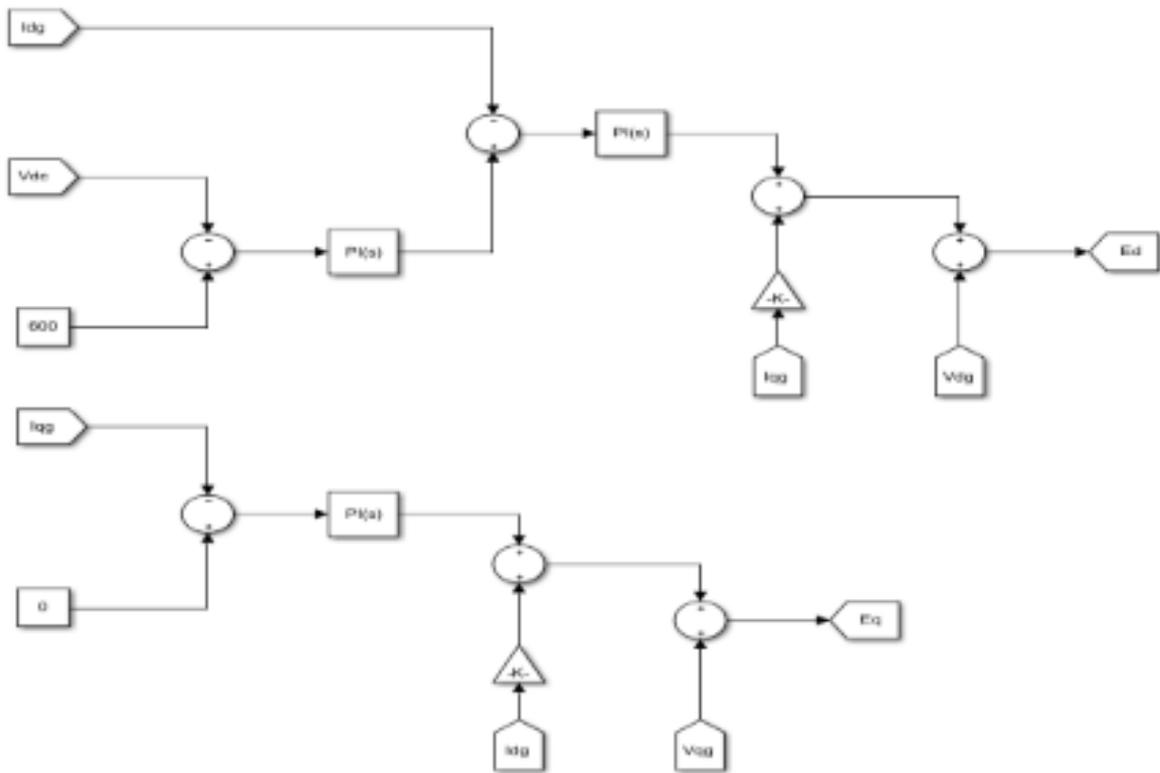


Figure 13 Control of inverter

PLL

In order to perform proper synchronization, it is necessary to determine the electrical angle of the network at the time of sampling. The diagram in the figure below (PLL) is used for this purpose. The input to this loop is the q voltage component that is compared to 0 to determine the difference between the required and current frequency.

In the end, the current frequency is obtained, the integration of which gives the grid angle. This loop is shown in Figure 14.

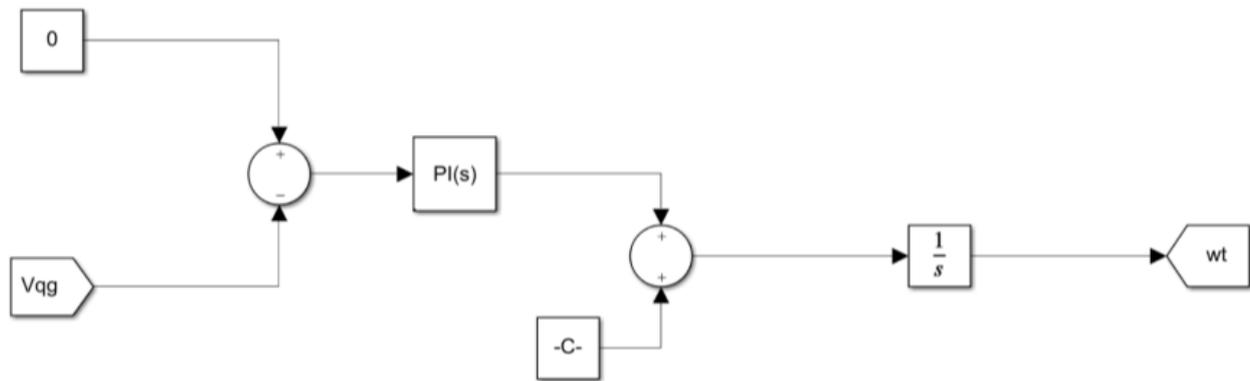


Figure 14 PLL

7 Simulation results

The figures below show the parameters and results of the simulation (lasts about 15s). It is clear from the pictures that the control is designed correctly because the responses are almost instantaneous. The simulation parameters are shown in Figure 15.

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Editor - C:\Users\Stevan Jokić\Downloads\Konferencija.m
Konferencija.m x +
1 %Parametri
2 fc=10000;
3 Rs=0.6;
4 Rr=0.23;
5 Landa_s=0.00522;
6 Landa_r=0.00522;
7 M=0.171887;
8 Ls=M*Landa_s;
9 Lr=M*Landa_r;
10 Ts=(Ls*Lr-M^2)/(Lr*Rs);
11 sn=29266.77/3;
12 Un=380;
13 Ugrid=220;
14 sn=-0.016;
15 nn=1500*(1-sn);
16 idn=3.706*sqrt(2);
17 Fir_n=idn*M;
18 ign=14.351*sqrt(2);
19 igmax=1.5*ign;
20 Mmax=1.5^2*M*igmax*Fir_n/Lr;
21 Mn=1.5^2*M*ign*Fir_n/Lr;
22 J=0.5;
23 p=1;
24 Tr=Lr/Rr;
25 Vdc=1000;
26 Ka=380*sqrt(2)/sqrt(3);
27 Ta=1/fc;
28 Tm=J;
29 Tpw=((1/0.2)^2-1)/(2*3.14159*400);
30
31 %Parametri filtra
32 Kpw=1/15;
33 Tpw=sqrt((1/0.1)^2-1)/(2*3.14159*30);
34 Te=Ta;
35
36 %Parametri regulatora
37 Ti=Ts;
38 Ki=Ti*Rs/(2*Ka*Ta);
39 Tw=4*(2*Te+Tpw);
40 Kw=2*Tm/(Tw*Kpw*1.5*p*M*Fir_n/Lr);
41

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Figure 15 Simulation parameters

In Figure 16 we see the appearance of wind speed. This input parameter can be selected arbitrarily.

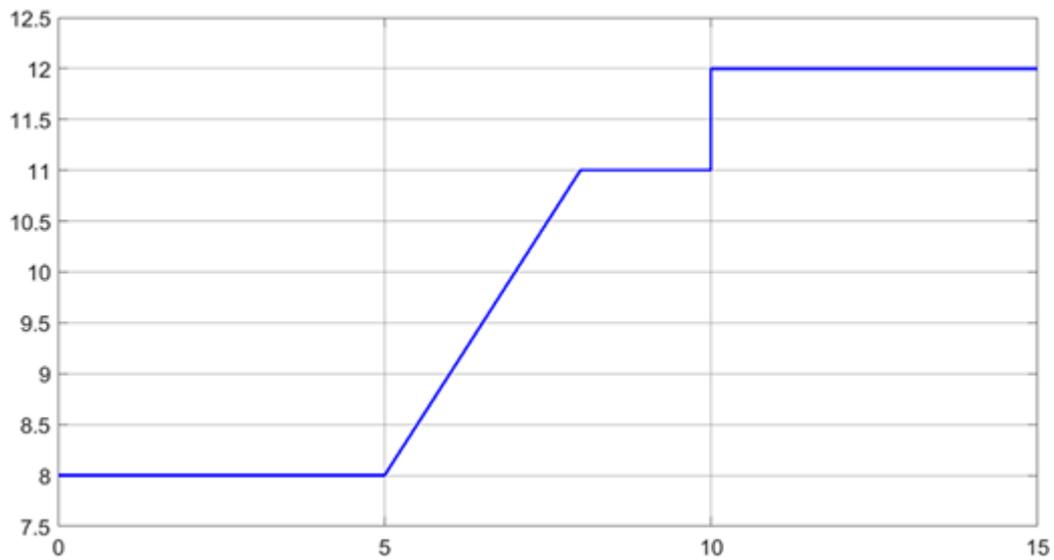


Figure 16 Wind speed

The figures below (17-21) show the simulation results.

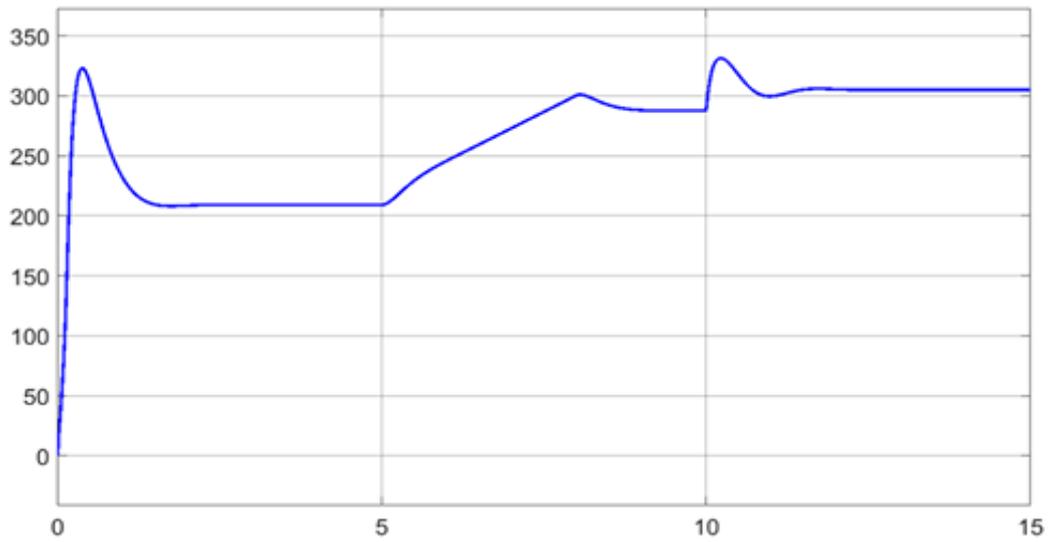


Figure 17 Rotor speed

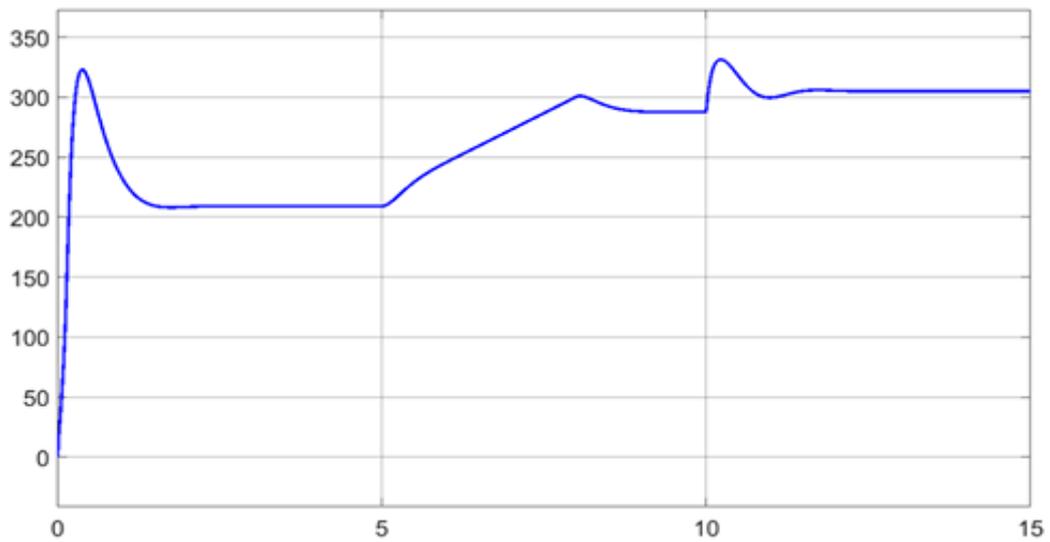


Figure 18 Grid current

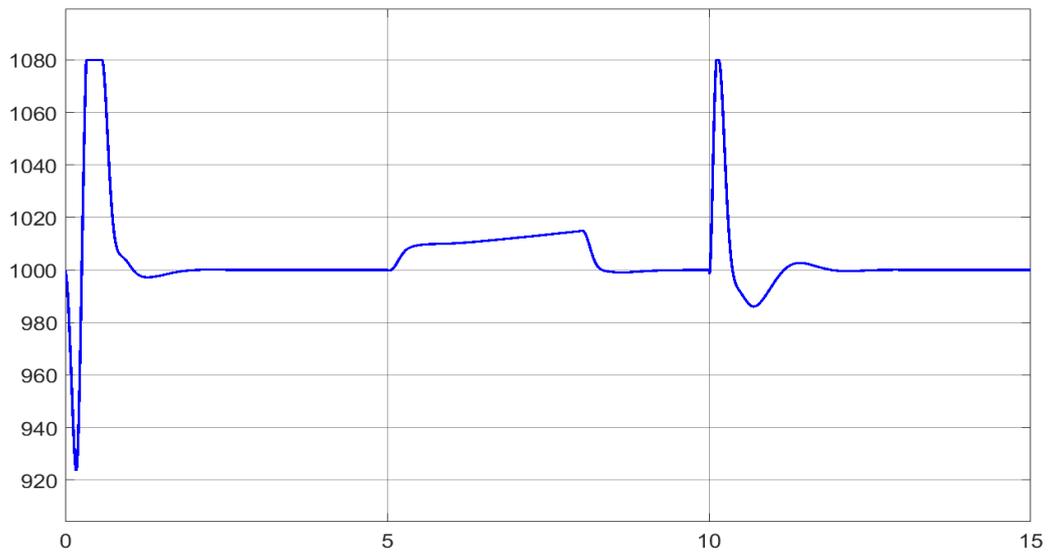


Figure 19 DC link voltage

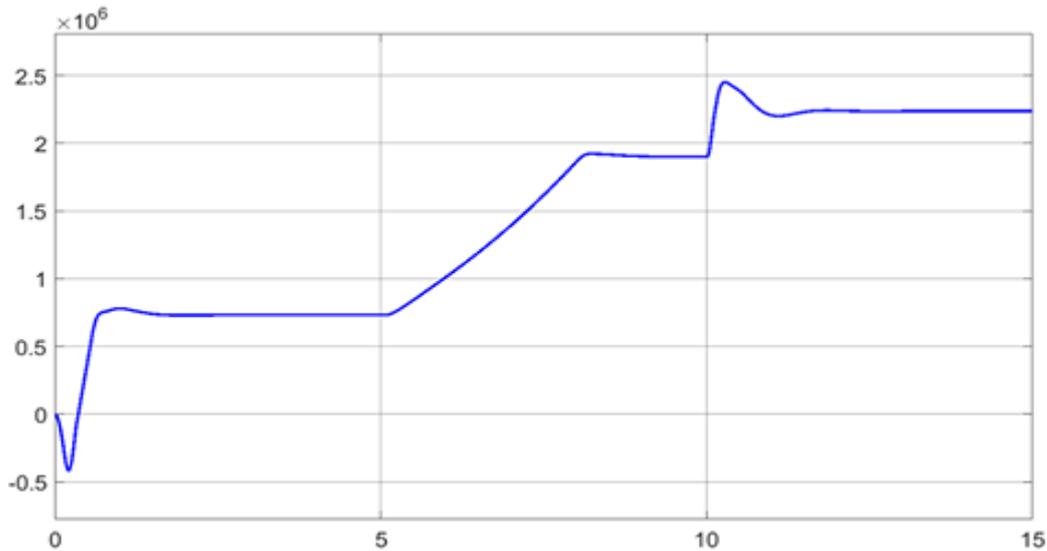


Figure 20 Active Power transmitted to the grid

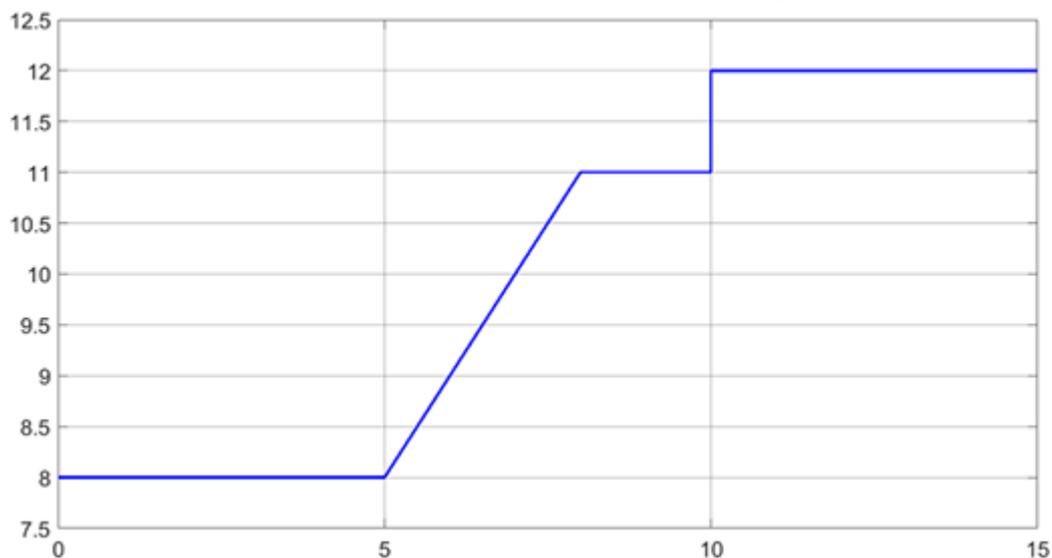


Figure 21 Reactive Power transmitted to the grid

8 Literature

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- [3] *** Materials from website www.pogoni.etf.bg.ac.rs,
- [4] *** Materials from website <http://ees.etf.bg.ac.rs/>,
- [5] *** Sliding Mode Control of a Variable- Speed Wind Energy Conversion System Using a Squirrel Cage Induction Generator, *Mohamed Zribi, Muthana Alrifai * and Mohamed Rayan*