Universitat Politècnica de Catalunya

Renewable Energy Systems
AY 2021/2022

UNITE! Programme

Wind Turbine Generators

FIRST LABORATORY ACTIVITY

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EXERCISE 1

In the first exercise is asked to determine the parameters of the squirrel cage generator and of the wind turbine. This data can be found at the beginning of the MatLAB script named "GEOENP2.m".

- Squirrel Cage Generator Parameters
    - Nominal Power = 2e6 W
    - Nominal Voltage (phase to phase) = 960 V
    - Nominal frequency = 50 Hz
    - Stator Resistance = 5e-3 Ω
    - Rotor Resistance = 9e-3 Ω
    - Stator Leakage Inductances = 0.4e-3 H
    - Rotor Leakage Inductances = 0.3e-3 H
    - Magnetic Inductance = 15e-3 H
    - Number of Poles = 2
    - Rotor Inertia = 90 kg*m^2

- Wind turbine parameters
    - Inertia = 9e6 kg*m^2
    - Parameters of Power Coefficient:
        - c1 = 0.5
        - c2 = 116
        - c6 = 5
        - c7 = 21
        - c9 = 0.035

EXERCISE 2

In the second exercise it is asked to determine how and where the following parameters are computed:

- Tip Speed Ratio λ

    The tip speed ratio is calculated in the block "lambda" of the wind turbine model in the "GEOENP2model" on Simulink. This block receives as input the angular velocity ω_t and the wind speed v and gives as output the tip speed ratio. Therefore, it is obtained by multiplying the angular velocity ω_t times the radius R and then divided by the wind velocity v, the formula followed is:

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

- Power Coefficient

The power coefficient is computed in the block “cp” of the wind turbine model in the “GEOENP2model” on Simulink, it depends on the tip speed ratio λ (that is an input data for this block) and it is calculated with the following formula:

$$c_P = c1(c2\left(\frac{1}{\lambda} - c9\right) - c6)e^{-c7(\frac{1}{\lambda}-c9)}$$

- Incoming Wind Power

The incoming wind power is the power available from the wind, it is calculated as:

$$P = \frac{1}{2}A\rho v^3$$

Where $A = \pi R^2$

It is computed in the wind turbine model in the “GEOENP2model” on Simulink after the calculation of the power coefficient. It is obtained by multiplying the cube of the wind velocity times the quantity ${}^1/_2\, A\rho$.

- Power Delivered to the Transmission System

The power delivered to the transmission system is the power that the wind turbine is able to extract from the wind, therefore it is equal to the power available from the wind P times the power coefficient c_p that is always lower than 59% due to the Betz limit.
It is computed in the wind turbine model in the “GEOENP2model” on Simulink after the computation of the incoming wind power P, as:

$$P_T = \frac{1}{2}A\rho v^3 c_P$$

- Torque Delivered to the Transmission System

The torque is computed in the wind turbine model in the “GEOENP2model” on Simulink after the calculation of the power P_T. It is obtained by dividing the power delivered to the transmission system by the angular velocity ω_t:

$$T_T = \frac{P_T}{\omega_t}$$

Regarding instead the conversion between generator and turbine torque to axis speed, it is computed in the transmission model in the "GEOENP2model" on Simulink with the following steps:

1. The turbine torque T_t and the generator torque T_g are summed
2. After the summation, they are divided by the inertia of the turbine J_t
3. Lastly, a time integration is performed with the initial condition equal to ω_{g0}/N

After the integration, the value of ω_t is found.

EXERCISE 3

After running the simulation, the following graphs are obtained:

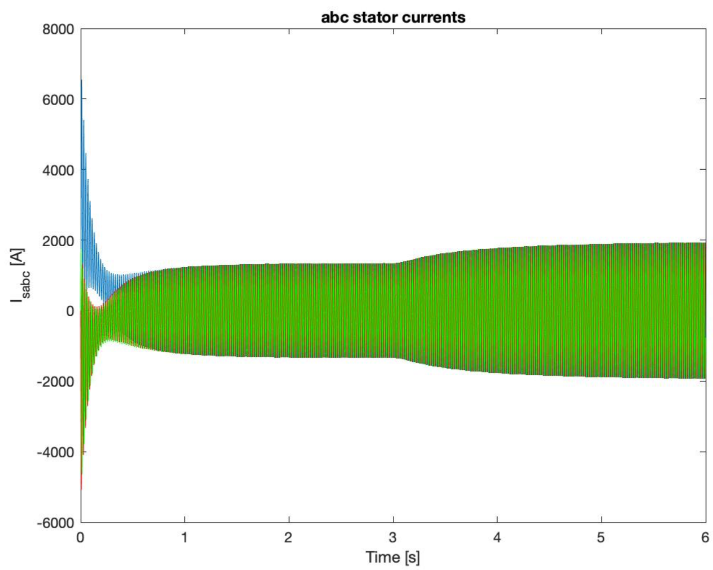

Figure 1 – abc stator currents

After an initial transient that lasts less than 0.5 seconds, the three currents stabilize between the value of about ± 1000 A. At the time t = 3 s, there is a step variation of the wind velocity that goes from 11 m/s to 13 m/s, therefore the absolute value of the three currents also rises, reaching the value of ± 2000 A.

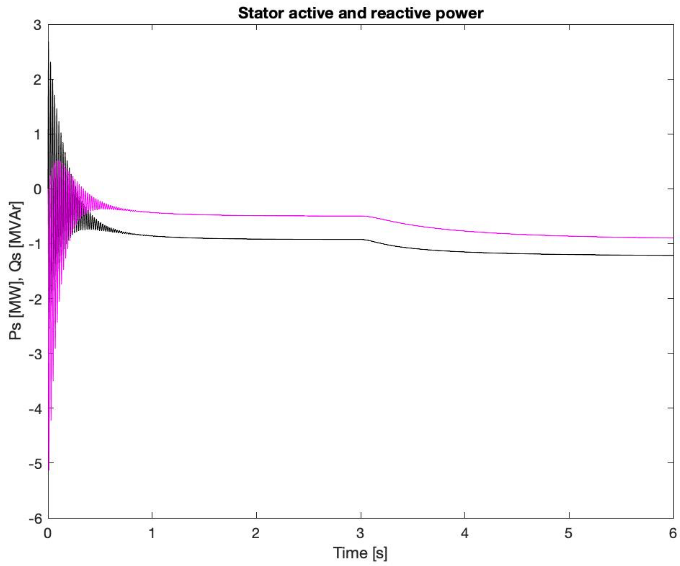

Figure 2 – stator active and reactive power

The two powers are computed as:

$$P_S = v_{sd} i_{sd} + v_{sq} i_{sq}$$

$$Q_S = v_{sq} i_{sd} - v_{sd} i_{sq}$$

Also the stator active and reactive power stabilize after an initial transient, when the velocity rises at t = 3s, they both rise in absolute value (while they diminish with respect to the signed value).

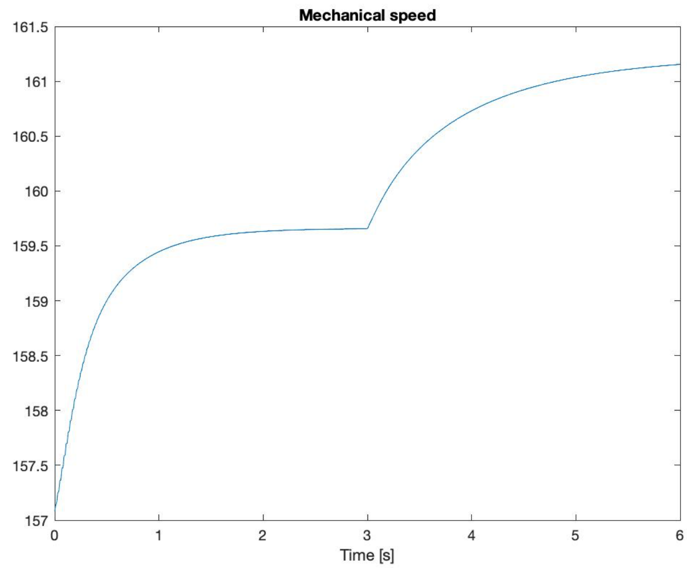

Figure 3 – mechanical speed

When the wind speed rises, also the mechanical speed of the generator becomes bigger.

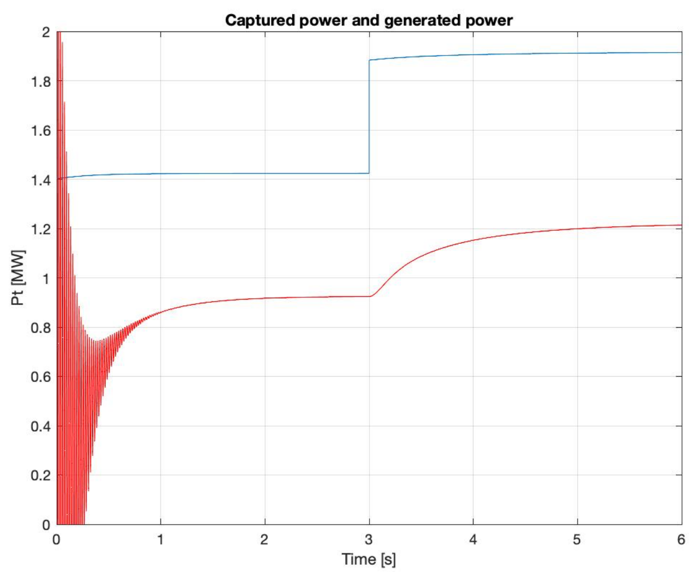

Figure 4 – captured power and generated power

The captured power (in blue) is always higher than the generated power, because the generated power is equal to the captured one multiplied by the power coefficient c_p that is always lower than 0.59.
When the speed of the wind rises, also the captured power (and, as a consequence, the generated one) rises, because the wind has more kinetic energy that can be transferred to the turbine.

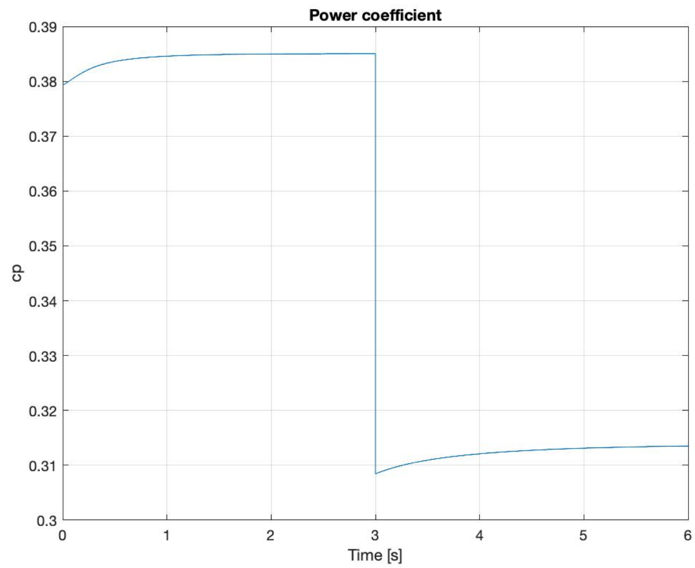

Figure 5 – power coefficient

As already said, the power coefficient is always lower than 0.59, in this case at the beginning it is about 0.385 and after the wind speed rises it decreases to about 0.313.
The power coefficient depends on the tip speed ratio with a negative exponential law:

$$c_p \sim e^{-\frac{1}{\lambda}}$$

Since the tip speed ratio decreases if the wind velocity increases (because it depends on 1/v), the exponent increases but with negative sign, so at the end the power coefficient decreases. This means that we can effectively extract from the wind less power than before, when the wind speed was lower.

EXERCISE 4

The fourth exercise requires to change the wind speed according to a sinusoidal law. In order to perform this change, in the "GEOENP2model" on Simulink, the constant and the step function have been eliminated and a block called "Sine Wave Function" has been put, the output of this block is a function of the type:

$$O(t) = Amp \cdot \sin(Freq \cdot t + Phase) + Bias$$

Where:

- "Amp" is the amplitude of the signal, in this case equal to 5 m/s
- "Freq" is the frequency of the signal, computed as $\frac{2\pi}{T}$ where T is the period of the signal, approximately equal to 6.2 seconds

- “Phase” is the phase of the signal, in this case equal to zero
- “Bias” is the value of the signal when t = 0 s, in this case it is equal to 10 m/s

The velocity result is shown in the figure below:

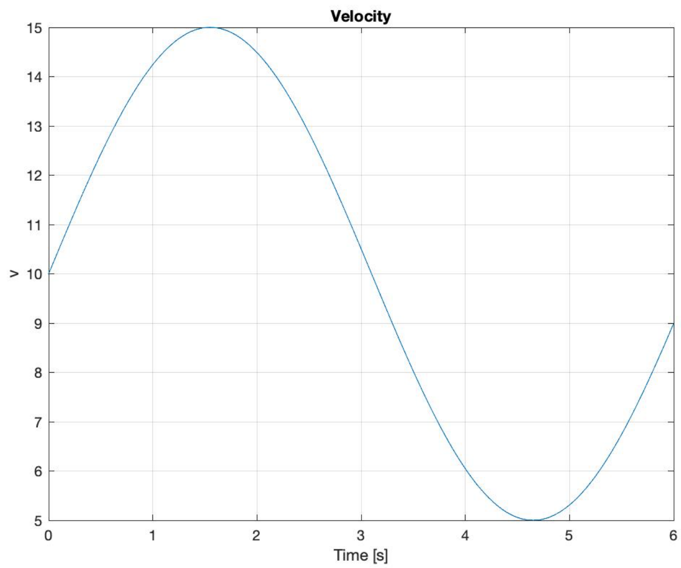

Figure 6 - sinusoidal velocity

With this new velocity the same parameters of the exercise 3 are plotted and the results are:

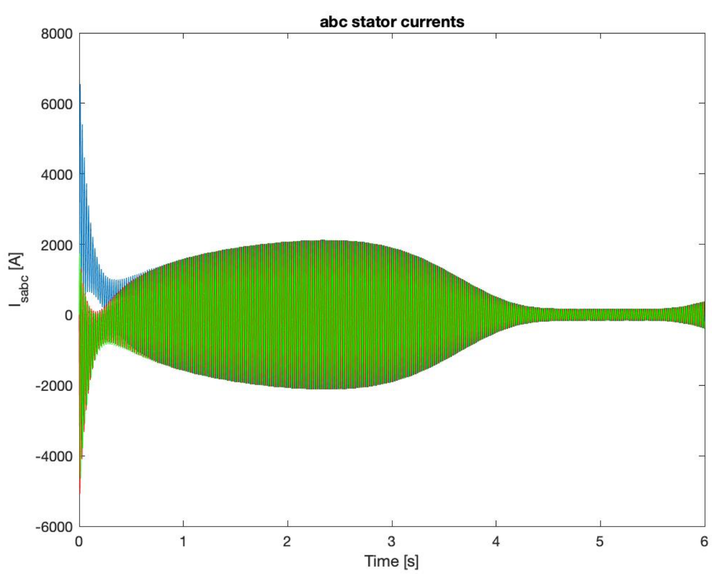

Figure 7 – abc stator currents

As already said, the currents follow the path of the velocity, between the seconds 1-2 the velocity is high and also are the currents (in absolute value), while for t = 4-6 s the velocity is very low and also the absolute values of the currents.

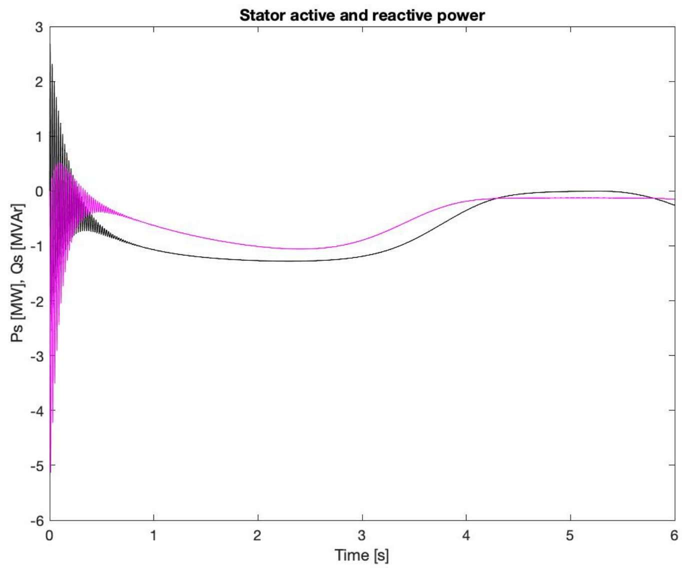

Figure 8 – stator active and reactive power

The stator active and reactive power have an opposite trend if compared to the velocity, in fact when the velocity is high they are smaller (not in absolute value but with their signed value) and vice versa.

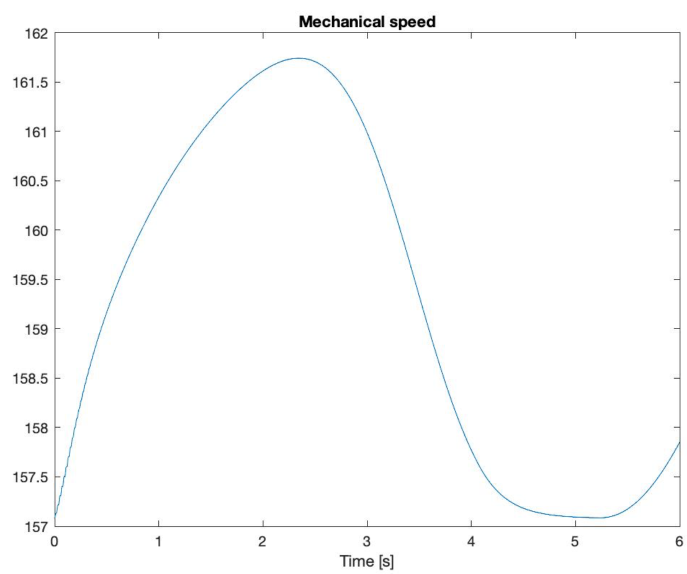

Figure 9 – mechanical speed

As said in the exercise 3, the mechanical speed follows the trend of the velocity.

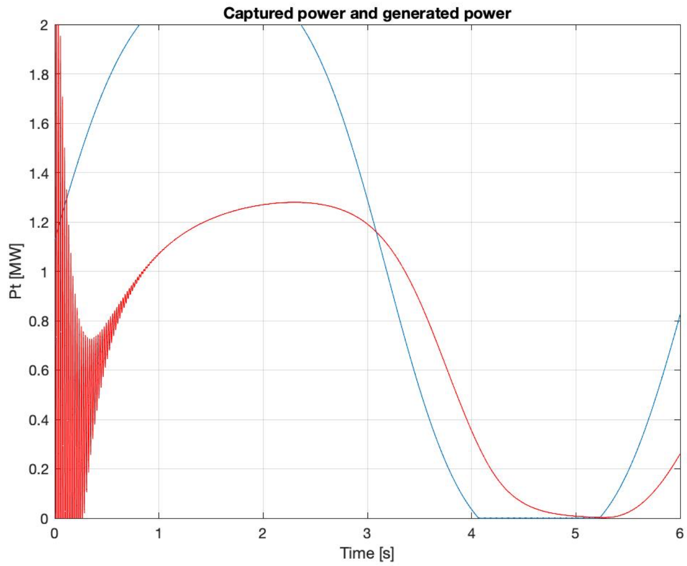

Figure 10 – captured and generated power

In this case the captured power is higher than the generated one only at t < 3 s, then it decreases until the value of 0 MW is reached. The fact that the generated power is zero means that the power coefficient is zero, so we are not extracting power from the wind at all.

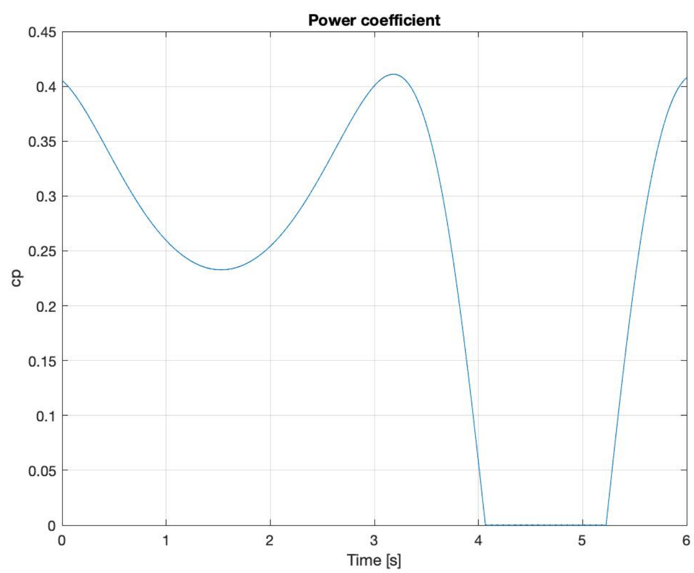

Figure 11 – power coefficient

The power coefficient reaches its maximum value for t = 0 s and about t = 3.2 s, when the velocity is equal to 10 m/s. When the velocity is higher and reaches 15 m/s, the power coefficient decreases, this is probably because of the regulation of the turbine. In fact, when the wind speed is too high we need to reduce the lift coefficient and therefore the power coefficient in order not to exceed the rated power.

Between t = 4-5 s, as already said, the power coefficient decreases abruptly until it becomes null. This can be due to the fact that the velocity of the wind may be too small, in fact if the wind speed does not exceed the cut-in speed, the turbine is not turned on as it is unable to produce power.

EXERCISE 5

In the last exercise it is asked to modify the model to explore stator and rotor fluxes. In order to do this, in the "GEOENP2model" on Simulink, the bus selector block has been modified. In particular, rotor and stator fluxes (both q and d fluxes) have been added to the variables to export on MatLAB in order to be plotted.

The four fluxes have been computed in three different wind velocity conditions: the first is the step function originally present in the model, the second is the sinusoidal function added in exercise 4 and the third is a constant speed of 11 m/s.
The results are summarized in the figures below:

- Step function velocity

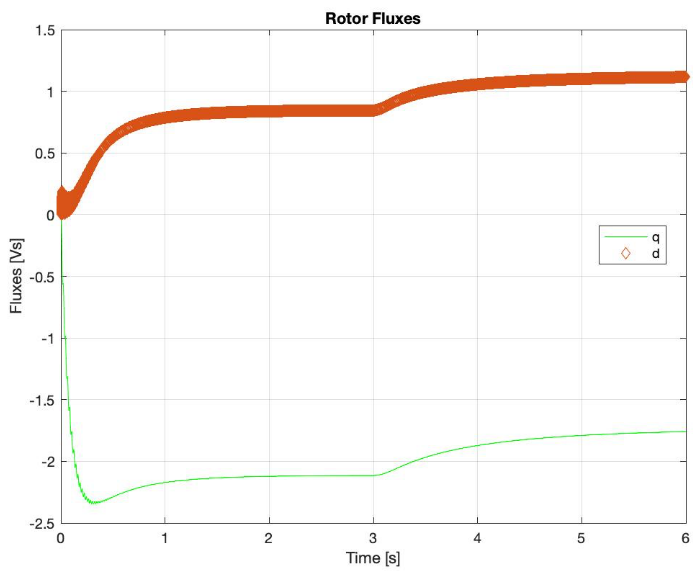

Figure 12 – rotor fluxes for step function velocity

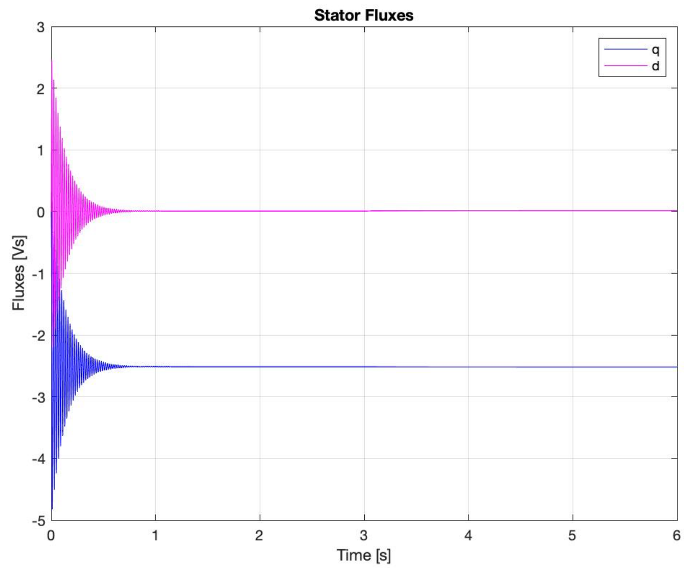

Figure 13 – stator fluxes for step function velocity

- Sinusoidal velocity

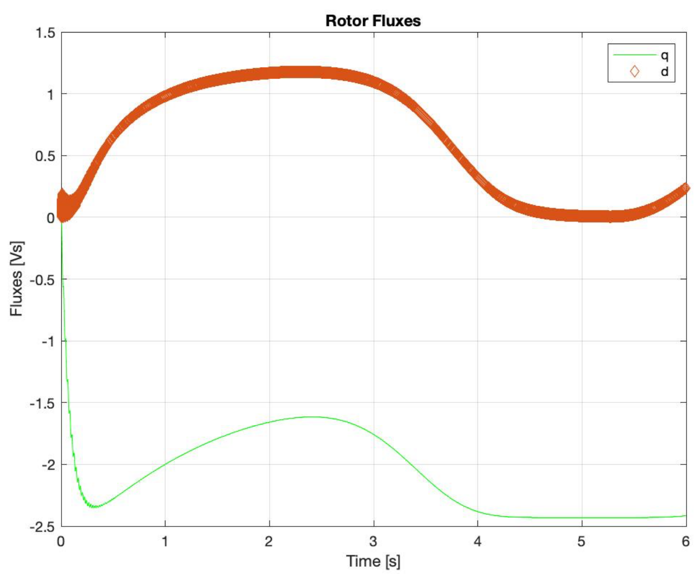

Figure 14 – rotor fluxes for sinusoidal velocity

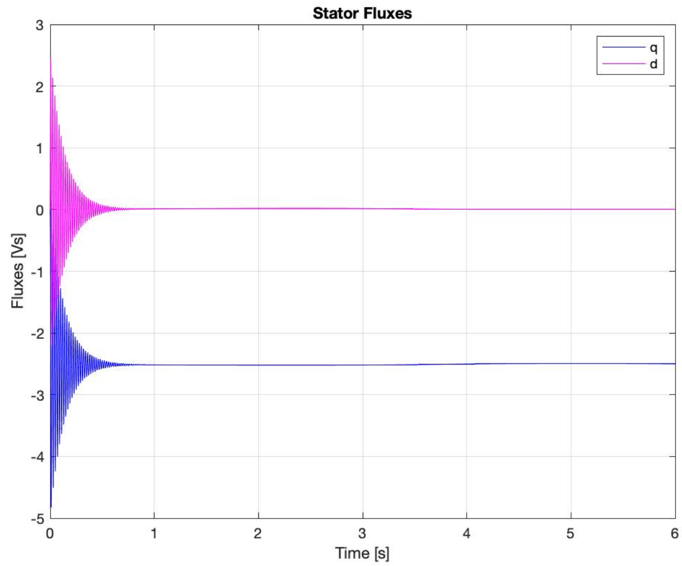

Figure 15 – stator fluxes for sinusoidal velocity

- Constant velocity

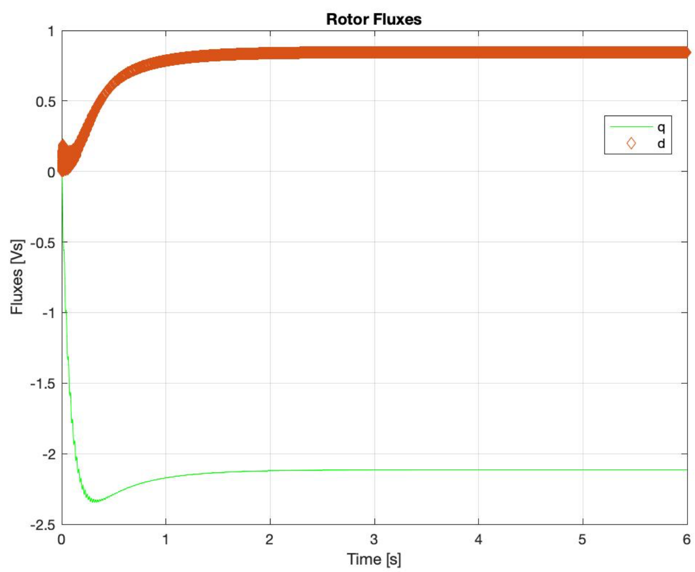

Figure 16 – rotor fluxes for constant velocity

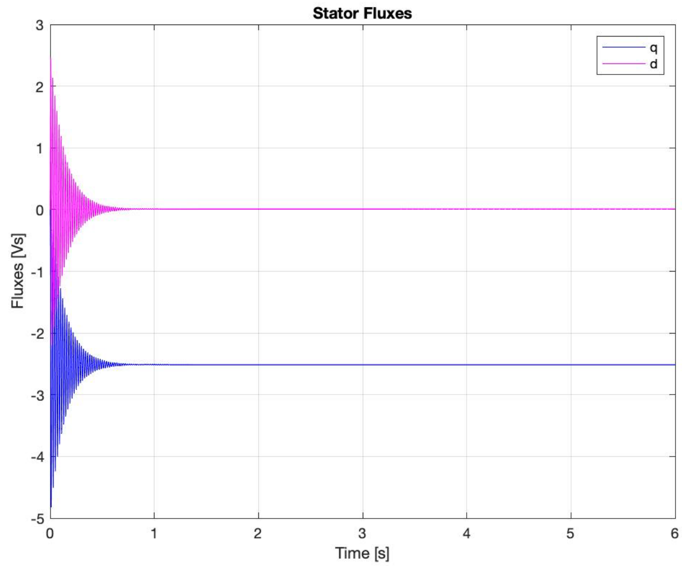

Figure 17 – stator fluxes for constant velocity

From the figures above it is clear that the q and d fluxes at the rotor follow the trend of the velocity, in fact they are constant when v is constant, they have a step when the velocity has a step and so on.
On the other end, as expected, the stator fluxes remain constant in all the analyzed wind speed conditions because the q and d fluxes at the stator do not depend from the wind speed.