Control of a Grid Converter

A report is to be written on this assignment in groups of two (or alone). Submit your report as a PDF file to the MyCourses portal (`mycourses.aalto.fi`) no later than on **Wednesday, 22.5.2024, at 20:00**. In your report, answer *briefly* the questions given inside this kind of framed boxes. The report should be clearly and consistently written. The requested figures describing the models and simulation results should be included in the report. Submit also the two requested Simulink models to MyCourses. These models will be used to check that you have built the models yourself. Name all your files starting with you last name, e.g., `Lastname_Assignment2.pdf`. Guidance is available in the classroom:

- Wednesday, 24.4. at 10:15–12:00
- Wednesday, 15.5. at 10:15–12:00

The assignment will be graded on a scale of 0. . . 15 (one point per problem). You are encouraged to discuss with other students but copying solutions from other groups is not allowed! The reports and models will be checked for plagiarism.

1 Introduction

This assignment deals with control of a grid converter equipped with an L filter, see Fig. 1(a). In Section 2, the DC bus is modelled with the constant DC-voltage source (or, equivalently, infinite capacitance) shown in Fig. 1(b), while the converter is controlled in the power-control mode. This control mode is used, e.g., if another converter connected to the same DC bus regulates the bus voltage.

In Section 3, the DC-bus capacitor is fed from a current source i_{dc}, cf. Fig. 1(c), while the studied converter regulates the bus voltage. This is a typical case, e.g., in active front-end rectifiers, grid-side converters of wind turbines, and solar inverters. Note that Fig. 1(c) can be used to model a power source (or sink) as well, i.e., $i_{\mathrm{dc}} = p_{\mathrm{dc}}/u_{\mathrm{dc}}$.

After this assignment, you should be able to:

1. Explain the basic control principles of a grid converter.
2. Explain the operating principles of DC-bus voltage control and phase-locked loop.
3. Manage the input and output ports of MATLAB Function blocks.

2 Power-Control Mode

Fig. 2 shows the control scheme. The grid voltage is 400 V (rms, line-to-line) and the grid impedance is omitted. The filter inductor is $L_{\mathrm{f}} = 10$ mH and the constant DC-bus voltage is $U_{\mathrm{dc}} = 650$ V. Download the Simulink model `converter.slx` and the initialization script `init.m` from the MyCourses portal. Open the model `converter.slx`, shown also in Fig. 3. Notice that you cannot simulate the model yet, since some parts are missing.

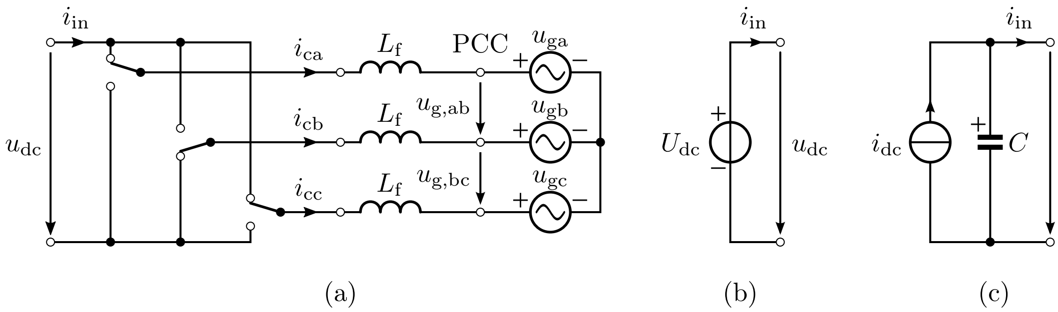

Figure 1: System model: (a) converter, filter inductors L_f, and grid; (b) constant DC-voltage source U_{dc}; (c) current source i_{dc} and DC-bus capacitor C.

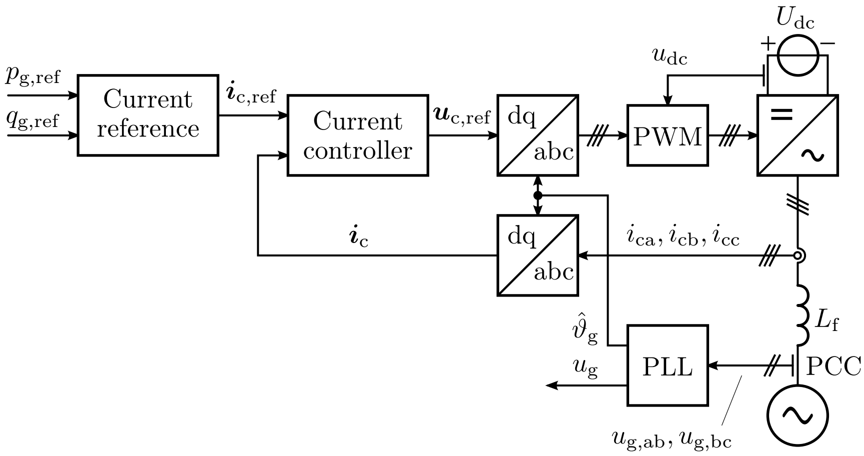

Figure 2: Block diagram of grid-voltage-oriented vector control.

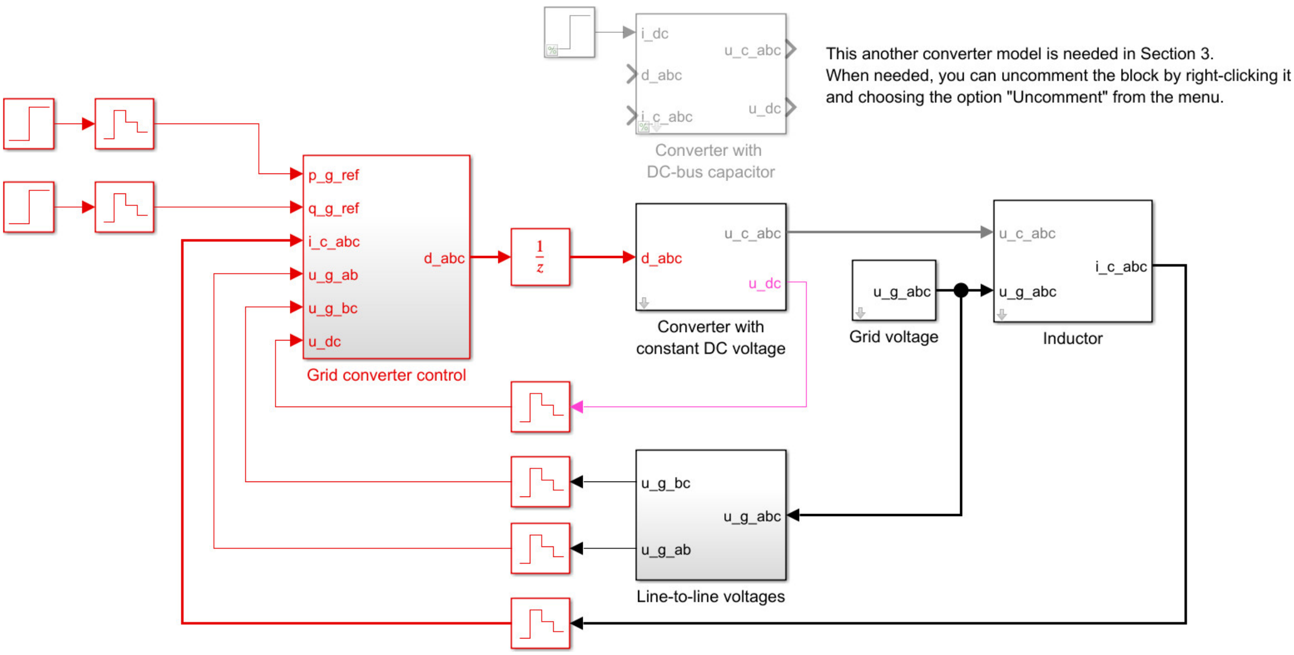

Figure 3: Simulink model of a grid converter system. The Unit Delay block models the one-sampling period computational delay, which exists in real systems. The Zero-Order Hold block models the sampling. The red color is associated with discrete-times signals and blocks (if the Sample Time Display Colors option is enabled). However, before the first simulation, the color coding does not work properly yet.

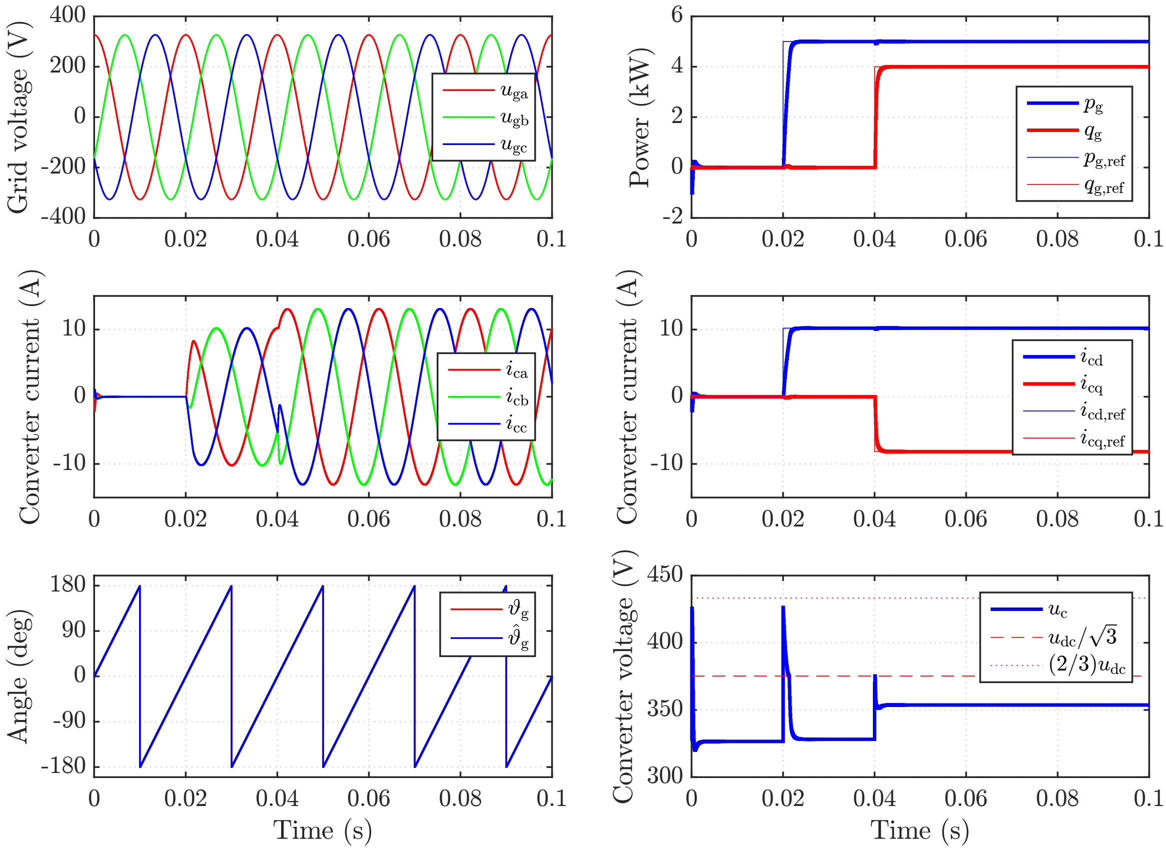

Figure 4: Simulated waveforms. The active power reference $p_{g,ref}$ is stepped from zero to 5 kW at $t = 0.02$ s and the reactive power reference is stepped from zero to 4 kVAr at $t = 0.04$ s. The angle ϑ_g is the angle of the grid-voltage vector and the angle $\hat{\vartheta}_g$ is the output of the PLL. The dashed line in the bottom subplot on the right-hand side shows the maximum available voltage in the linear modulation region and the dotted line shows the length of active voltage vectors of the converter. The switching ripple cannot be seen in the waveforms, since synchronously sampled signals were used to plot this figure.

1. Open the Grid voltage subsystem. Implement the balanced three-phase voltages:

$$u_{ga} = u_g \cos(\omega_g t) \quad u_{gb} = u_g \cos(\omega_g t - 2\pi/3) \quad u_{gc} = u_g \cos(\omega_g t - 4\pi/3)$$

2. Open the Inductor subsystem and then the Inductor voltage equation subsystem. Implement the inductor voltage equation there. Note that the inputs and outputs of the block are complex space vectors.
3. Open the Line-to-line voltages subsystem. Implement the calculation of the two line-to-line voltages, $u_{g,ab}$ and $u_{g,bc}$.
4. Open the Grid converter control subsystem. Open the MATLAB Function named Current reference. Complete the calculation of $\boldsymbol{i}_{c,ref}$:

```
function i_c_ref = curr_ref(p_g_ref, q_g_ref, u_gN)

% Current references in grid-voltage coordinates
i_c_ref = ...  % Complete this
```

5. Open the MATLAB Function inside the PLL subsystem. Complete the calculation of $\boldsymbol{u}_\mathrm{g}^\mathrm{s}$, $\boldsymbol{u}_\mathrm{g}$, and u_gq:

```
function [abs_u_g, theta_g_new, w_gi_new] = ...
    pll(u_g_ab, u_g_bc, theta_g, w_gi, u_gN, w0_pll, T_s)

% Parameters
% (Tuning is analogous to that of the DC-voltage controller.)
zeta = 1;   % Damping ratio
k_p = 2*zeta*w0_pll/u_gN;
k_i = w0_pll^2/u_gN;

% Space-vector transformation from line-to-line components
u_gs = ...  % Complete this

% Coordinate transformation to "estimated"
% grid-voltage coordinates
u_g = ...  % Complete this

% Error signal, which is drive to zero by the PLL
u_gq = ...  % Complete this

w_g = k_p*u_gq + w_gi;

% Update the integral state
w_gi_new = w_gi + T_s*k_i*u_gq;

% Update the grid-voltage angle
theta_g_new = theta_g + T_s*w_g;
while(theta_g_new > pi)
    theta_g_new = theta_g_new - 2*pi;
end
while(theta_g_new < -pi)
    theta_g_new = theta_g_new + 2*pi;
end

% Absolute value of the grid-voltage vector
abs_u_g = abs(u_g);
```

6. Now your model should be ready to be simulated. Fig. 4 shows reference waveforms. Add To Workspace blocks (or search for the existing ones) in order to monitor relevant signals (at least those shown in Fig. 4, but you may study also other signals). Prepare an m-file for plotting the waveforms. You may calculate the powers either in the Simulink or in your plotting m-file. Run the `init.m` file and simulate the model. If everything is working properly, the results should look similar to those in Fig. 4. Show the waveforms in your report. Submit this version of your model to MyCourses.
7. Consider the previous simulation sequence after $t = 0.04$ s. Using the power references $p_\mathrm{g,ref}$ and $q_\mathrm{g,ref}$ and the grid-voltage magnitude u_g as inputs, calculate u_cd, u_cq, and $|\boldsymbol{u}_\mathrm{c}|$ analytically in the steady state. Compare the analytically calculated voltages to the simulated realizable voltage references.

8. Increase the final value of the step $q_{\mathrm{g,ref}}$ to 8 kVAr and repeat the simulation. Explain why there are sixth-harmonic components in the results. After this test, change the step back to its original value.
9. In order to simulate a single-phase grid fault, drop u_{gb} to 50% of its nominal value. Simulate your model and show the waveforms in your report.
10. Using the previous case, plot the orbit of the grid-voltage vector (after the `plot` command, use the `axis('equal')` command for setting the aspect ratio. What is the direction of the ellipse? After this test, change the grid voltage back to its original value.

3 DC-Voltage Control Mode

In this section, the DC-bus capacitor of the converter is fed from the current source i_{dc} according to Fig. 1(c). The control system will be augmented with the DC-voltage controller, which regulates the DC-bus voltage. The resulting control system is shown in Fig. 5.

The model from Section 2 is used as starting point. Replace the Converter with constant DC voltage subsystem with the Converter with DC-bus capacitor subsystem. Rename the input port `p_g_ref` of the Grid converter control as `u_dc_ref`. Parametrize $u_{\mathrm{dc,ref}}$ to step from 600 V to 650 V at $t = 0.02$ s. Connect signals as shown in Fig. 6.

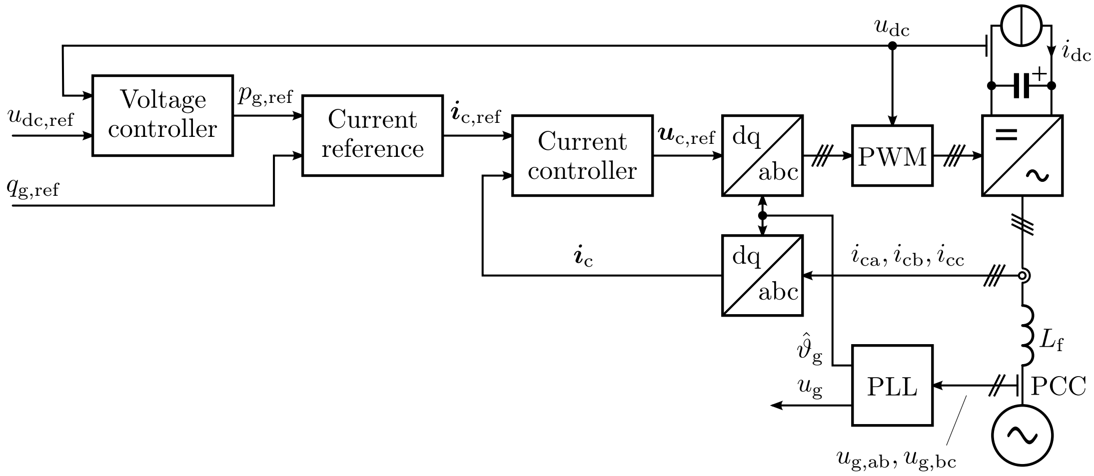

Figure 5: Block diagram of grid-voltage-oriented control with a DC-bus voltage controller.

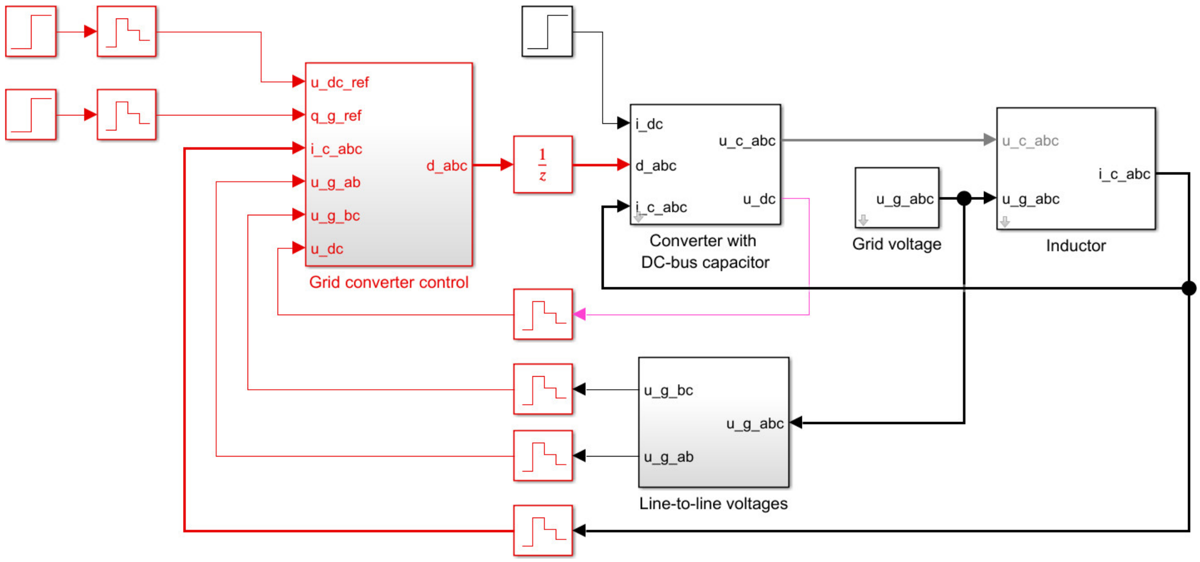

Figure 6: Simulink model of a grid converter system after modifications.

11. Implement the DC-bus voltage controller as a MATLAB Function block. Use the following PI controller (after completing it):

```
function [p_g_ref_lim, p_gi_new] = dc_voltage_ctrl( ...
    u_dc_ref, u_dc, p_gi, w0_dc, C, p_max, T_s)

% Gains (see Exercise 4)
zeta = 1;
k_p = 2*zeta*w0_dc;
k_i = w0_dc^2;

% Error signal (the capacitor energy)
e =       % Complete this

% PI controller
p_g_ref = -k_p*e - p_gi;

% Limit the output reference
p_g_ref_lim = p_g_ref;
if(p_g_ref_lim > p_max)
    p_g_ref_lim = p_max;
elseif(p_g_ref_lim < -p_max)
    p_g_ref_lim = -p_max;
end

% Update the integrator state (the last term is antiwindup)
p_gi_new = p_gi + T_s*k_i*(e + (p_g_ref_lim - p_g_ref)/k_p);
```

You need also one Unit Delay block as a memory. When your MATLAB Function is open, choose the Function toolstrip and click the button Edit Data. Then, you can manage the properties of the input and output ports of MATLAB Function blocks. Set the scope of the inputs `w0_dc`, `C`, `p_max`, and `T_s` to Parameter, cf. Fig. 7. This setting means that values of these inputs are read from the workspace.

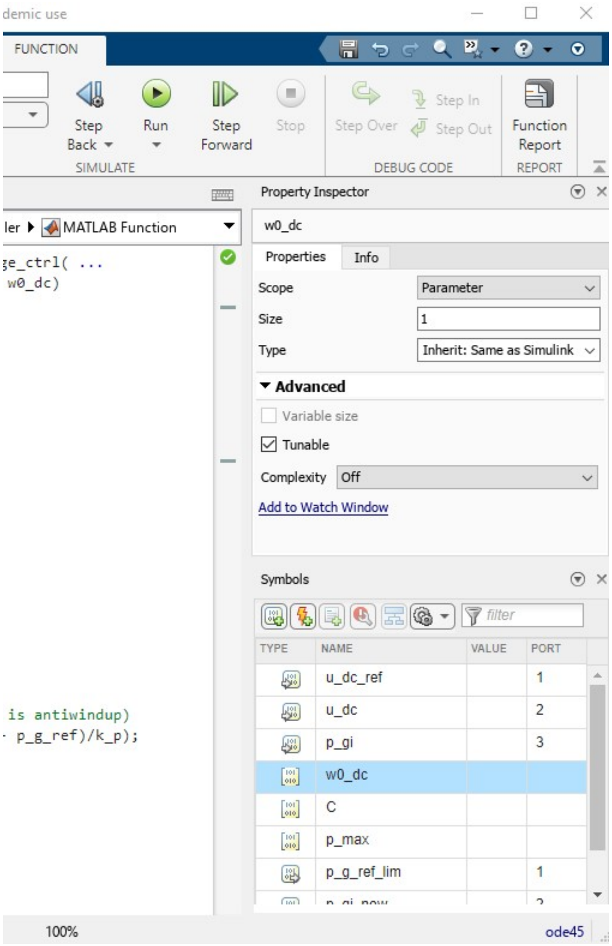

Figure 7: Changing the properties of the MATLAB Function inputs and outputs.

Place your controller inside the Grid converter control subsystem and connect it properly. Simulate your model. The results should look similar to those in Fig. 8. Show your results in the report. Submit this version of the model to MyCourses.

12. Consider the previous simulation results. Explain why there is an impulse in the real power p_g after $t = 0.02$ s and why it is negative? Why the real power changes again after $t = 0.06$ s?
13. Open the Converter with DC-bus capacitor subsystem. Explain what is the signal `i_in` and plot it together with the phase currents.
14. Explain also how the DC-bus capacitor is modelled.
15. Calculate and plot the actual real and reactive power so that the switching ripple is included in them. You need to place the To Workspace blocks to the system model. What happens to this ripple if the switching frequency is reduced.

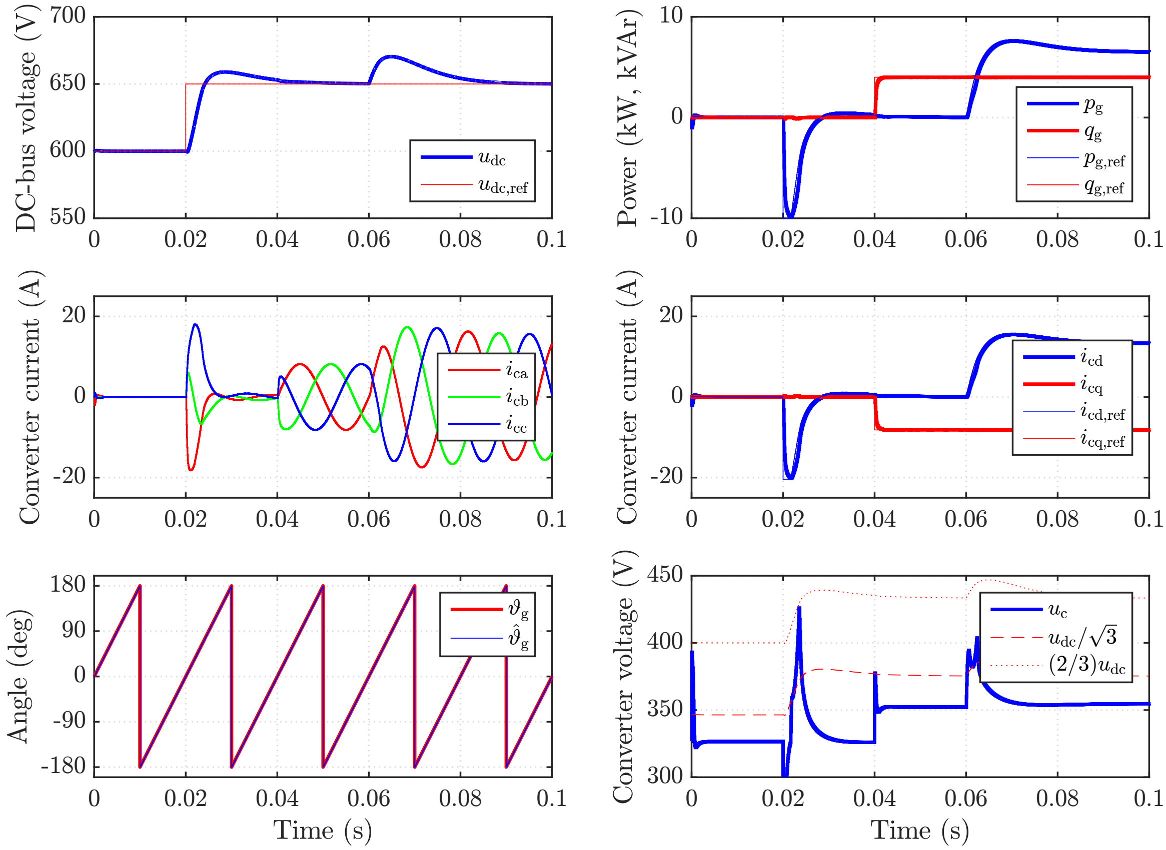

Figure 8: Simulated waveforms. The DC-voltage reference $u_{dc,ref}$ is stepped from 600 V to 650 V at $t = 0.02$ s and the reactive power reference is stepped from zero to 4 kVAr at $t = 0.04$ s. The current i_{dc} steps from zero to 10 A at $t = 0.06$ s.

Give us Feedback

In order to improve this assignment, please give us feedback. We would also be happy to know how many hours did you use to do this assignment. All other comments are also welcome.