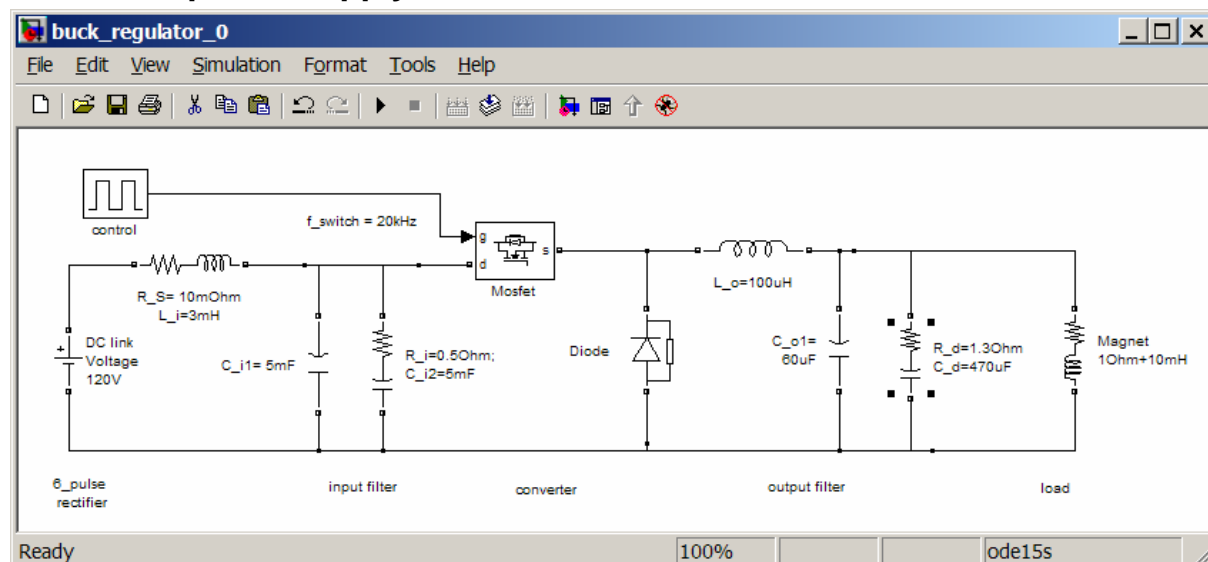# 6. Circuits and modeling

For the discussions a buck converter with input and output filter will be used as a model.

6.1 'Model power supply'

Converter data

100V / 100A at the load, switching frequency 20 kHz (above the audible range).
The 3db frequency of the input filter is chosen to be 30Hz: L_i= 3mH / C_i1+ C_i2= 10mF.
Although the ripple frequency of a 6 pulse rectifier is 300Hz, also 50 Hz have to be expected in the dc-link voltage, due to voltage asymmetry in the mains.
The maximum ripple of the current through L_o is chosen to be 15% of the maximum dc-current, i.e. 15App. The 3db frequency of the output filter shall be one decade below the switching frequency, i.e. 2 kHz: L_o1= 100µH / C_o1= 60µF.
Input and output filter are both damped with small damping resistors in series with capacitors. Both filters are coupled through the FET!

Semiconductors and snubbers

The models of FET and diode contain serial inductances as well as parallel RC-snubbers.
With the rule of thumb '1m of wiring introduces an inductance of 100nH…1µH' 10nH are introduced as serial inductances for both elements.
For the FET the snubber resistor value is chosen for a discharge current of the magnitude of the nominal current, i.e. 120V/ 100A $\approx 1\Omega$ (in reality the current will be less, due to the finite switching time of the semiconductor). At turn-off the snubber resistor is responsible for the over voltage across the FET $\rightarrow$ the smaller the resistor the better!
For the simulation the snubber capacitor is now chosen in such a way that the wave impedance of the LC-circuit is smaller than the snubber resistor:

$$Z_W = \sqrt{L_S / C_S} < R_S \rightarrow C > L_S / R_S^2$$

Therefore, in our model the snubber capacitor has to be greater than 10nF. $\rightarrow$100nF was chosen. (Caution: the bigger the capacitor, the more losses occur in the snubber resistor!) The same snubber was chosen for the diode

6.2 Simulation of the model power supply

For the simulation of a circuit the simulation tool has to be set-up.

Simulation time:
As a first approach for the simulation time approximately 3 to 5 times the largest time constant of the system is recommended.
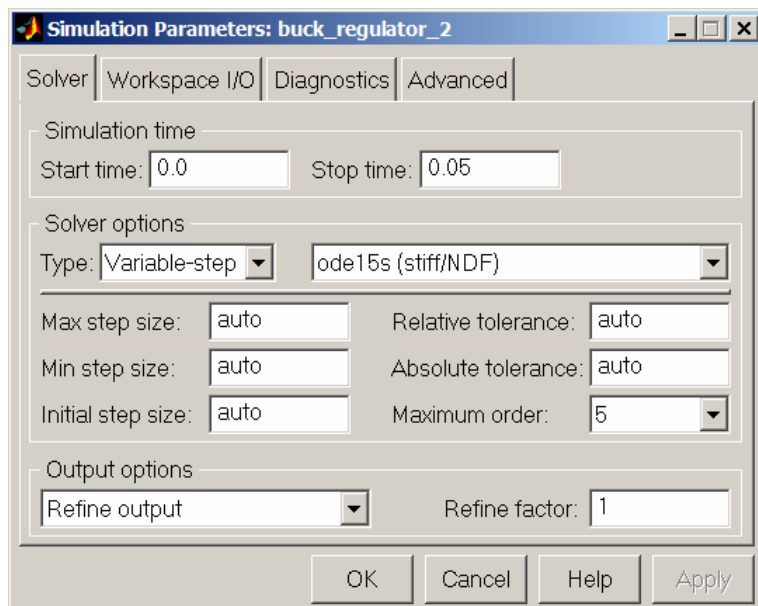

Integration-algorithm
For a model that contains switching actions an algorithm with adaptive step size can speed up the simulation very much. In Matlab / Simulink there are several algorithms which have this capability.

Usually, the other parameters of the simulation tool can be left on their default values.

Measurements
Depending on the simulation tool the data to be measured have to be specified. In Matlab / Simulink this is done with 'scopes' or 'data export to workspace'.

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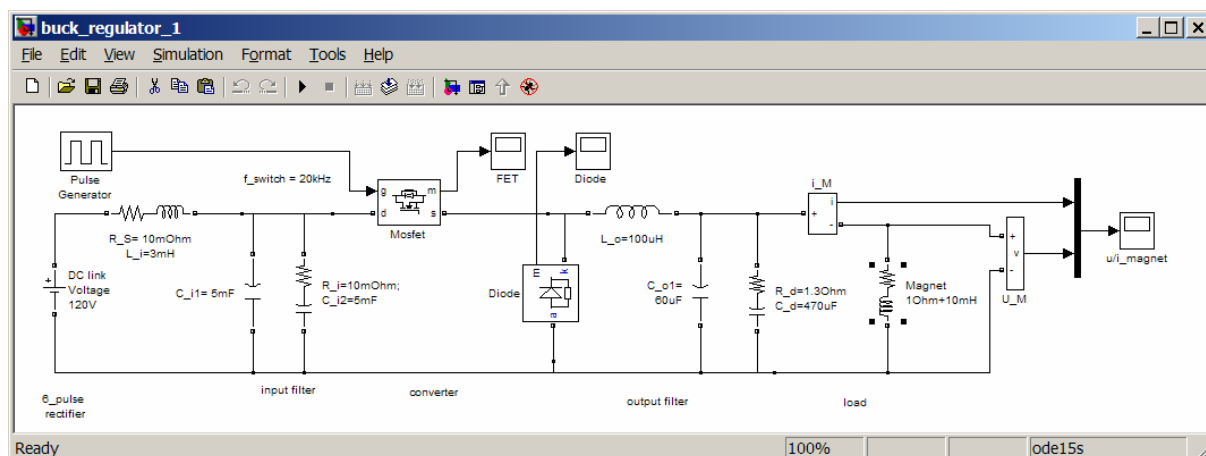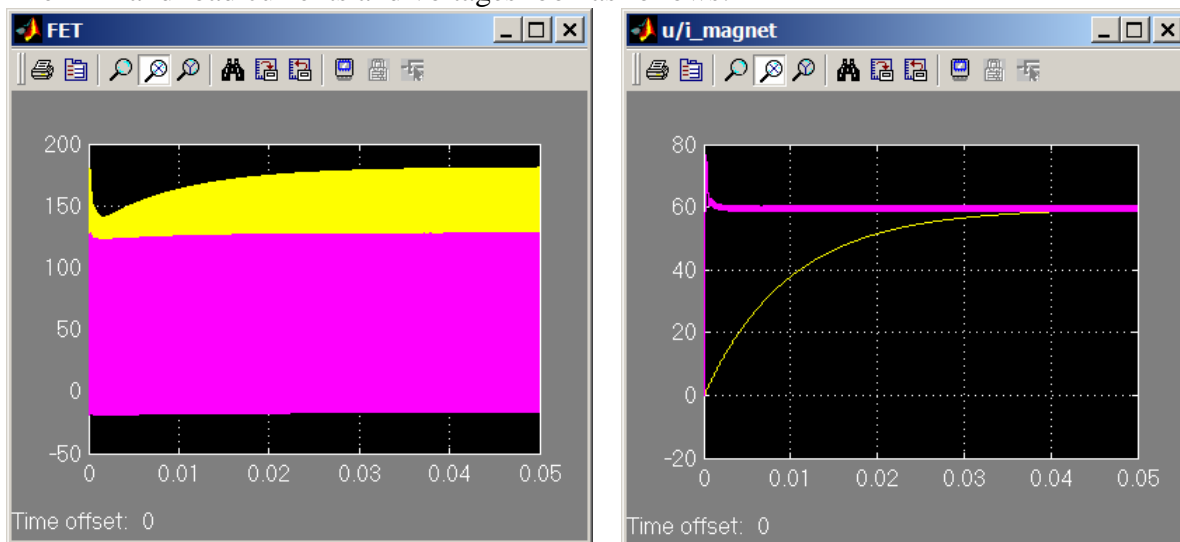
6.3 Electrical behavior of a reduced model

With the built model simulation can start. That will be first demonstrated for the output part of the converter only. The dc-link filter is replaced by a stable voltage source only.

The largest time constant is that of the load: $\tau=L/R=10ms$ →chosen simulation time 50ms.
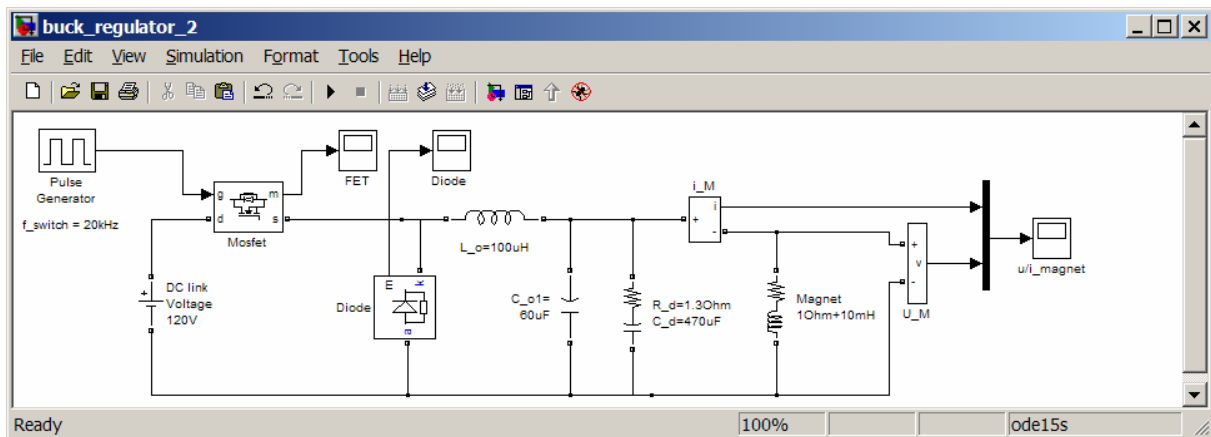
The FET and load currents and voltages look as follows:

The interpretation of the FET-voltage and -current is difficult in the chosen time-span. But, the load data seems to be correct: after an overshoot the voltage reaches a stable value and the current rises according to an e-function.

Zoomed data:
With the zoom-function a better view of details is easily possible. The plot shows the voltage across and the current through the FET. Of special interest are:
- The current peak caused by the snubber network.
- The current rise during the on-time of the FET

The left picture shows also a problem of the insufficient solver resolution: voltage and current are not correct in the region of the switching. In the right simulation the maximum time step has been reduced until correct waveforms have been reached.

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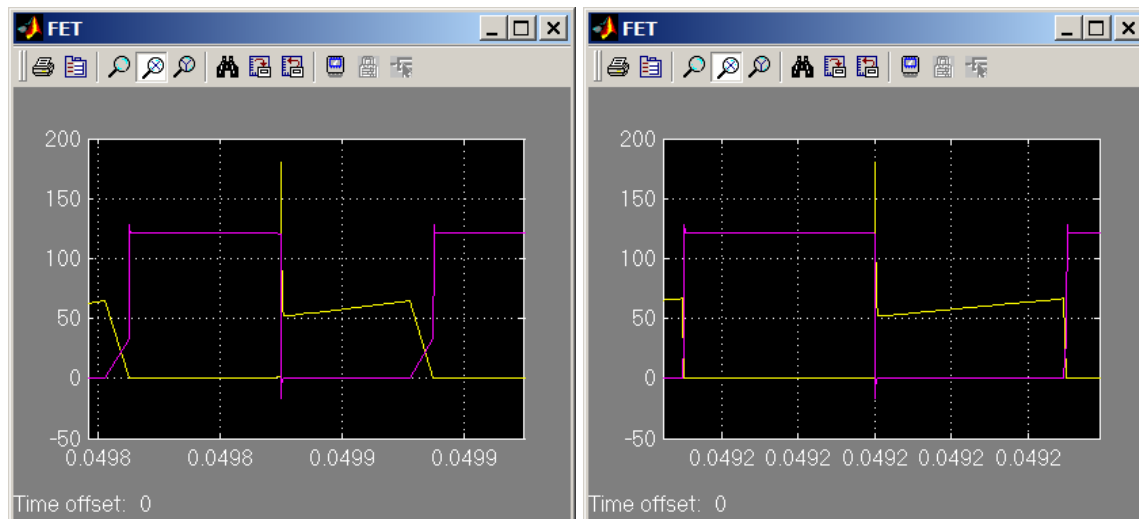
6.4 Time continuous model

For the controller design and considerations of the behaving of the controlled circuit it is preferable to have a faster simulation than a switched model can provide. For that purpose the linear model of the combination FET and diode is very helpful:
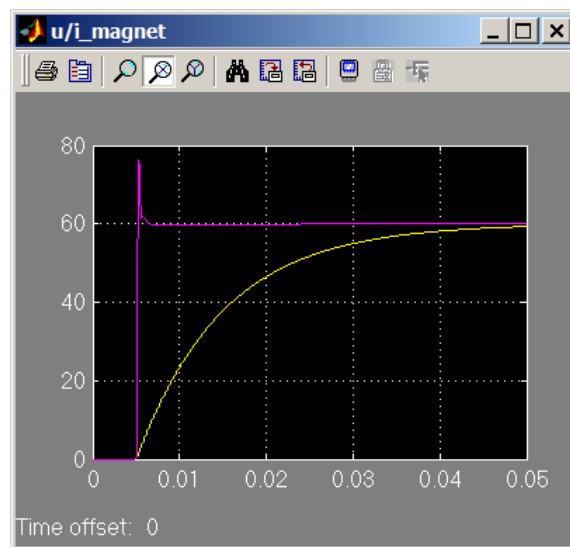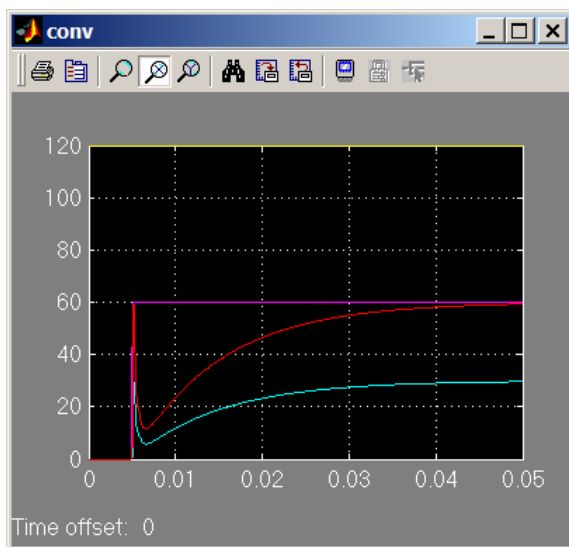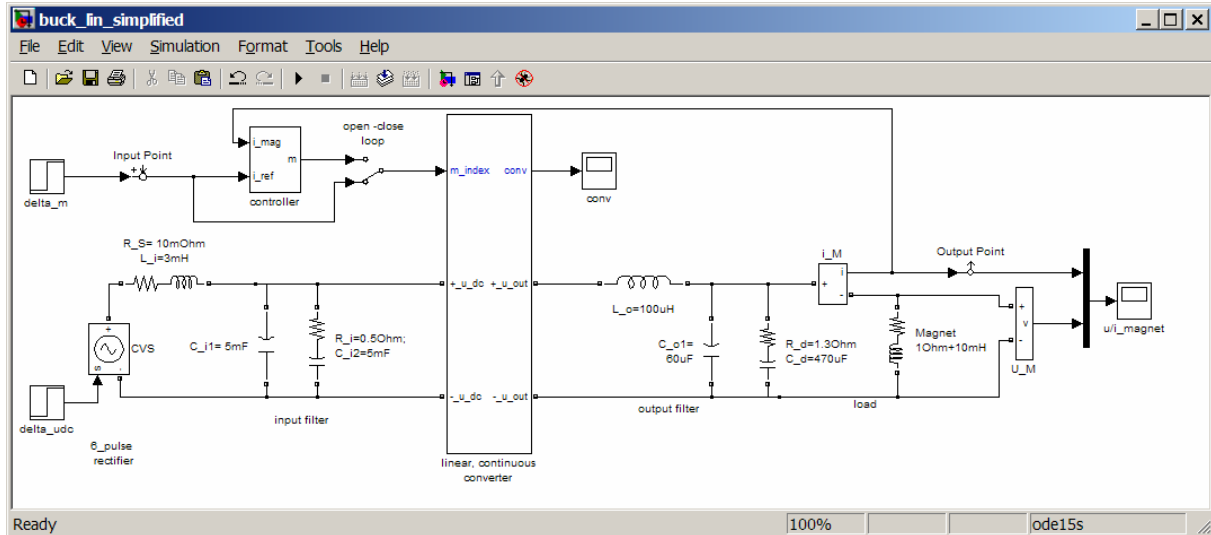

Simulation results:

The left picture shows the internal properties of the converter: input voltage and current as well as output voltage and current.

The magnet data can be compared with the simulation of the switched converter: The load current looks identical in both cases. But, the magnet voltage of the switched model has an additional voltage ripple. This ripple, caused by the switched voltage at the filter input, does not exist in a continuous model.

7. Controller design

The design of controller is a wide field: PID-controller, state controller, linear and nonlinear controller, adaptive controller and so on.

According to the practical usage linear PID controller design will be discussed in the following. As an example a power supply controller with additional feed forward, adaptation of a coefficient, di/dt limiter and further features will be presented.
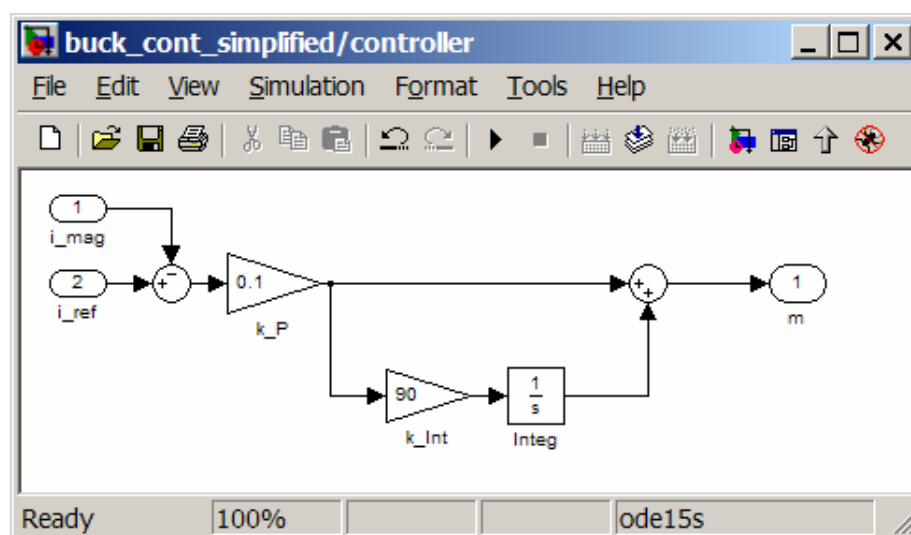
7.1 Controller design with help of the linear model

The controller design will be made with help of the bode diagram. For that purpose a linear representation of the circuit, together with the PWM modulator, is necessary. Some programs are capable to generate such a model automatically. For the demonstration the already presented linear Matlab / Simulink model will be used.

With this linear model the output- to input- frequency response can be analyzed in various points of operation. The result for a modulation index of m=0.5 is shown as a bode plot.
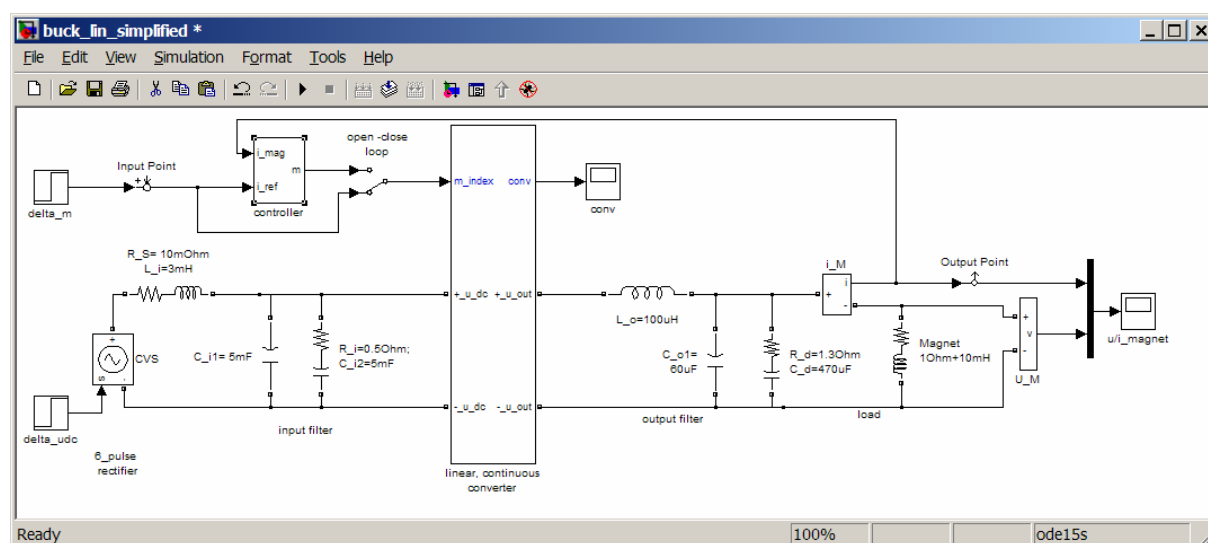
With help of the bode-diagram and the rules of Bode the layout of a PI- controller is a simple task (with a bit of routine…). (No PID if ever possible – they suffer from the amplified noise!)

The behavior of the model with the designed controller can be demonstrated in the bode diagram or as a step response.

For a fast controller with minor overshoot:
Phase margin: $> \pi/3$ (60 degree); Amplitude margin: > 2 (6dB)
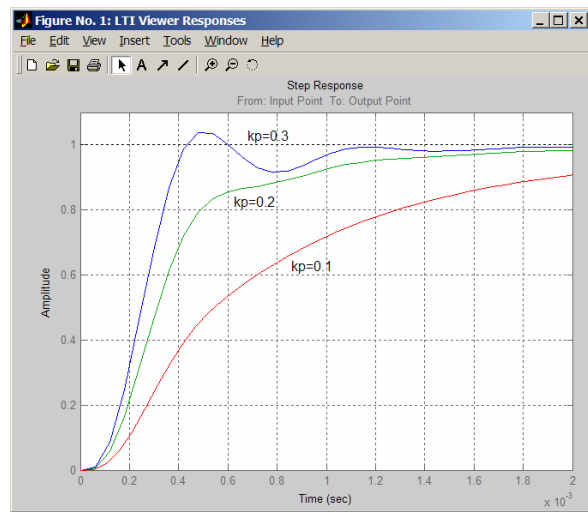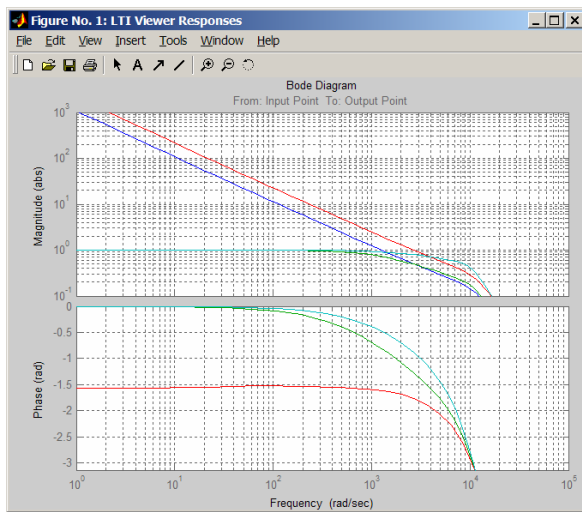With this rule the P-Gain (red lines) is 1/3 and the integrator constant 90 (green lines).
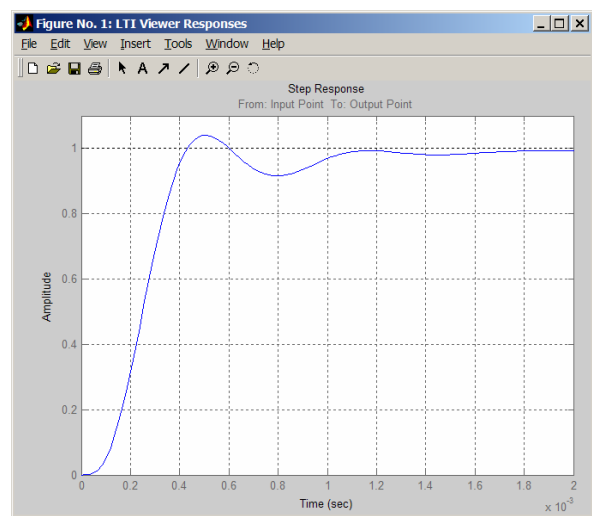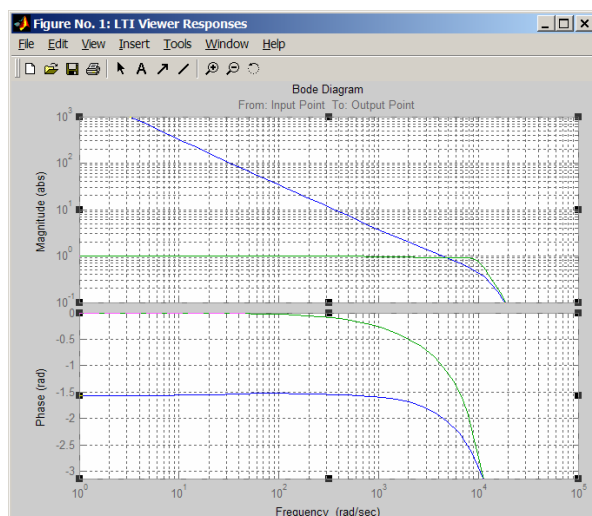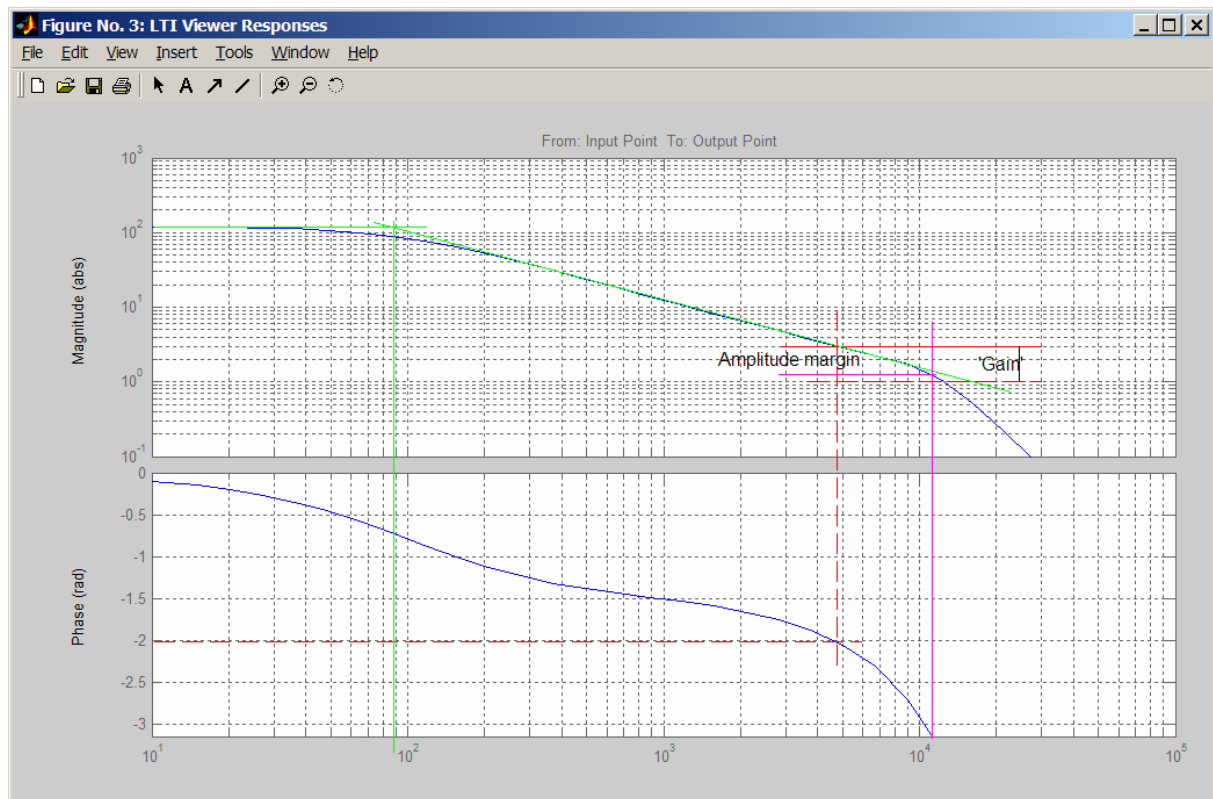
For a controller with no overshoot:
Phase margin: π/3 < φ< π/2; Amplitude margin: > 2   (6dB)
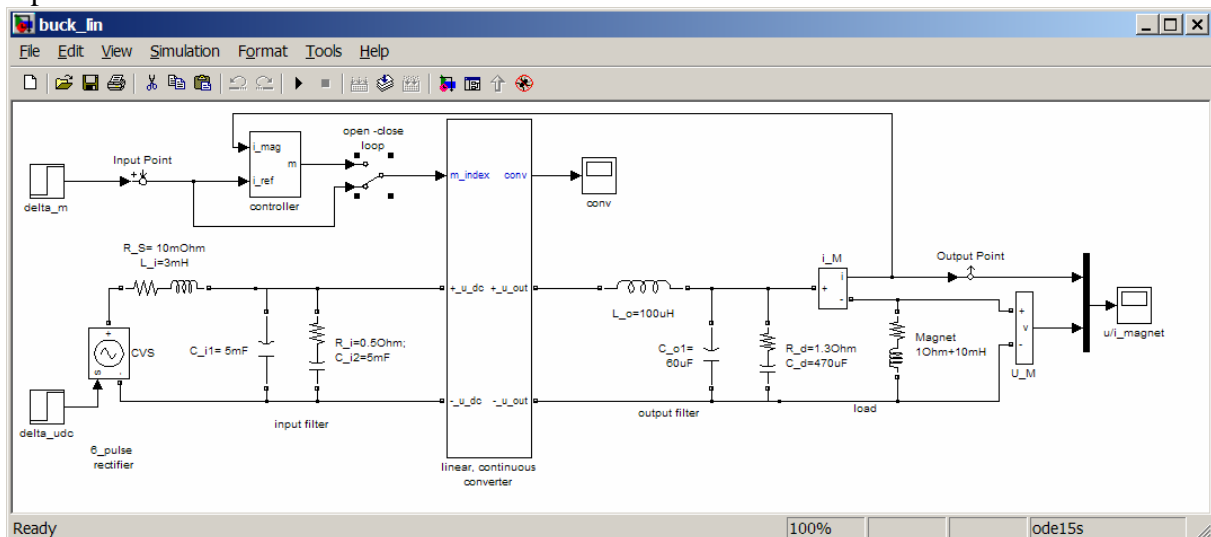With this rule the P-Gain is between 0.1 and 0.3 and the integrator constant does not change.

The designed controller can now be implemented in the nonlinear model.

7.2 Controller for the converter with input filter

In the same way as for the reduced model a controller can be designed for the converter with input filter:

The result of the simulation shows that the system is stable, but the oscillation of dc-link voltage can not be entirely suppressed in the load current, due to the limited amplification.
(Controller: P-Gain: 0.1; Integration-constant: 90)
For an additional suppression of the influence of any dc-link voltage variation, a voltage feed forward is added in the next demonstration.

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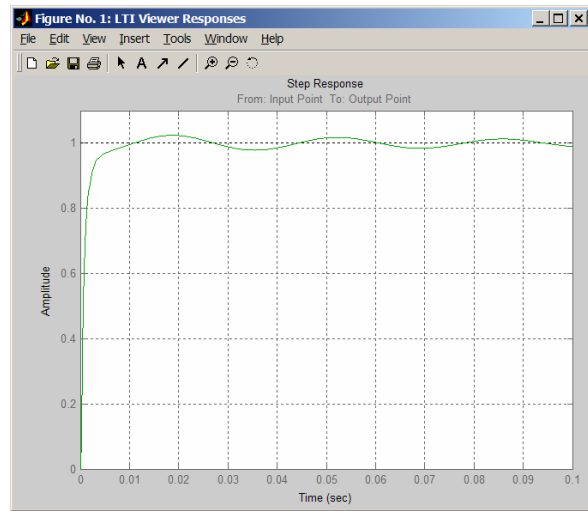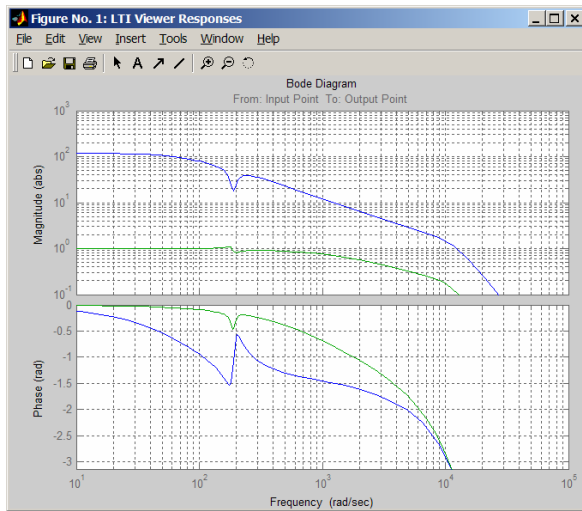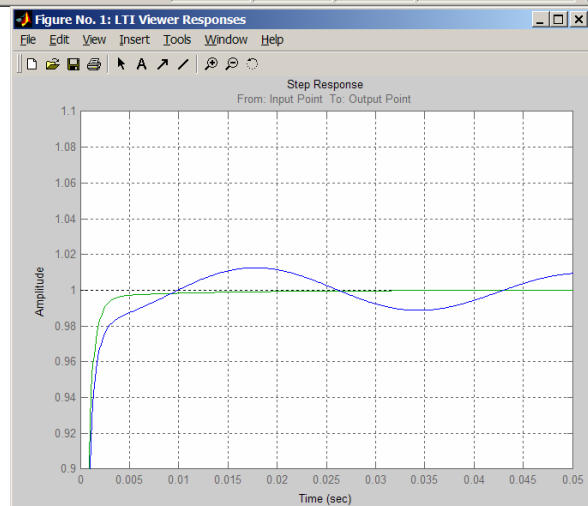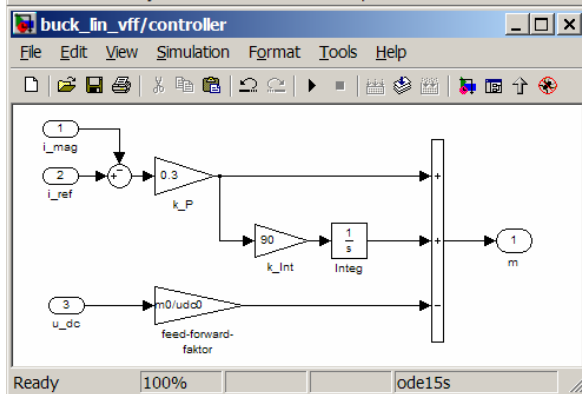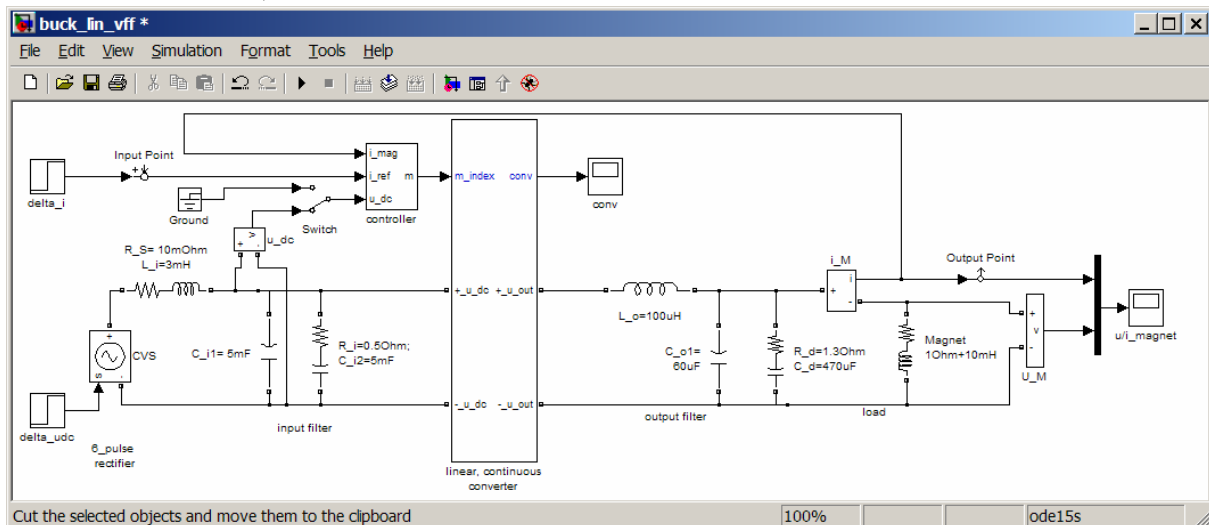
7.3 DC-link voltage feed forward

For the voltage feed forward the equation for the linearized converter is used:

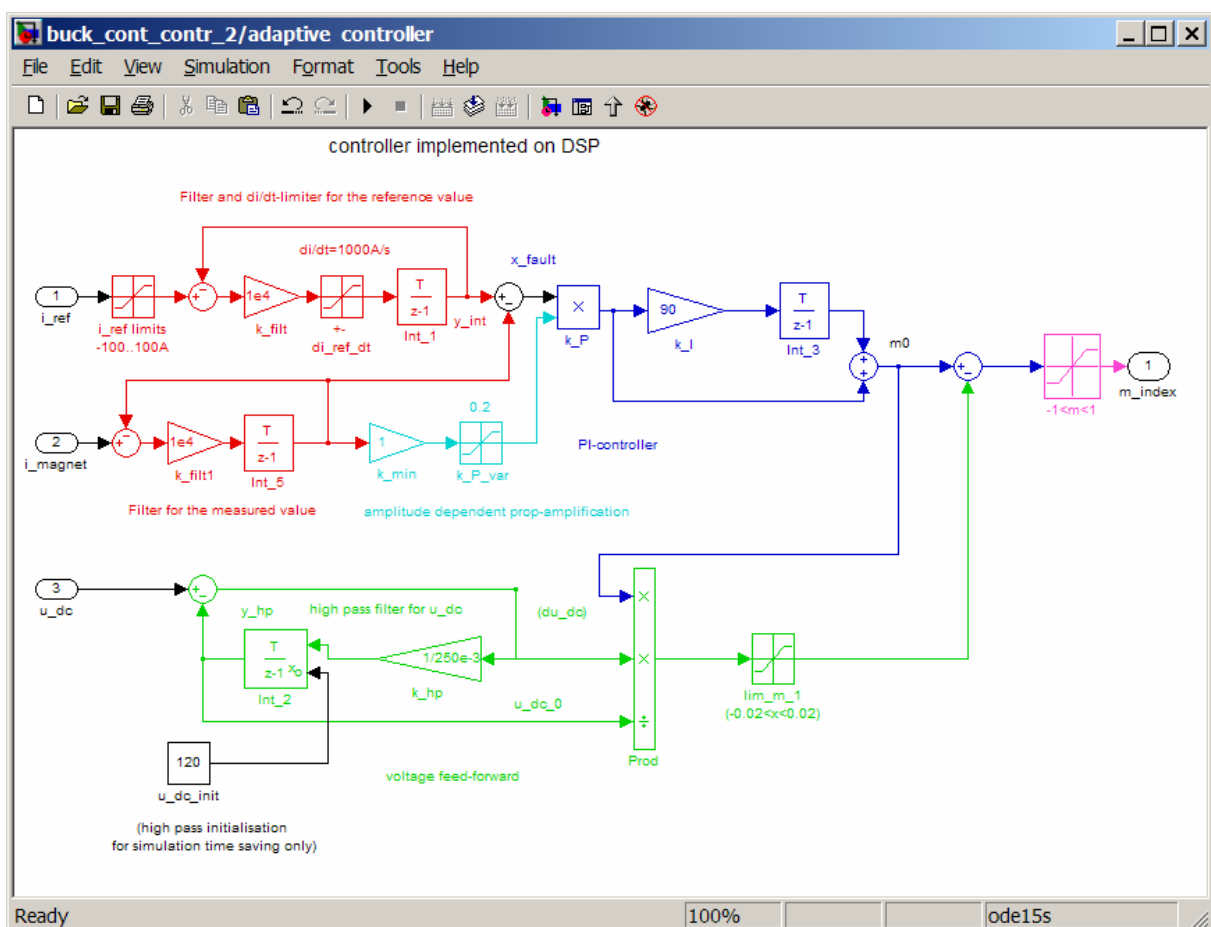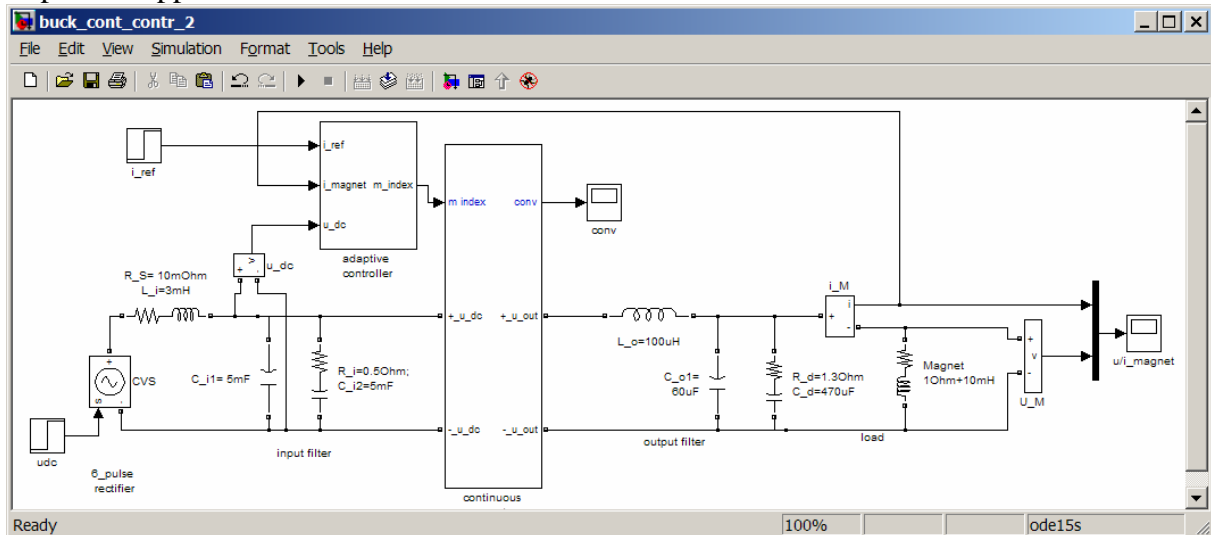$$\Delta u_o = \Delta m \cdot u_{i,0} + m_0 \cdot \Delta u_i = 0$$

$$\longrightarrow \Delta m = -\frac{m_0}{u_{i,0}} \Delta u_i$$

8. 'Full'-controller

Up to this point the controller parameter have been tested on a linear model with no limits and restrictions.

The following example shows a simplified controller as it is implemented in a large number of power supplies at PSI. This model will be used for demonstrations.

9. Present challenges in simulation

Simulation tools made big improvements in the last years. Nevertheless, further improvement and extension of the capabilities were welcome. Depending of the used tool, some of the following 'wishes' are already fulfilled:

A)   Core of a simulation tool
- Intuitive usage (most engineers do not like manuals…)
- Libraries of correct models and elements (as simple as possible…)
- Fast models / high simulation speed
- Macros and sub circuit capabilities
- Good access to all properties of a simulation (at the end of a simulation and during simulation)
- Overall loss calculation of a entire model
- ……

B)   Environment
- Toolboxes for additional tasks (analysis, simulation of non-power-electronics tasks…)
- Open to other programs (data import and export)
- Automatic code generation of blocks of a simulation for the implementation on other processors. (E.g. the implementation of a simulated controller on a DSP in C).
- Extended online help
- User support by the manufacturer of the tool
- Transferability of models between various versions of the (same) simulation program
- Lower prices
- …

These lists can be expanded by every engineer himself.

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