Control of the DCDC converter connecting Super-caps to a DC bus

Tuning of two PI control loops to regulate the inductor current and the DC bus voltage

In [1]:
```
import numpy as np
pi = np.pi
```

Parameters of the system

In [2]:
```
# Super-caps:
C_sto = 20. #[F]
# Inductance in series with the Super-caps
L = 3e-3 # [H]
# DC bus capacitor:
C_dc = 50e-3 #[F]
```

In [3]:
```
# Set point for the DC bus voltage
V_dc_set = 1300 # [V]
```

In [4]:
```
# Switching frequency
Fs = 2000. # [Hz]
# SEAREV production frequency:
F_prod = 1./4 # [Hz
```

Frequency spans for Bode diagram plotting:

In [5]:
```
# frequency vectors:
f = np.logspace(-1,4,500) # .1 Hz to 10 kHz
w = f*2*pi
# Laplace variable "s"
s = 1j*w
```

1) Current loop

Objective: control the current i_L in the inductor to a reference value i_L^*.

The control is achieved by acting on the duty cycle d

PI controller :

$d = (K_i + \frac{1}{T_i s})\varepsilon$

with $\varepsilon = i_L^* - i_L$ being the control error (in A).

Parameters: K_i (in A^{-1}) and T_i (in A.s)

Closed loop transfer i_L/i_L^*:

$$H_i = \frac{1 + K_i T_i s}{1 + K_i T_i s + L T_i / V_{dc} s^2}$$

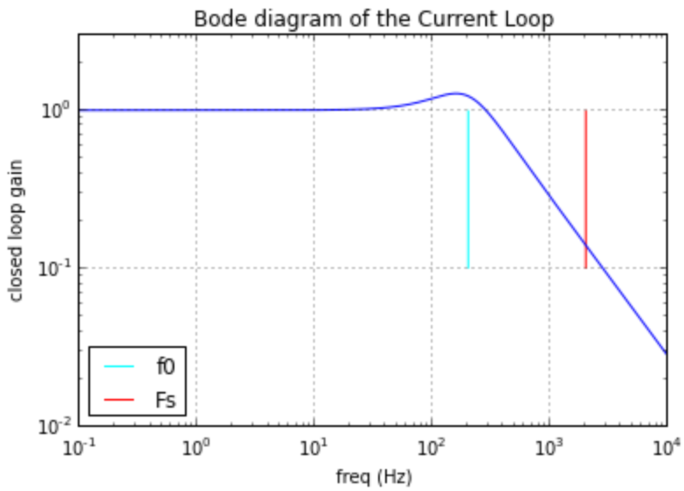
In [6]:

```
# 1) Choose the 2nd order parameters of the closed loop:
f0_i = 200. # natural frequency [Hz}
m_i = .7 # damping factor

# 2) Deduce the PI parameters (K,T)
V_dc = V_dc_set
T_i = V_dc/(L*(2*pi*f0_i)**2)
K_i = 2*m_i/(T_i*2*pi*f0_i)

## A set of good enough values:
#K_i=0.01
#T_i=0.1
#f0_i = sqrt(V_dc/(L*T_i))/(2*pi)
#m_i = K/2*sqrt(V_dc*T_i/L)

## 3) Display:
print('natural frequency f0 = %.1f Hz' % f0_i)
print('  1/f0 = %.2f ms' % (1e3/f0_i))
print('damping factor m = %.2f' % m_i)
print('PI params:\n  K={:.5f} \n  T={:.3f}'.format(K_i, T_i))
```

```
natural frequency f0 = 200.0 Hz
  1/f0 = 5.00 ms
damping factor m = 0.70
PI params:
  K=0.00406
  T=0.274
```

Bode diagram

In [7]:
```
# Numerical eval of the transfer function:
Hi = (1 + K_i*T_i*s)/( 1 + K_i*T_i*s + L*T_i/V_dc*s**2 )
# Plot
loglog(f, abs(Hi))
vlines(f0_i, 0.1,1, color='cyan', label='f0')
vlines(Fs, 0.1,1, color='red', label='Fs')
ylim(ymax=3)
xlabel('freq (Hz)')
ylabel('closed loop gain')
title('Bode diagram of the Current Loop')
legend(loc='lower left')
grid(True, which='major'); grid(False, which='minor');
```



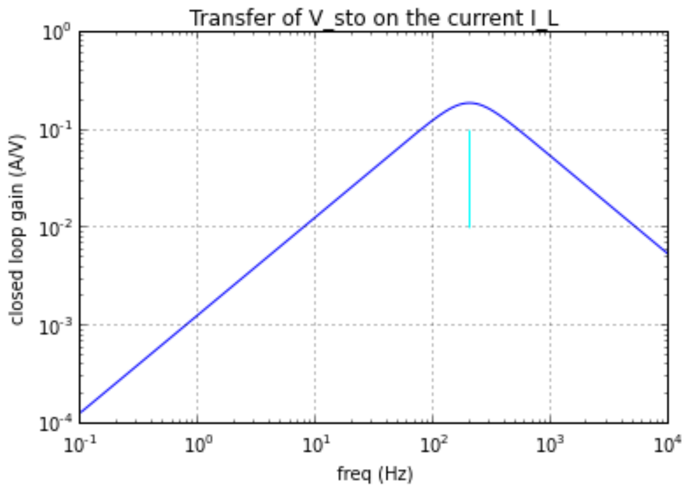
Rejection of the perturbation (V_{sto})

The voltage V_{sto} of the Super-caps acts as a perturbation in the current control loop.

Closed loop transfer is a 2nd order band pass:

$$\frac{1}{K_i V_{dc}} \frac{K_i T_i s}{1 + K_i T_i s + L T_i / V_{dc} s^2}$$

```
In [9]: Hi_perturb = (K_i*T_i*s)/( 1 + K_i*T_i*s + L*T_i/V_dc*s**2 ) / (K_i*V_dc)

# Plot
loglog(f, abs(Hi_perturb))
vlines(f0_i, 0.01,.1, color='cyan', label='f0')
xlabel('freq (Hz)')
ylabel('closed loop gain (A/V)')
title('Transfer of V_sto on the current I_L')
grid(True, which='major'); grid(False, which='minor');
```



Conclusion: since the variations of the super-caps voltage are below 1 Hz, it should have no influence on the current loop.

Voltage loop

Objective: control the voltage v_{dc} of the DC bus capacitor to a reference value v_{dc}^*.

The control is achieved by acting on the current reference i_L^*

PI controller :

$$i_L^* = -(K_v + \frac{1}{T_v s})\varepsilon$$

with $\varepsilon = v_{dc}^* - v_{dc}$ being the control error (in V). (the "$-$" sign compensates for the "$-$" in the tranfer of the system)

Parameters: K_v (in A/V) and T_v (in V.s/A)

Closed loop transfer v_{dc}/v_{dc}^*:

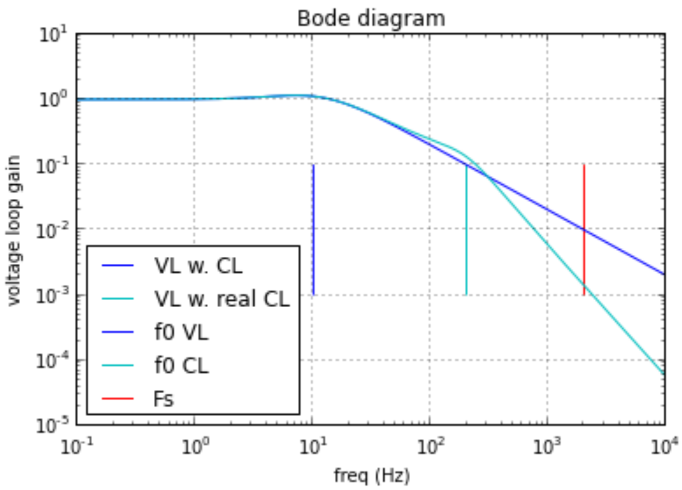
$$H_v = \frac{1 + K_v T_v s}{1 + K_v T_v s + C_{dc} T_v / d s^2}$$

In [10]:
```python
# 1) Choose the 2nd order parameters of the closed loop:
f0_v = 10. # natural frequency [Hz}
m_v = 1 # damping factor

# 2) Deduce the PI parameters (K,T)
V_sto = 800. # half charge
V_dc = V_dc_set
alpha = V_sto/V_dc

T_v = alpha/(C_dc*(2*pi*f0_v)**2)
K_v = 2*m_v/(T_v*2*pi*f0_v)

## A set of good enough values:
#K_v = 10
#T_v = 0.001

## 3) Display:
print('natural frequency f0 = %.1f Hz' % f0_v)
print('  1/f0 = %.2f ms' % (1e3/f0_v))
print('damping factor m = %.2f' % m_v)
print('PI params:\n  K={:.5f} \n  T={:.3f}'.format(K_v, T_v))
```

```
natural frequency f0 = 10.0 Hz
  1/f0 = 100.00 ms
damping factor m = 1.00
PI params:
  K=10.21018
  T=0.003
```

In [11]:
```python
# Compute the closed loop tranfer numerically:

# TF of the Controler
Cv = - K_v - 1/(T_v*s)

# Open-loop tranfer, with and without the current loop influence:
Hv_ol1 = Cv*1*-alpha/(C_dc*s)
Hv_oli = Cv*Hi*-alpha/(C_dc*s)

Hv1 = Hv_ol1/(1 + Hv_ol1)
Hvi = Hv_oli/(1 + Hv_oli)
```

In [12]:
```
# Plot
loglog(f, abs(Hv1), color='blue', label='VL w. CL')
loglog(f, abs(Hvi), color='c', label='VL w. real CL')

vlines(f0_v, .001,.1, color='blue', label='f0 VL')
vlines(f0_i, .001,.1, color='c', label='f0 CL')
vlines(Fs, .001,.1, color='red', label='Fs')
#ylim(ymax=3)
legend(loc='lower left')
xlabel('freq (Hz)')
ylabel('voltage loop gain')
title('Bode diagram');
grid(True, which='major'); grid(False, which='minor');
```



TODO:

- plot the gain for several alpha (ie. V_sto) values -> smaller duty cycle implies higher resonance...
- see the effect of the inner current loop

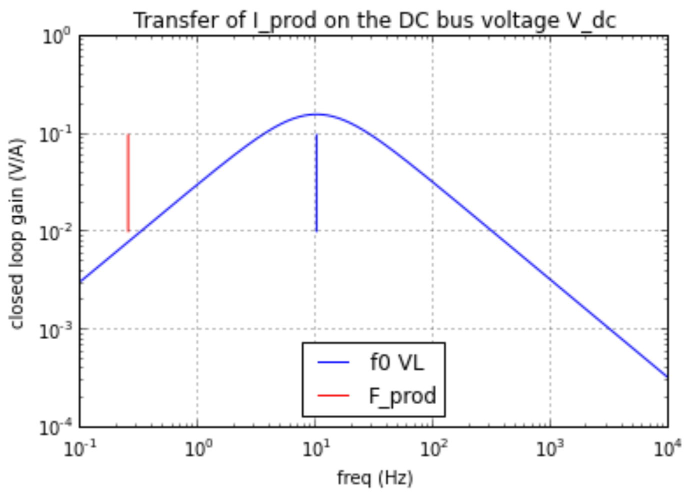
Rejection of the perturbation ($I_{prod} - I_{grid}$)

The currents I_{prod} and I_{grid} injected on the DC bus acts as a perturbation in the voltage control loop.

Closed loop transfer is a 2nd order band pass:

$$\frac{1}{K_v d} \frac{K_v T_v s}{1 + K_v T_v s + C_{dc} T_v / d s^2}$$

In [14]:
```
Hv_perturb = (K_v*T_v*s)/( 1 + K_v*T_v*s + C_dc*T_v/alpha*s**2 ) / (K_v*alpha)

# Plot
loglog(f, abs(Hv_perturb), color='b')
vlines(f0_v, 0.01,.1, color='b', label='f0 VL')
vlines(F_prod, 0.01,.1, color='r', label='F_prod')
legend(loc='lower center')
xlabel('freq (Hz)')
ylabel('closed loop gain (V/A)')
title('Transfer of I_prod on the DC bus voltage V_dc')
grid(True, which='major'); grid(False, which='minor');
```



Analysis:

The pulsation of the current from the SEAREV production is about 1000 A peak-to-peak.

Located at about 0.3 Hz, it should therefore generate v_{dc} variations of less than $1000 \times 9.10^{-3} \approx 10$ V

Theses variations are small enough compared to the DC bus voltage reference (1300 V) : it is *acceptable*.

In [ ]: