A DC-motor drive without integrators in the current loops for a laboratory two-mass system model – an experimental study.

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Abstract

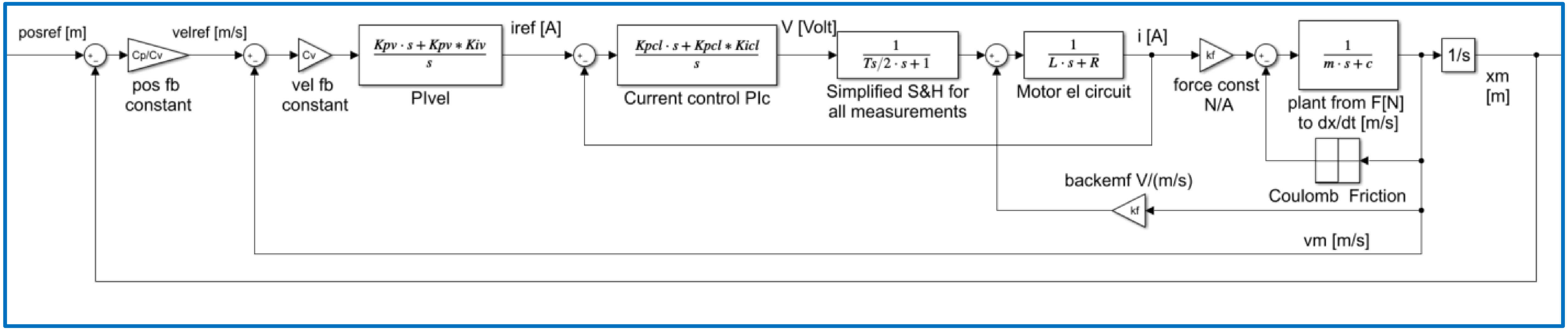
- It is demonstrated, by simulation, experimentation and analysis that a **current loop without integrator can achieve the same closed loop performance with respect to position or velocity reference specifications, as a current loop with an integrator**, both for a Brush DC-motor, as well as for a Brushless DC motor (BLDC), with additional benefits such as higher closed current loop bandwidth, and increased true total system open loop phase margin.

- The experiments were performed on a generic two-mass laboratory system.

- It should be noted that a current loop without integrators demands that **the saturation limit of the *current command reference*, generated by the outer loop(s) should be increased**, in order to ensure the intended full exploitation of the current range.

- The conclusion that **integrators in the inner loops should be foregone**, can be applied to all inner loops in a cascaded setting whose outputs are not primary controlled variables with specifications.

Simplified position control system without reference trajectory feedforwards

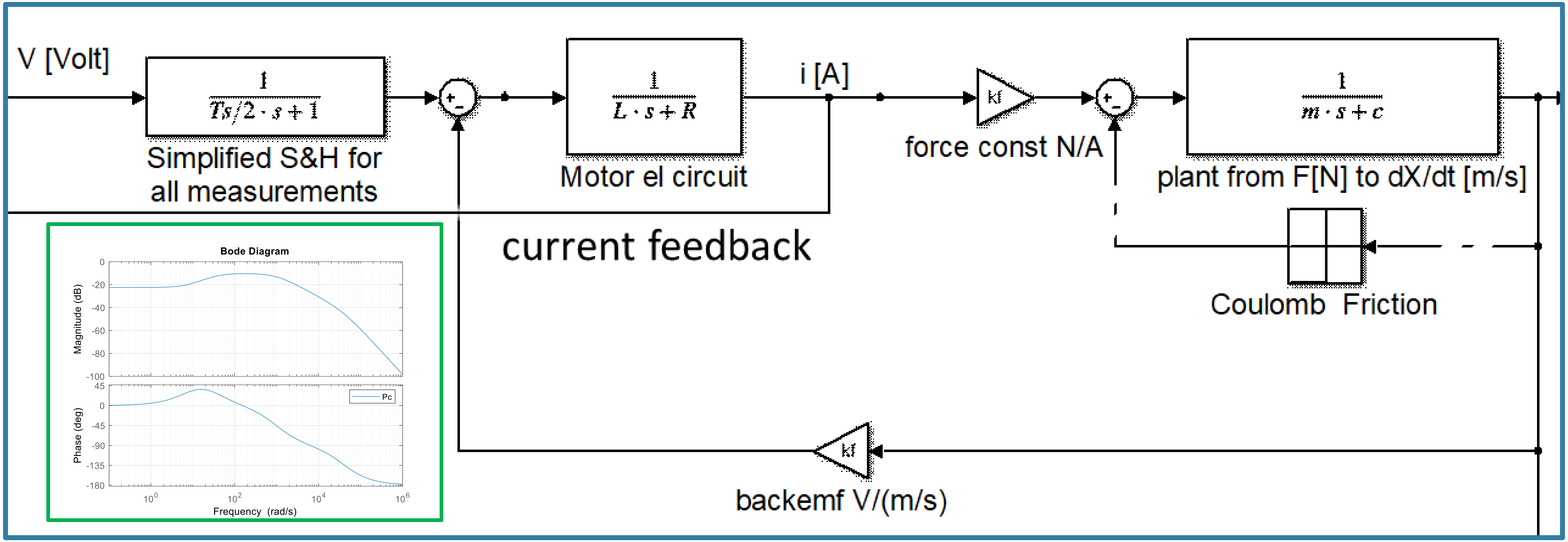


Contents

- Current loop, with and w/o integrator in controller
- Why current loop? Why integrator in current loop?
- The DC-motor, and the BLDC
- The closed current loop. The closed position loop.
- True Open Loop with all controllers present
- Disturbance rejection
- Experiments with DC and BLDC
- Some concluding comments

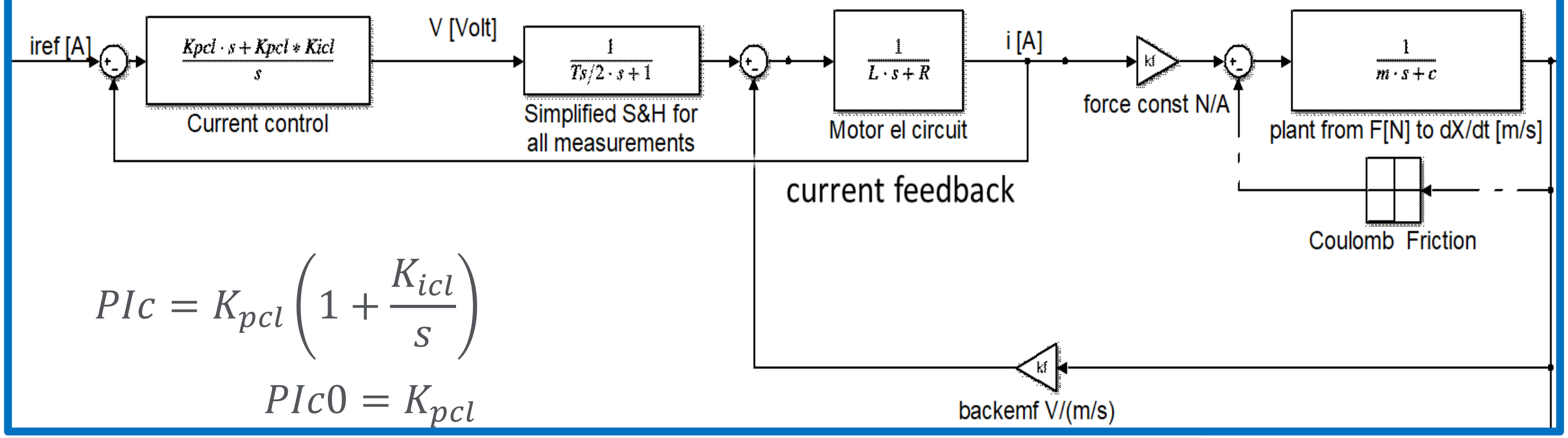
- Only linear loop properties in the frequency domain are analyzed, to which feedforwards do not contribute.
- Friction will be represented by a step disturbance at the plant input.
- The control structure is a typical industrial one, however without additional high frequency features like LPF and notches.
- There is **only two measured outputs**, *i* [A], and *xm* [m] from which velocity *vm* [m/s] is computed in the controller. Hence this is a **two**-loop system (i.e. not a three-loop system).
- The outer loop controller is in fact a PD·PI-controller.

P_c = current plant from V [volt] to i [A]



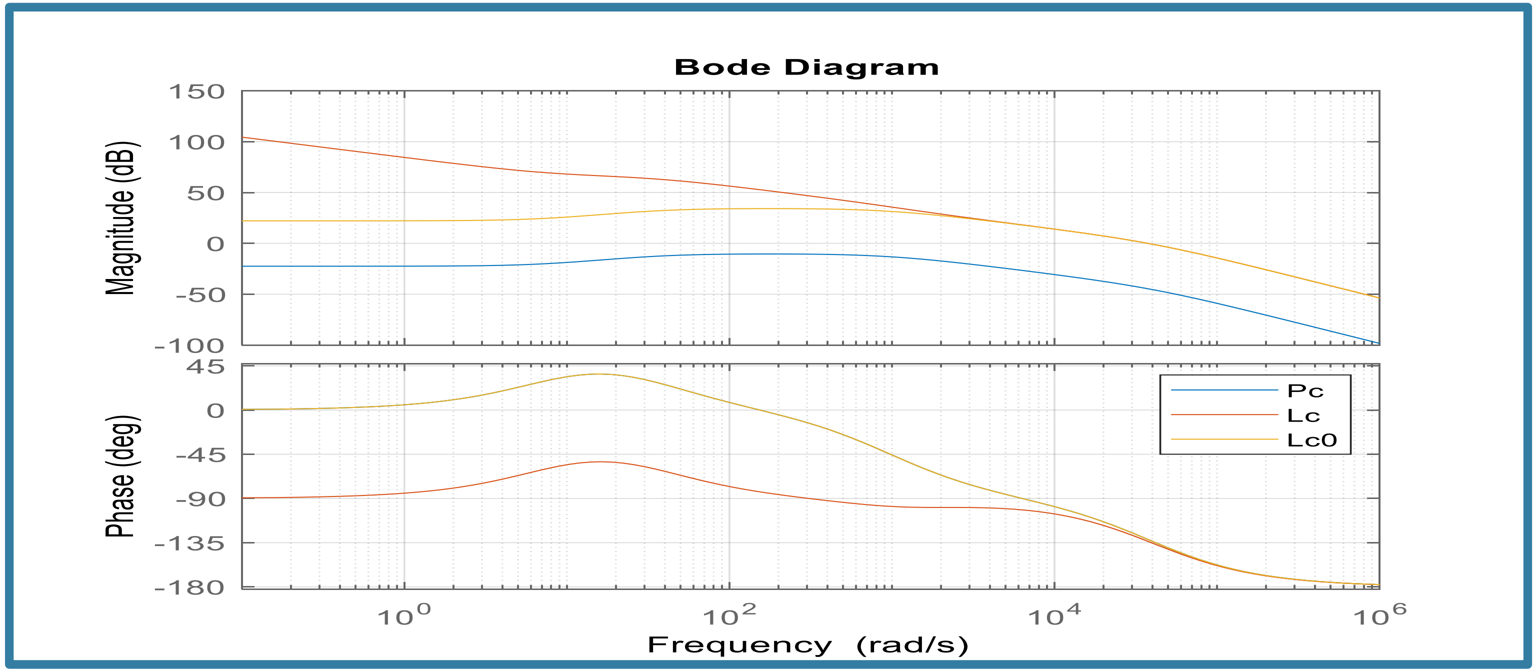
$$i = \frac{ms+c}{Lms^2+(Lc+Rm)s+(\mathrm{Rc}+k_f^2)} \cdot \frac{1}{1+\frac{T_s}{2}s} V = P_c(s)V$$

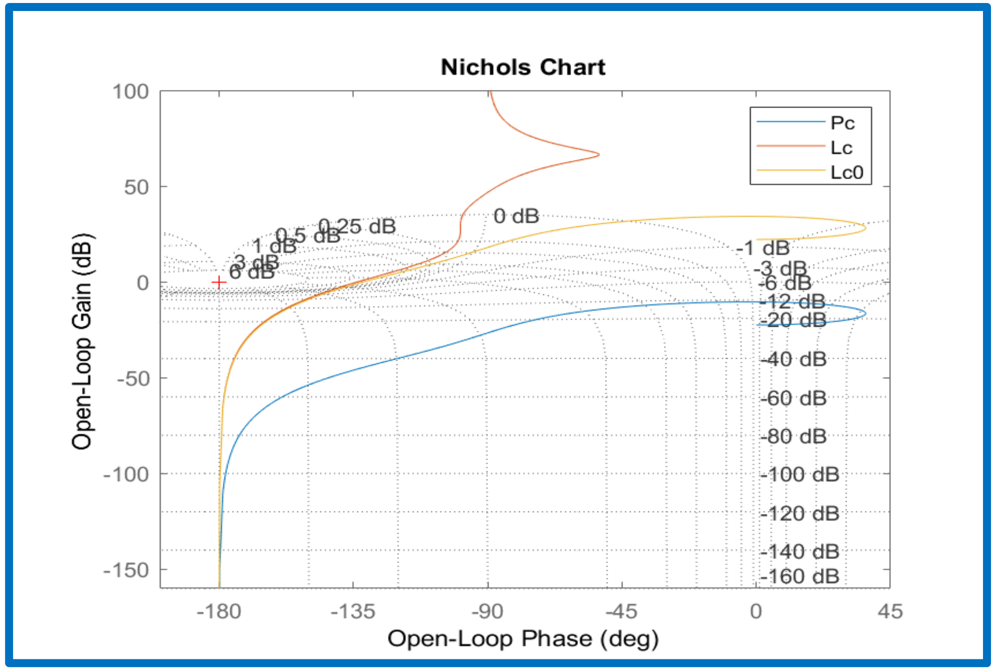
Open current loop, with and w/o integrator: L_c=PIc*P_c ; L_{c0}=PIc0*P_c



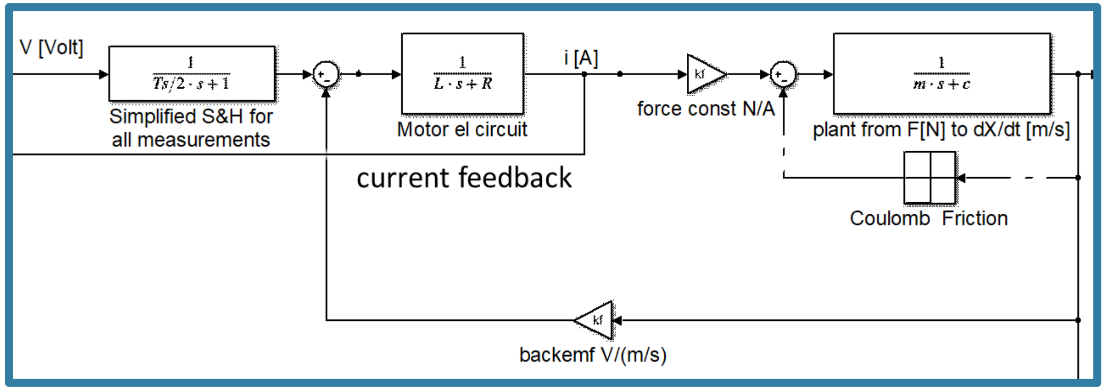
$$PIc = K_{pcl}\left(1 + \frac{K_{icl}}{s}\right)$$

$$PIc0 = K_{pcl}$$





Why current loop at all?



- The closed current loop overcomes uncertainties in the **open loop current plant $P_c(s)$**,

$$\mathrm{i} = \frac{ms+c}{Lms^2+(Lc+Rm)s+(\mathrm{R}c+k_f^2)} \cdot \frac{1}{1+\frac{T_s}{2}s} V = P_c(s)V$$

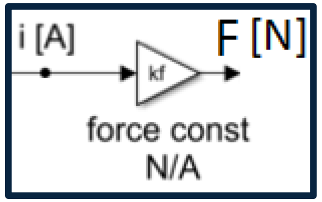
  in particular temperature dependent uncertainty in R;
- The driver vendor may demonstrate a closed current loop for her client.

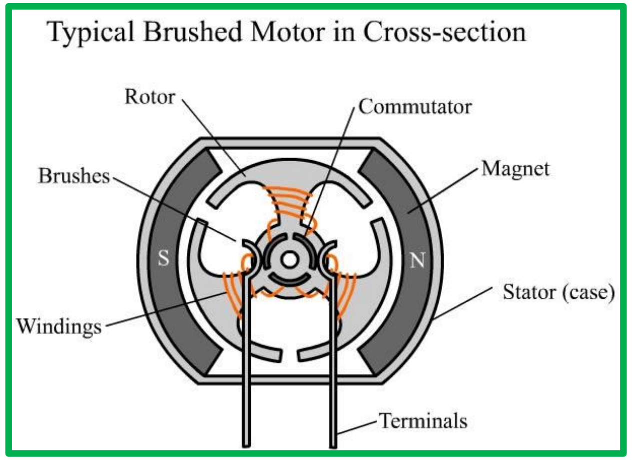
Why an integrator the current loop?

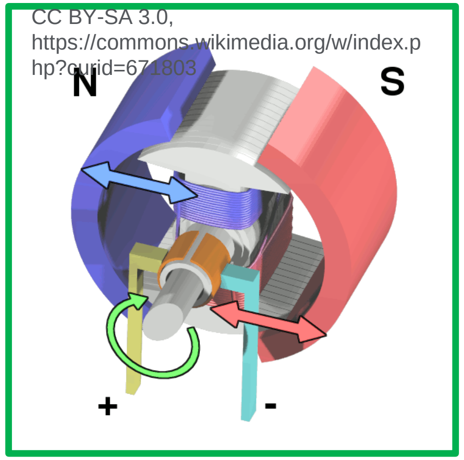
- The driver vendor may demonstrate zero steady state current error for a step command to the closed current loop.
- For the lazy driver constructor who does not know how to do velocity dependent vector control for the commutation in a BLDC motor, the integrator gives ≈90 deg phase difference at low frequencies between the *V* and *i* vectors which is desirable from an energy efficiency point of view.
- However, **the integrator is not necessary if the commutation is done properly**, and may even be harmful, as demonstrated below.

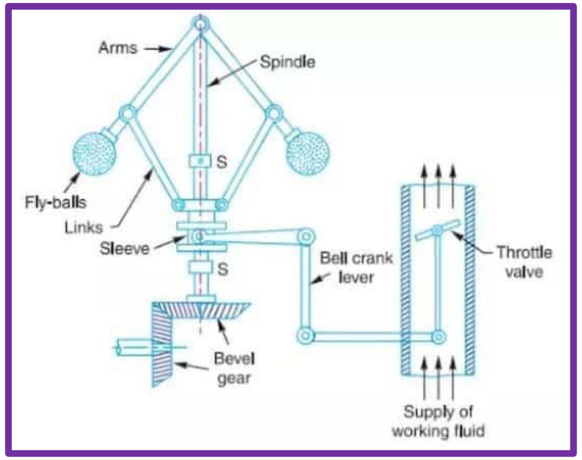
The DC-motor, and the Brushless DC-motor (BLDC)

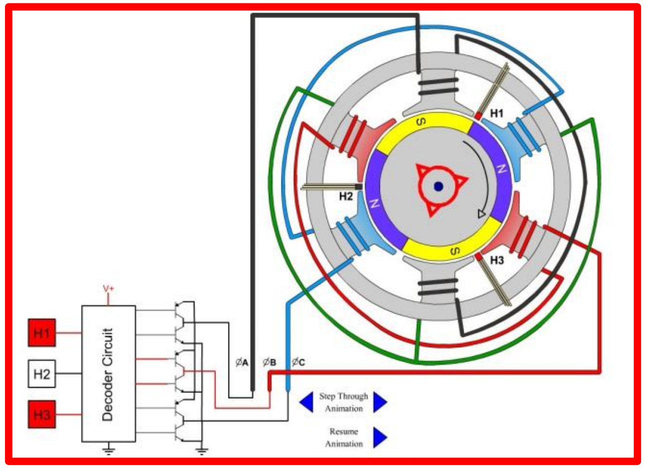
- Ideally, $F = k_f i$. However, there is polarity effects (ripple), and lower *de-facto* force constant, due to misalignment between the “rotor” and “stator” magnetic fields.
- More misalignment causes more passive power, wasted as heat.







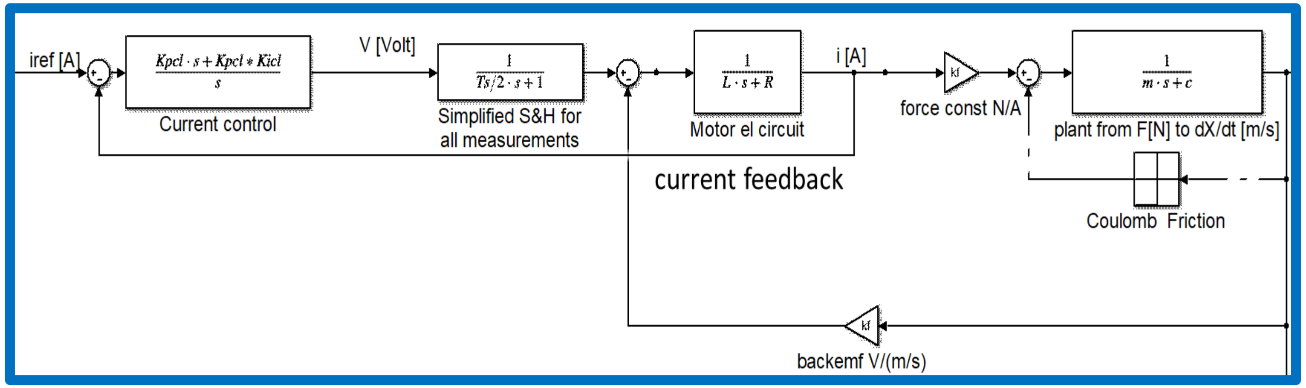


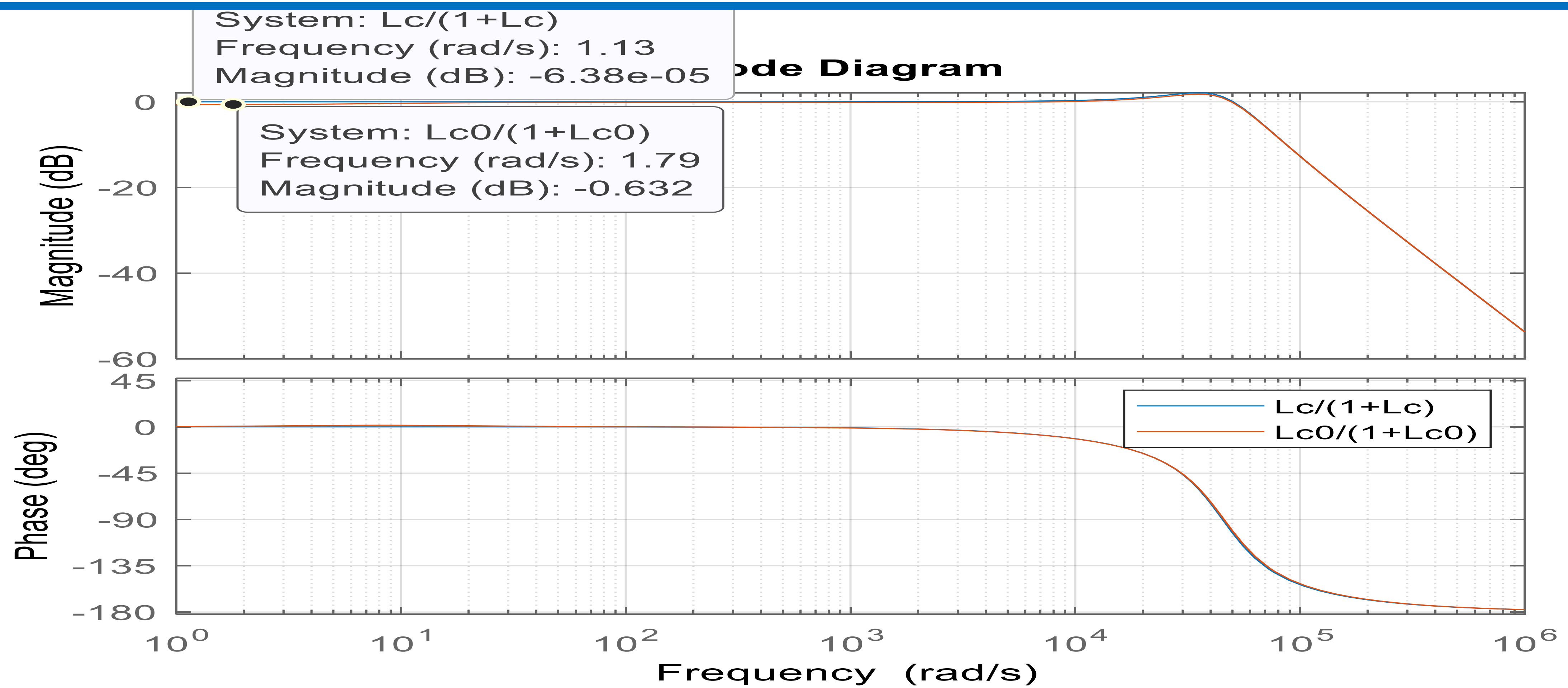


- “The faster the rotor spins, the further the degree of field distortion. Because the dynamo operates most efficiently with the rotor field at right angles to the stator field, it is necessary to either retard or advance the brush position to put the rotor's field into the correct position to be at a right angle to the distorted field”.
- A better force equation is $F = k_f i\Phi(\theta, v)$, where Φ is normalized effective total magnetic flux that depends on the angle θ between the rotor and stator, and on v = the rotor velocity. [https://en.wikipedia.org/wiki/Brushed_DC_electric_motor#Torque_and_speed_of_a_DC_]
- The commutator is a mechanical computer to align the magnetic fields. Using a centrifugal governor, one may mechanically shift the commutator angle as a function of rotor velocity.
- In a BLDC, the permanent magnet sits on the rotor, and the electromagnet on the stator. Commutation and magnetic field angle adjustment is done electronically.
- **So, no integrator is needed in the current control loop if electronic commutation is done properly!**

Closed current loop: $i = (L_c/(1+L_c))i_{ref}$

Comment: Current loop w/o integrator makes the DC gain 0.6 dB lower which is easily compensated for in the outer loop





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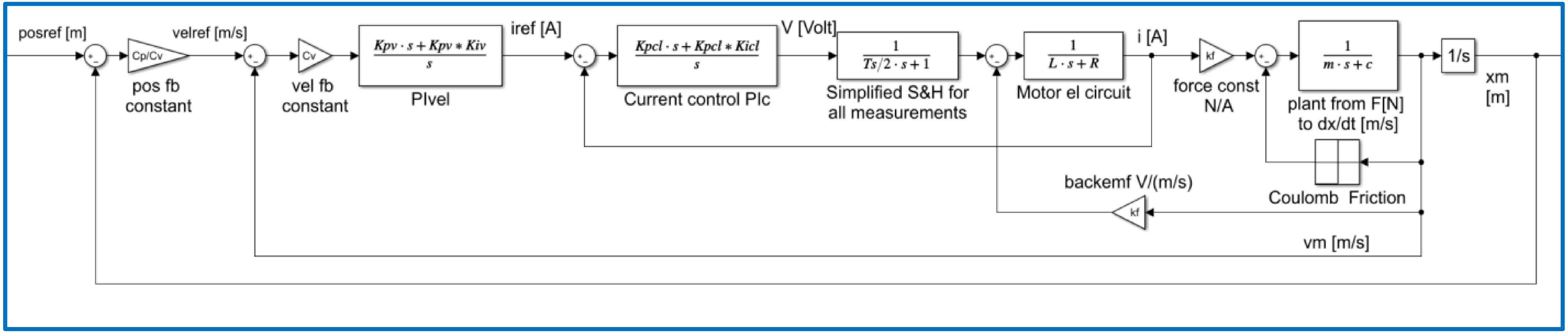
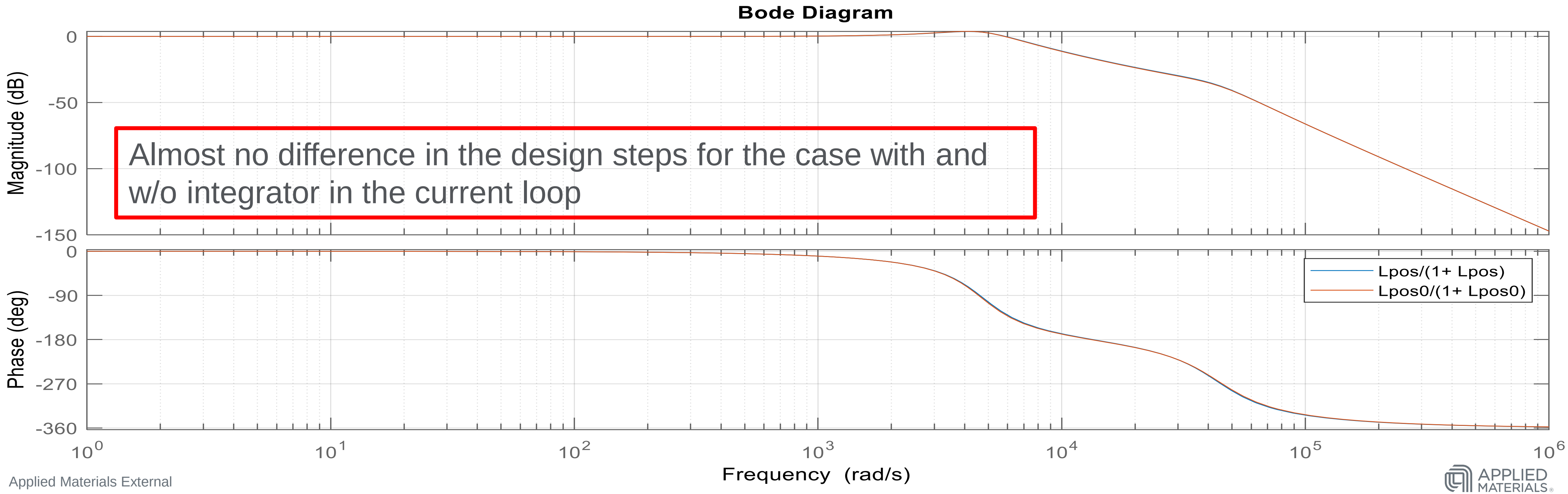
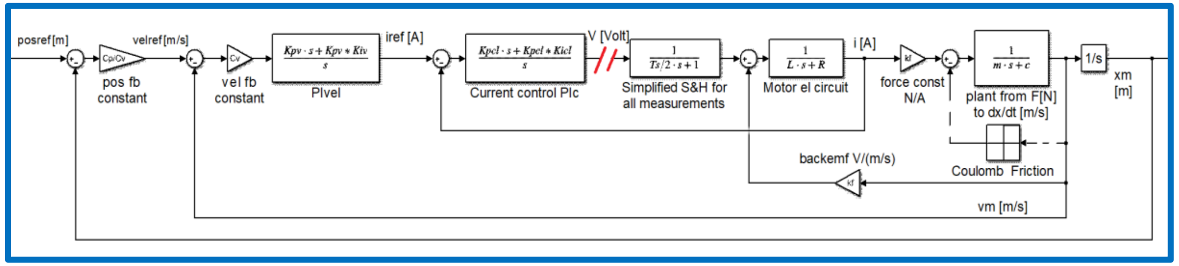
Closed position loop from posref to xm: Lpos/(1+Lpos) ; Lpos0 /(1+Lpos0) for Kicl=0





Equivalent cascaded block diagram, and True Open Loop: TOL ; TOL0



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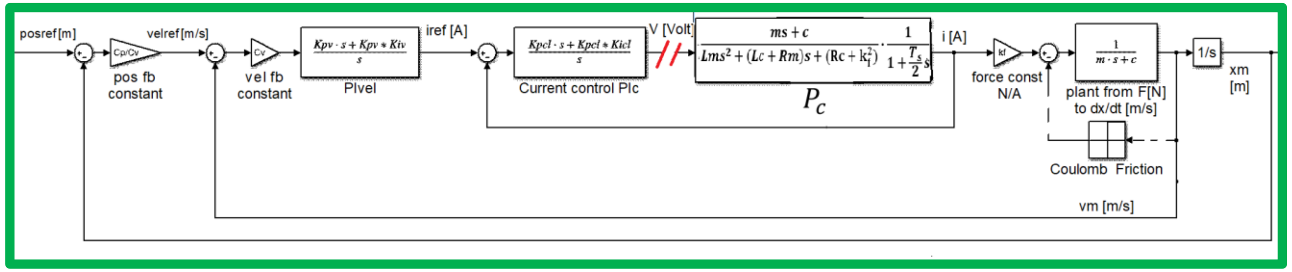
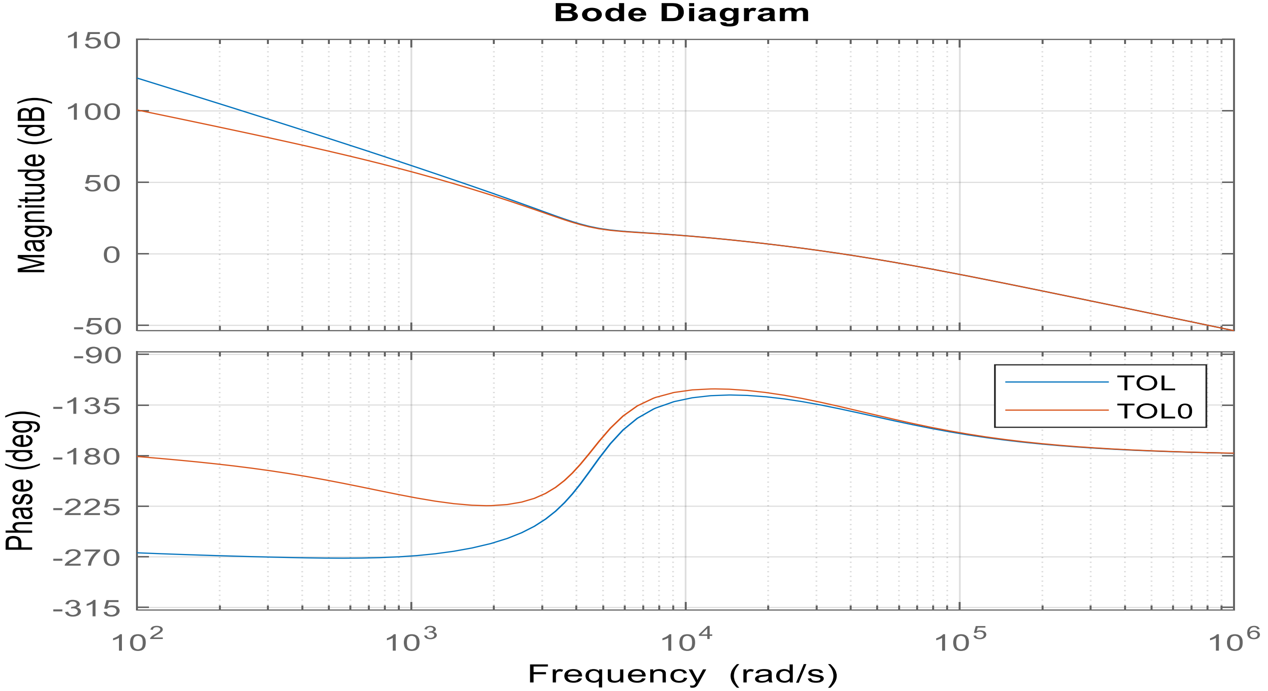
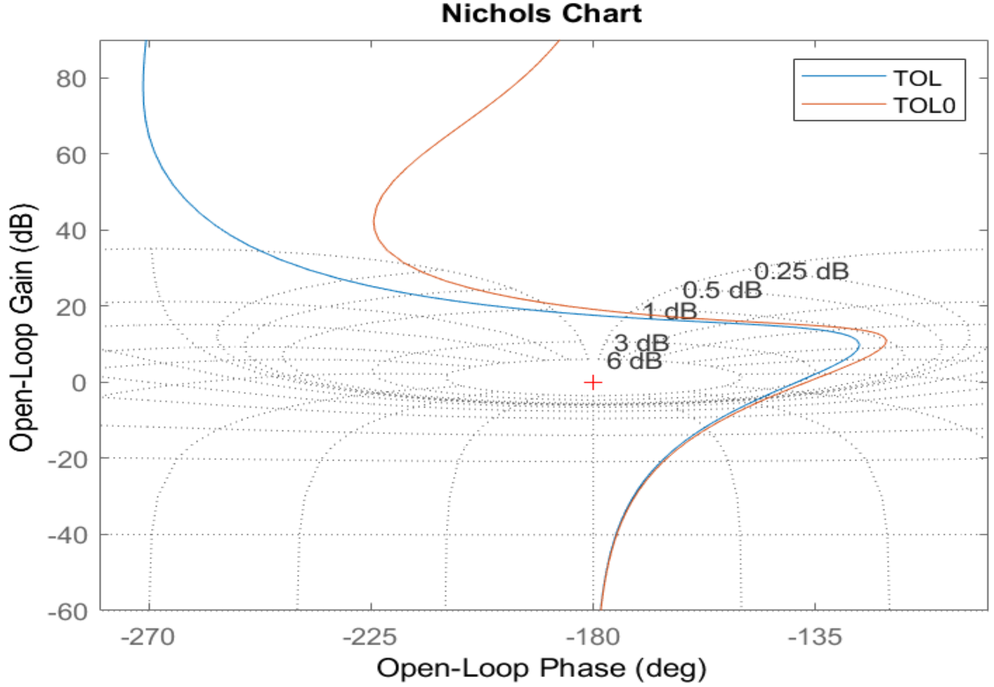


$$TOL = PIc \cdot P_c + PIc \cdot P_c \cdot PIvel \cdot \frac{k_f}{ms+c} \cdot \left(C_v + \frac{C_p}{s}\right)$$

$$TOL0 = PIc0 \cdot P_c + PIc0 \cdot P_c \cdot PIvel \cdot \frac{k_f}{ms+c} \cdot \left(C_v + \frac{C_p}{s}\right)$$





W/o integrator in the current loop the phase is about 5 deg better at cross-over. Conditional stability could have been avoided, if desired, which is not possible with an integrator in the current loop. Note, that an integrator in the outer controller is mandatory.

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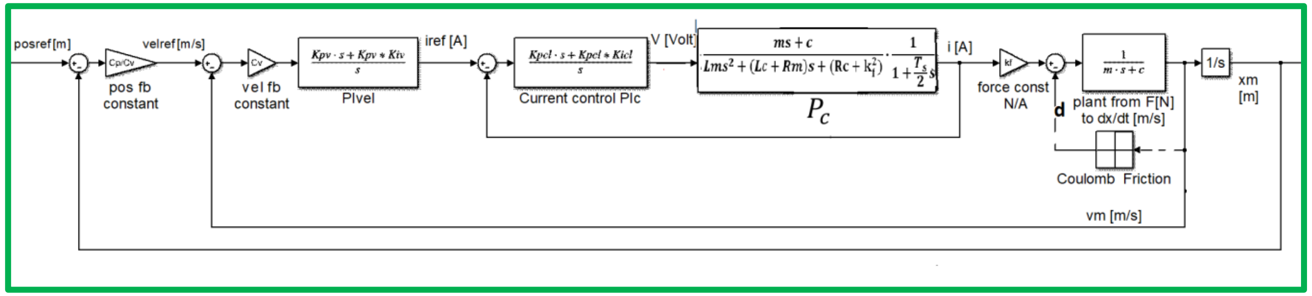
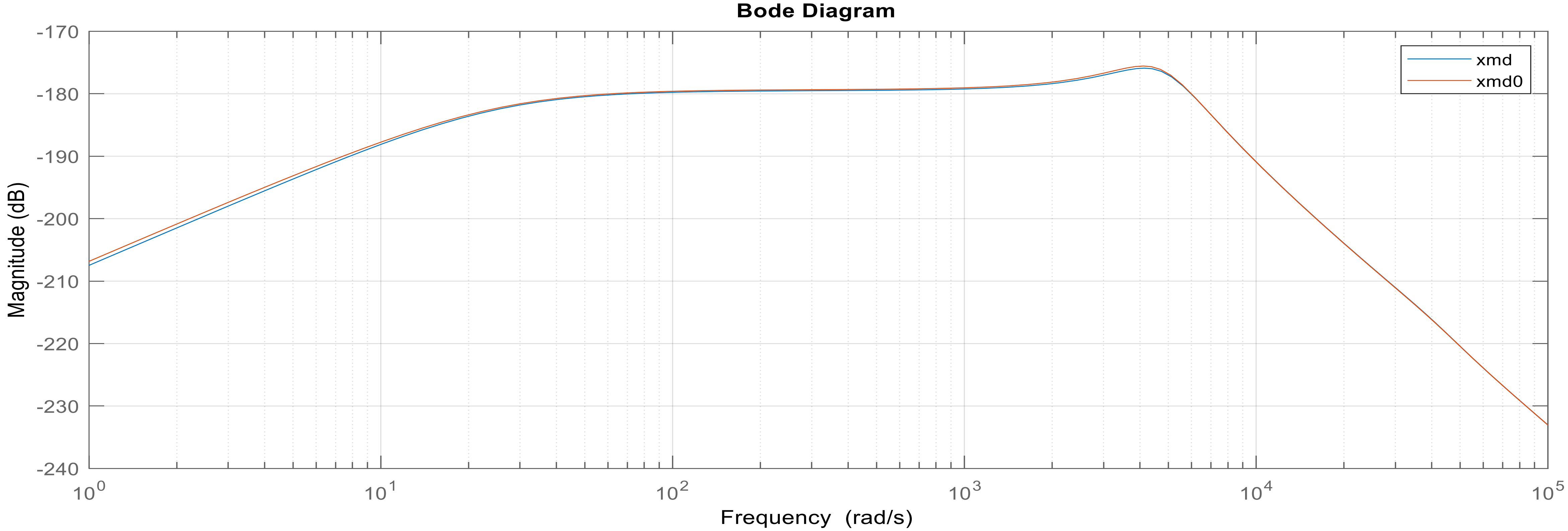
Disturbance rejection, from d to xm

$$x_m d = 1/\left((ms + c)\cdot s + \frac{k_f \cdot PIvel \cdot L_c}{1 + L_c}\cdot (C_p + C_v s)\right)$$

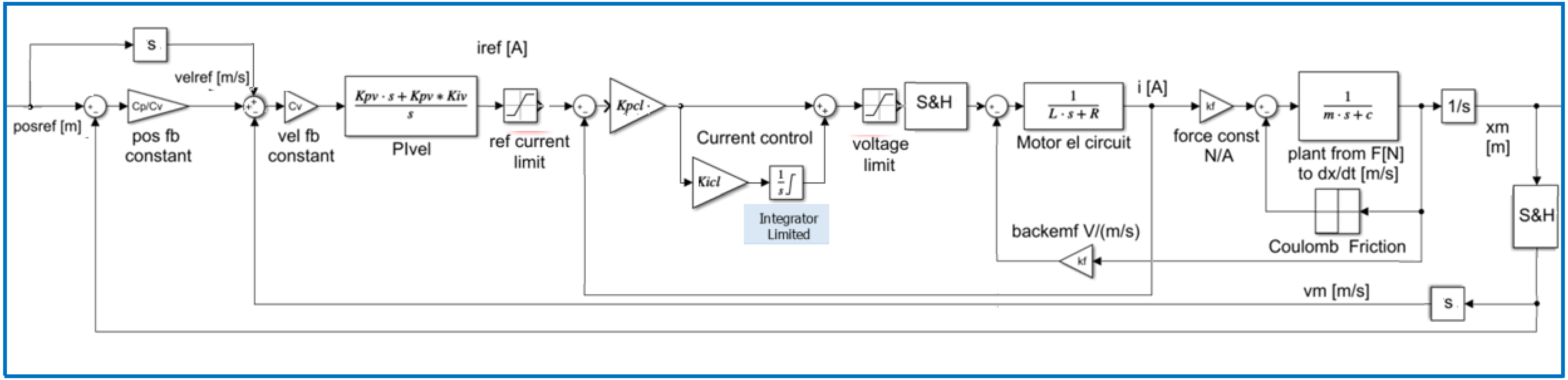
$$x_m d0 = 1/\left((ms + c)\cdot s + \frac{k_f \cdot PIvel \cdot L_{c0}}{1 + L_{c0}}\cdot (C_p + C_v s)\right)$$



Conclusion: Possible to design the inner loop with an integrator. There is however a disadvantage in that the phase margin is lower, and a conditionally stable design is unavoidable.

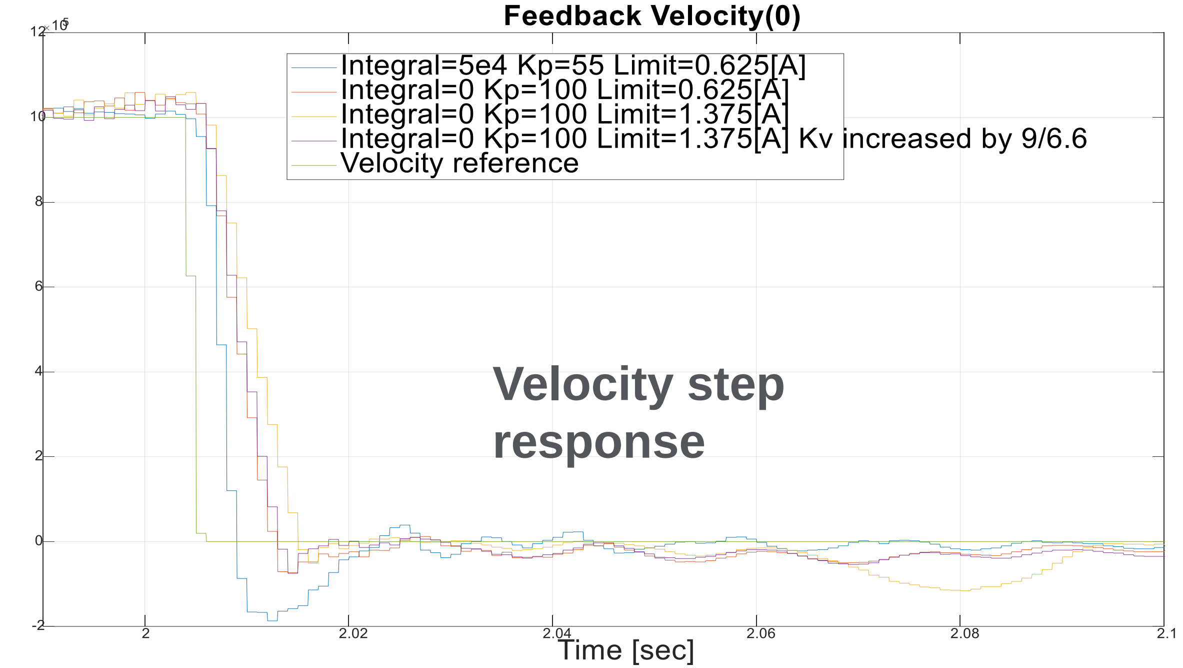


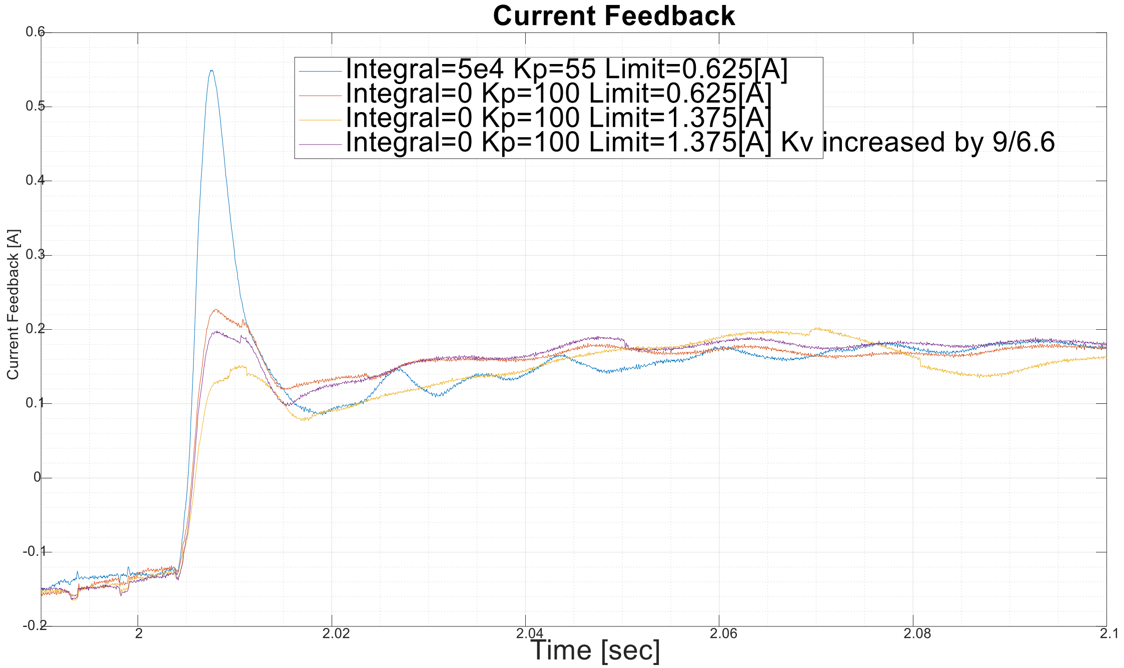
Block diagram of experimental setup for DC-motor

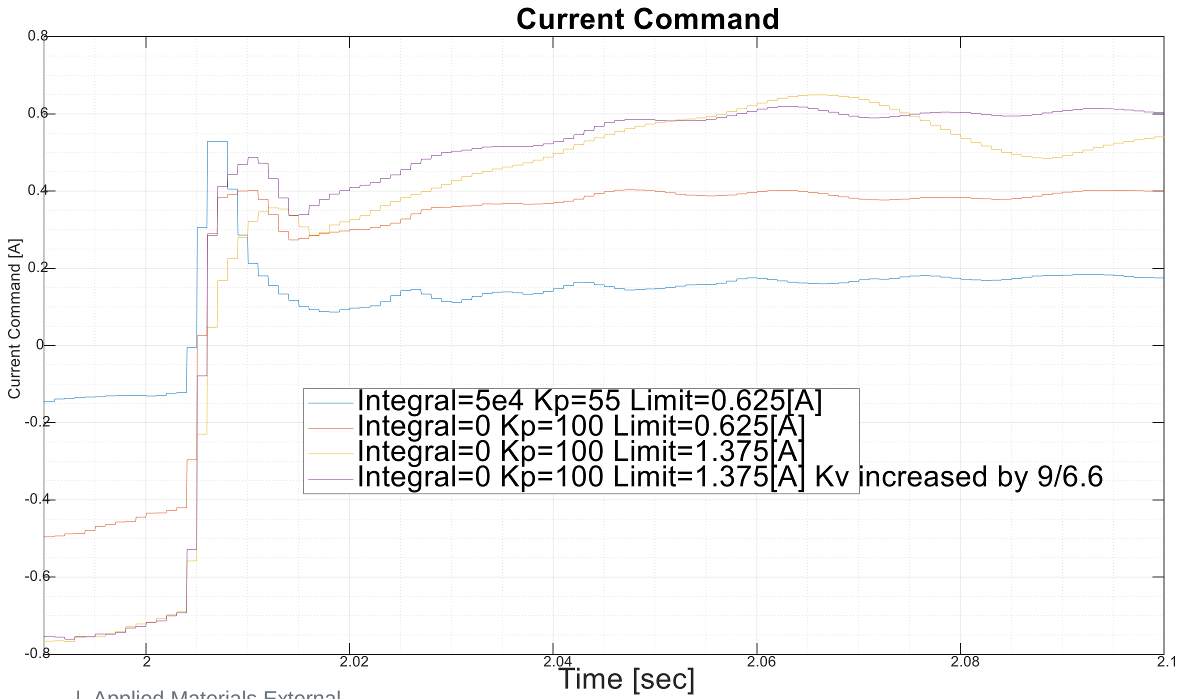


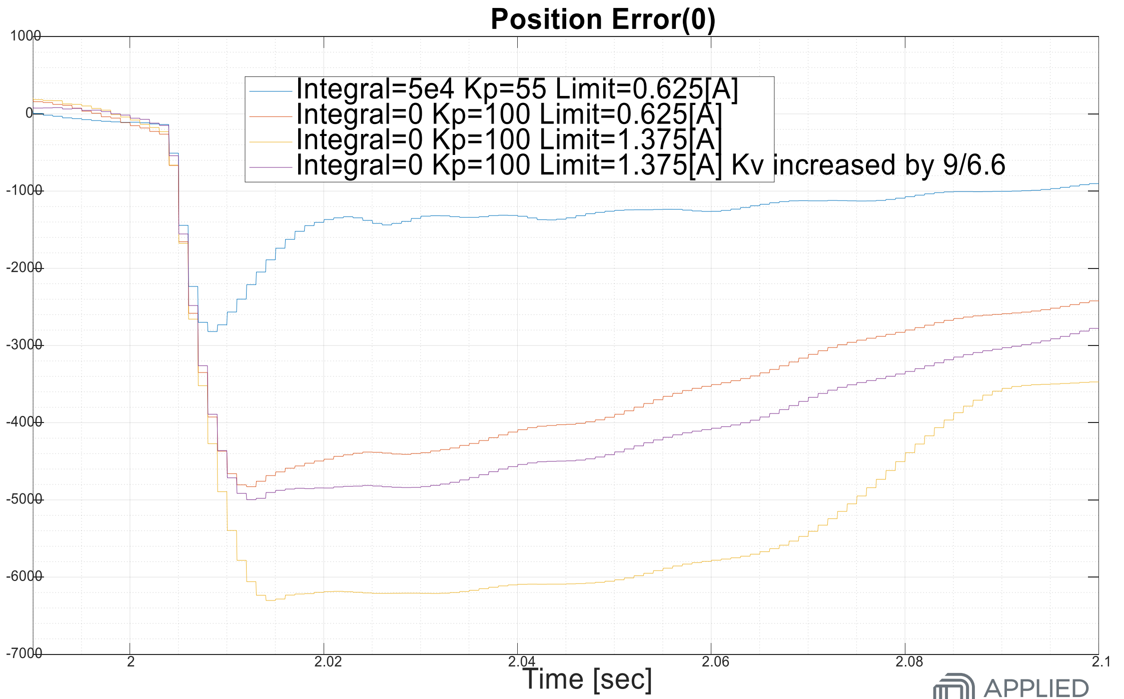
On the next slide, step responses are presented with Kicl>0, and Kicl=0, respectively.

Velocity step response

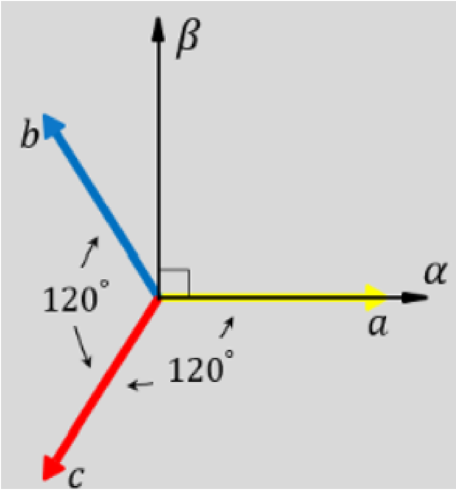


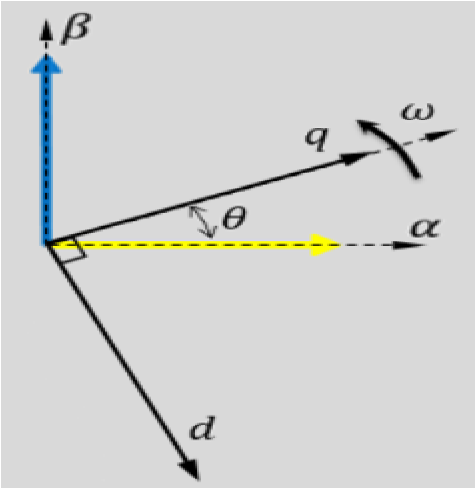






BLDC-motor experiment





References from the Matlab/Simulink documentation:

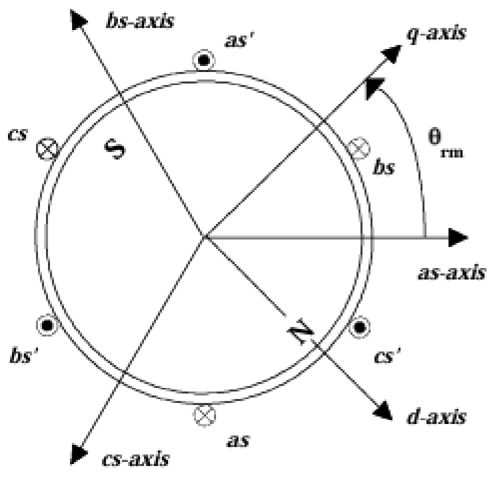
https://www.mathworks.com/help/mcb/ref/clarketransform.html
https://www.mathworks.com/help/mcb/ref/parktransform.html
https://www.mathworks.com/help/mcb/ref/inverseclarketransform.html
https://www.mathworks.com/help/mcb/ref/inverseparktransform.html

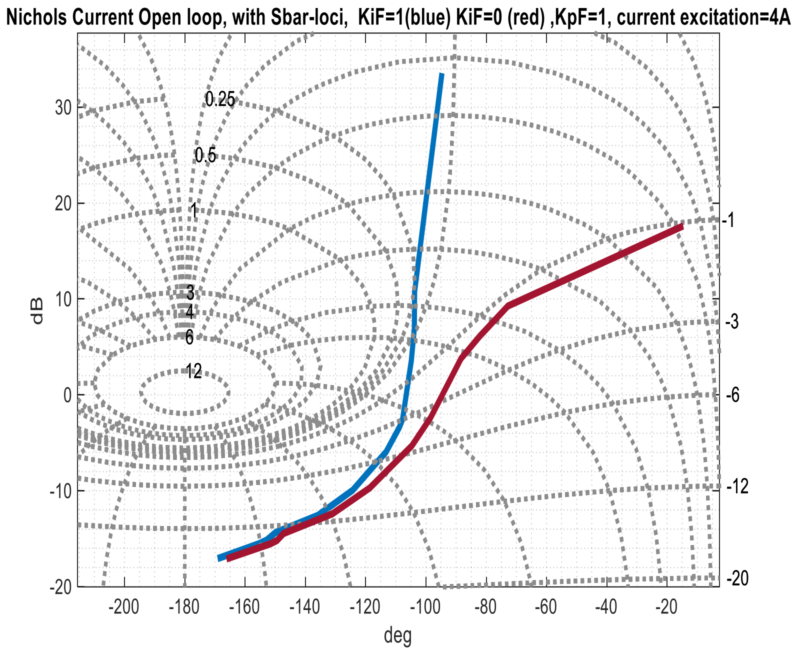
- It is common that the balanced three-phase current components (*a, b, c,* 120° apart) in a BLDC are transformed to the balanced two-phase orthogonal components in the stationary *αβ* reference frame, using the Clarke Transform.
- Further, the Park transform is used to output the orthogonal direct (*d*) and quadrature (*q*) axis components in the rotating *dq* reference frame.

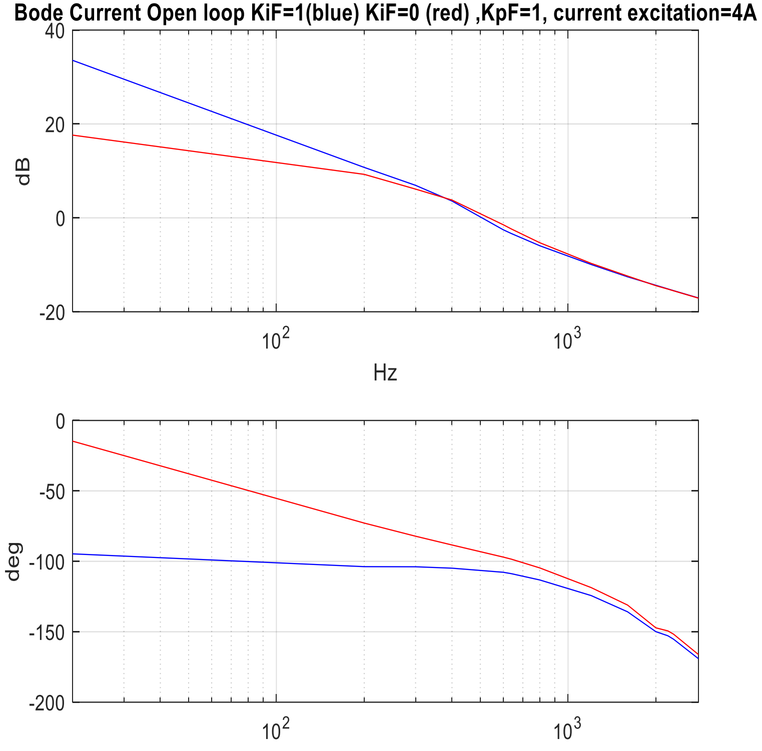
- The *q*-component i_q [A] transmits the force (or torque) to the moving mass, while i_d [A] should be kept at 0, in order to ensure that rotor field is at right angle to the stator field.
- In a standard BLDC controller, both the i_q-loop and the i_d-loop are controlled each by its own PI-controller.
- We retained the i_d-regulator, but zeroed the integrator of the i_q-controller.

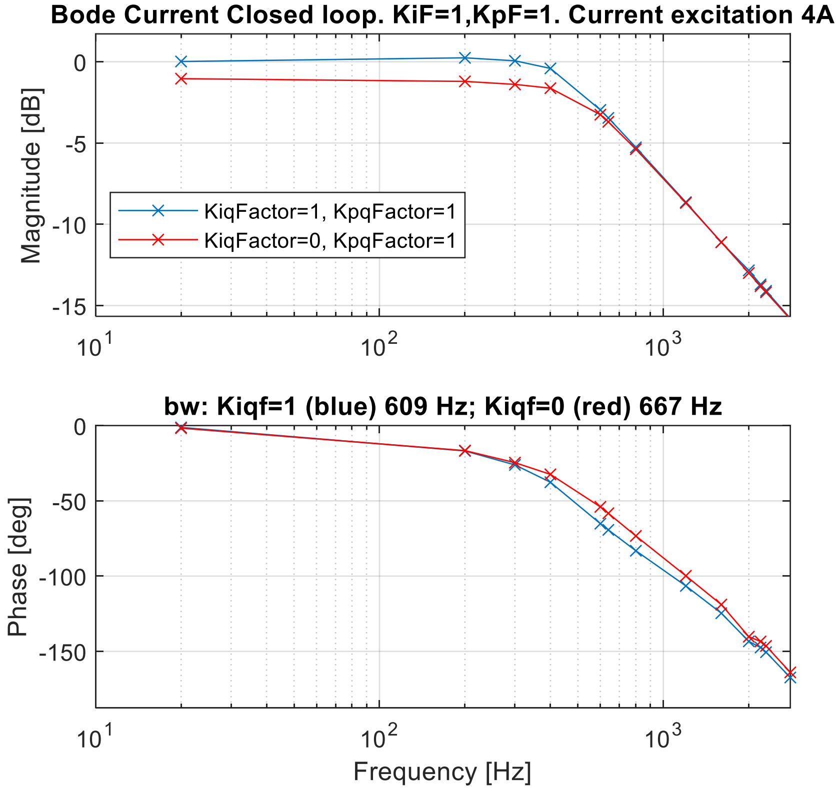
Next two slides: Red is with no integrator in i_q-controller.

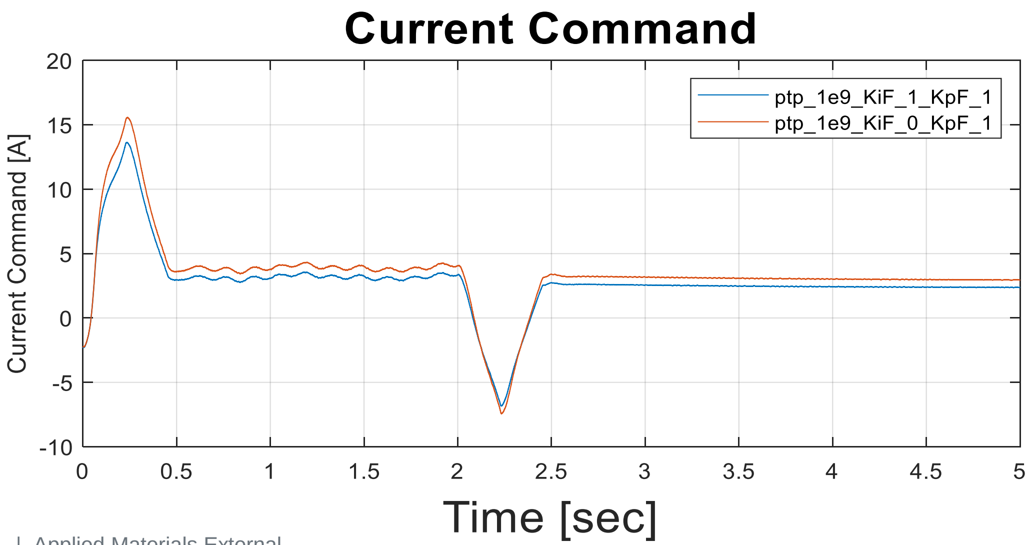
From fig. 1 in
Chapman PL, Sudhoff SD, Whitcomb CA. Multiple reference frame analysis of non-sinusoidal brushless DC drives. *IEEE Transactions on Energy Conversion*. 1999 Sep;14(3):440-6.

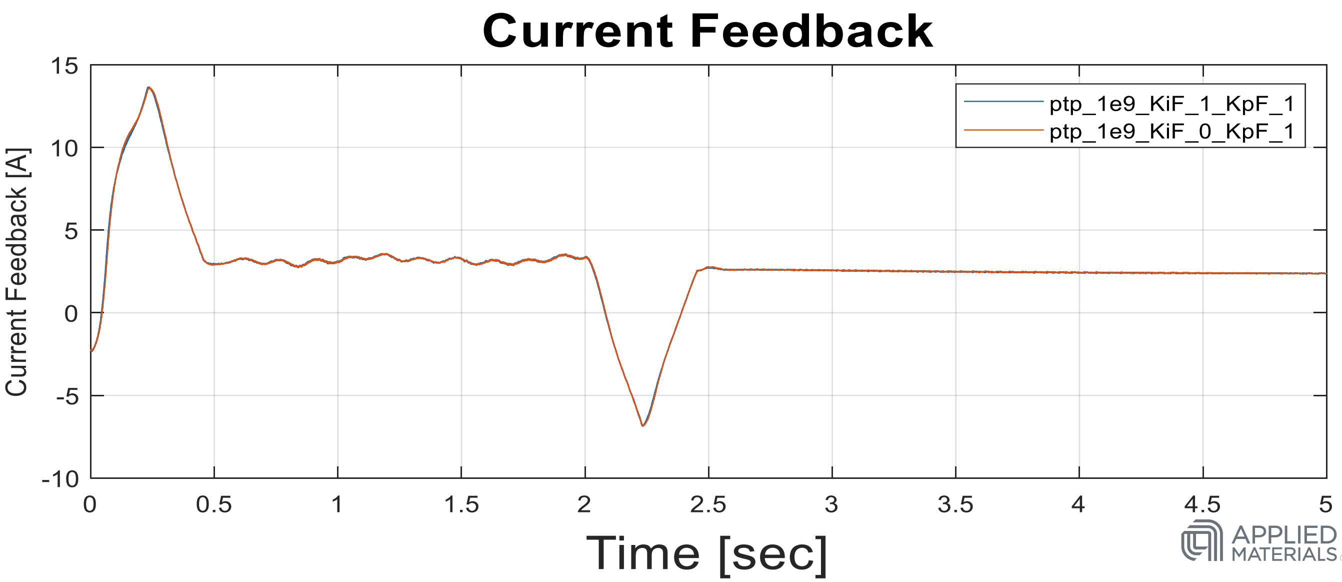


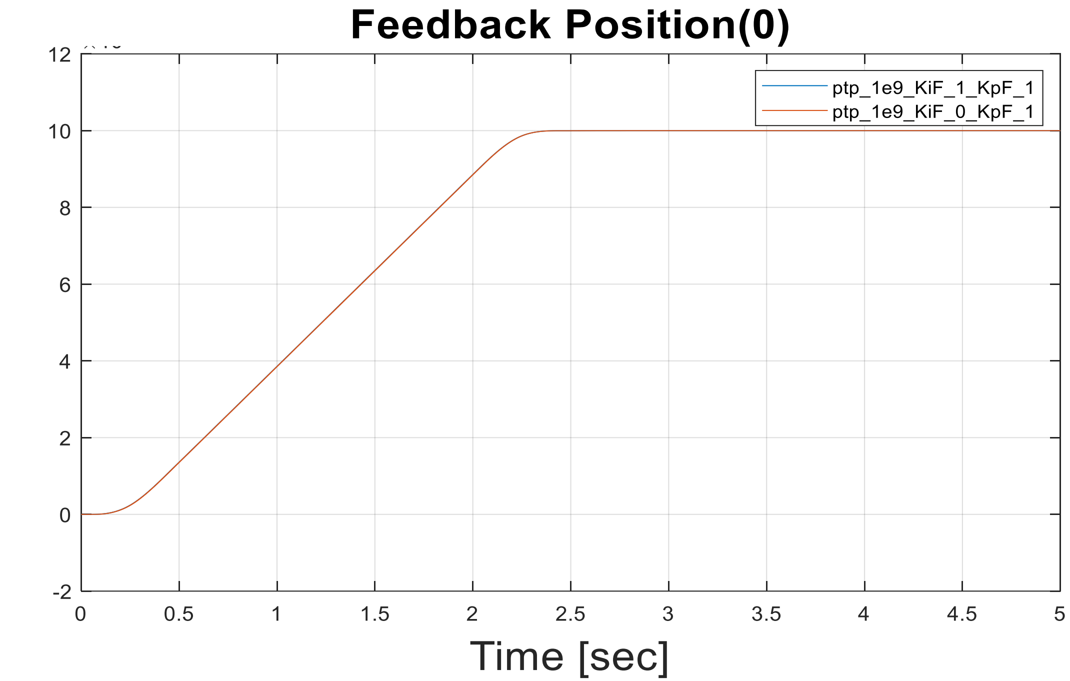

Nichols Current Open loop, with Sbar-loci, KiF=1(blue) KiF=0 (red) ,KpF=1, current excitation=4A
dB
deg

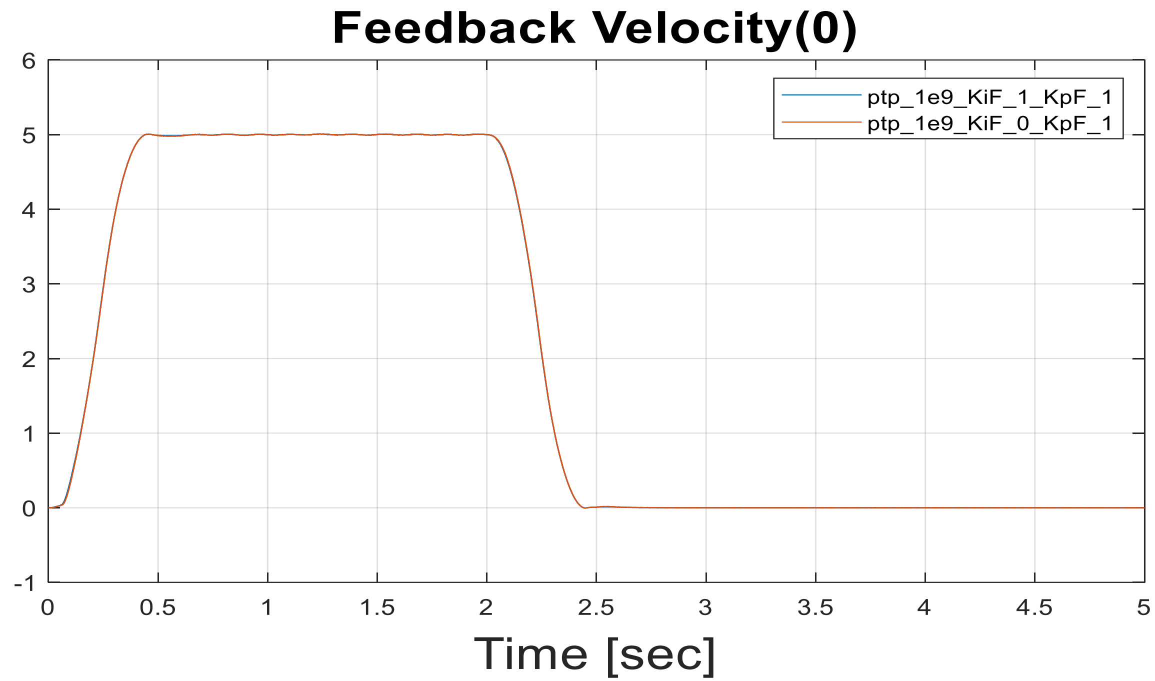

Bode Current Open loop KiF=1(blue) KiF=0 (red) ,KpF=1, current excitation=4A
dB
Hz
deg

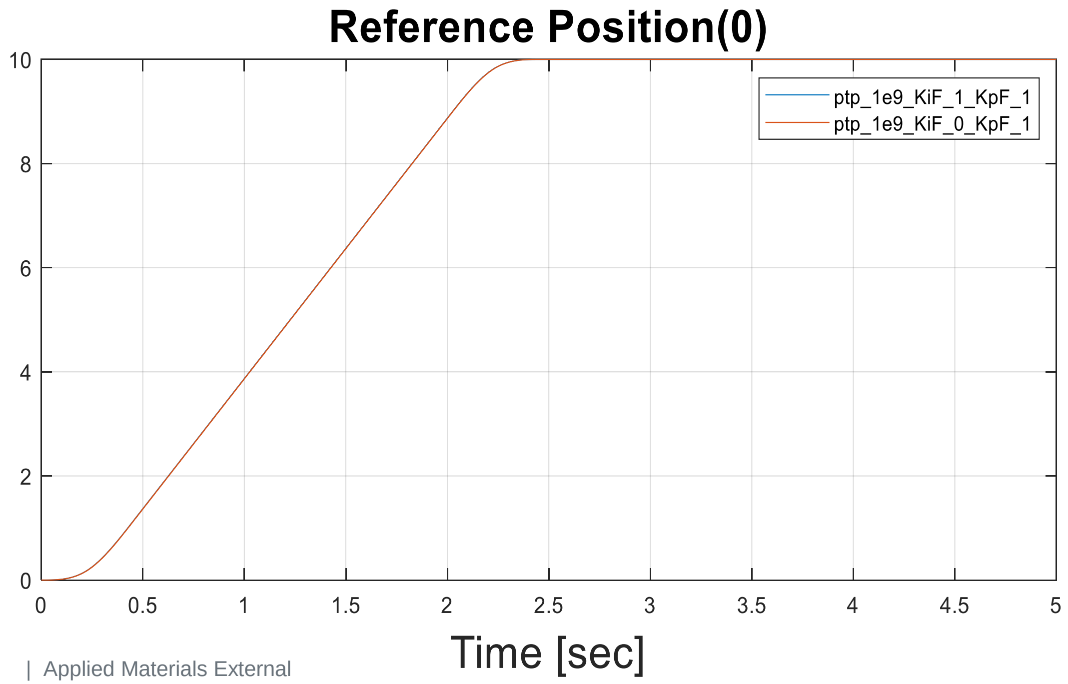

Bode Current Closed loop. KiF=1,KpF=1. Current excitation 4A
Magnitude [dB]
KiqFactor=1, KpqFactor=1
KiqFactor=0, KpqFactor=1
bw: Kiqf=1 (blue) 609 Hz; Kiqf=0 (red) 667 Hz
Phase [deg]
Frequency [Hz]


Current Command
Current Command [A]
ptp_1e9_KiF_1_KpF_1
ptp_1e9_KiF_0_KpF_1
Time [sec]


Current Feedback
Current Feedback [A]
ptp_1e9_KiF_1_KpF_1
ptp_1e9_KiF_0_KpF_1
Time [sec]


Feedback Position(0)
ptp_1e9_KiF_1_KpF_1
ptp_1e9_KiF_0_KpF_1
12
10
8
6
4
2
0
-2
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time [sec]


Feedback Velocity(0)
ptp_1e9_KiF_1_KpF_1
ptp_1e9_KiF_0_KpF_1
6
5
4
3
2
1
0
-1
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time [sec]


Reference Position(0)
ptp_1e9_KiF_1_KpF_1
ptp_1e9_KiF_0_KpF_1
10
8
6
4
2
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1.5
2
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3
3.5
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4.5
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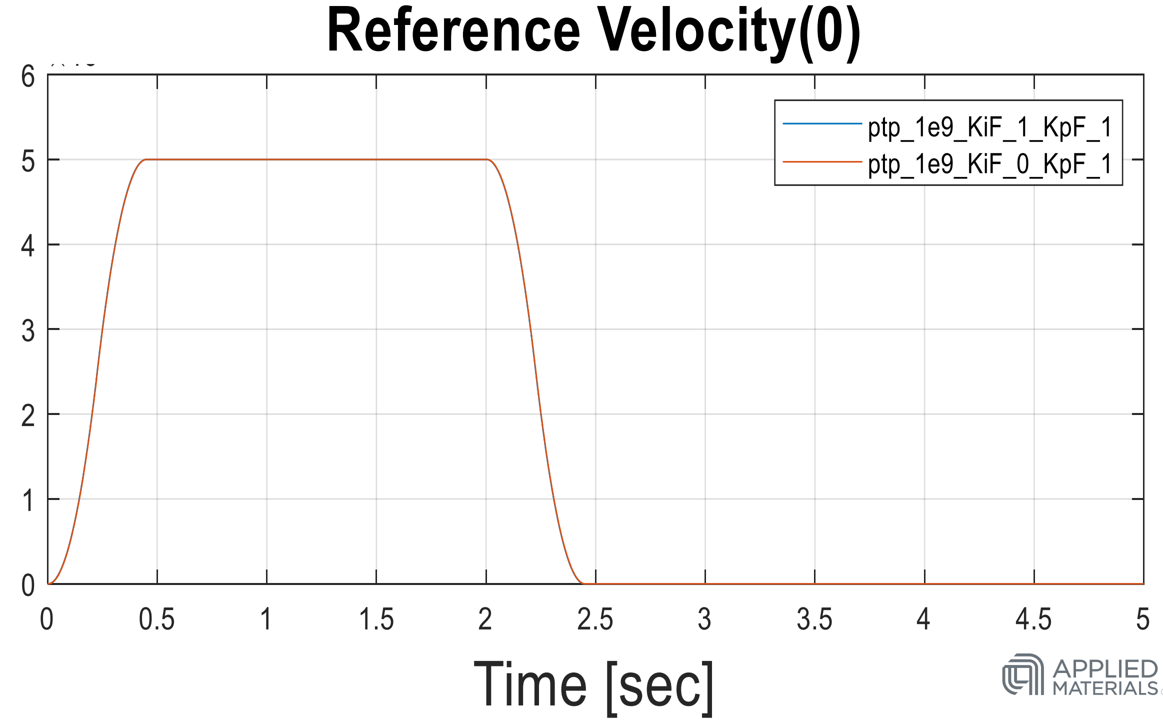
Time [sec]


Reference Velocity(0)
ptp_1e9_KiF_1_KpF_1
ptp_1e9_KiF_0_KpF_1
6
5
4
3
2
1
0
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Time [sec]

Some concluding comments

- Easily designed "inside-out": current loop, and then PI(D) position/velocity loop.
- Complex lead-lags in outer position/velocity loop could potentially give a better design.
- The Coulomb friction was represented as the disturbance *d.*
- Non-linear features such as saturations and the ensuing need for Anti-Reset Windup is not considered here.
- However, **when there is saturation and an integrator, ARW or equivalent is necessary**. Multi-loop ARWs are complicated, see Berger and Gutman (2016). **ARW for saturation in the outer loop, and ARW for the inner current loop must be carefully tuned together**. This is another good reason not to include integrators in inner loops.
- In the comparison of the True Open Loop with and w/o an integrator in the inner loop, the **detrimental effect of the inner loop integrator on stability margins** was not very pronounced. There exist worse examples.
- Note that **an integrator in an inner loop does not replace the need for an integrator in the outer loop**, if the specifications require an outer integrator. E.g. notice in the disturbance rejection transfer function that the slope for low frequencies is the same +20 dB/dec, even though there are 3 (three) integrators in the True Open Loop (only two if inner loop is w/o integrator). Inner loop integrators are not helpful!!!!!!

Reference: Ari Berger and Per-Olof Gutman (2016), A new view of anti-windup design for uncertain linear systems in the frequency domain. *Int. J. Robust Nonlinear Control* 2016; 26:2116–2135.