Technical Report

Course Project of
DYNAMICS OF ELECTRICAL MACHINES AND DRIVES

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Exercise Description

(Lesson34, page 15-17)

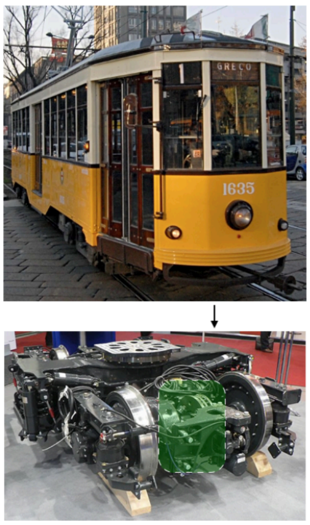
Title: Speed Control of a SE-DC Motor for Traction Unit

A DC separately excited motor is used to move an ATM tramway vehicle "Carelli 1928" with the following characteristics:

- Line voltage: 600V
- Motor rated speed: 314rad/s
- Efficiency: 0.9 (neglecting excitation losses and iron losses)
- Armature circuit time constant:10ms
- Excitation circuit rated voltage: 120V
- Excitation circuit rated current: 1A
- Excitation circuit time constant: 1s

The tramway should accelerate from 0 to 60km/h in 25s. The tramway mass is 10T and you should consider 200 people as the tramway trainload with a standard weight of 80kg. The friction force is proportional to the speed and at rated speed (60km/h or 314rad/s) is 1/3 of traction force.

- Compute the system parameters of the DC motor according to the data
- Design and simulate speed and current control in order to cover a 10km track considering the Table I characteristics. The slope is $s\% = 100\tan\theta$



track	**slope %**	**speed**
$0-1km$	0	$35km/h$
$1-3km$	0	$60km/h$
$3-4km$	5%	$60km/h$
$4-6km$	0	$75km/h$
$6-8km$	0	$60km/h$
$8-9km$	-5%	$60km/h$
$9-10km$	0	$35km/h$

- If we not perform the filed weakening, what happen at 75km/h? Give an explanation.
- Sometimes, if you not "interpretate" correctly the motor parameters some drawbacks can rise into the dynamical responses, even with good controller bandwidth.

DC Machine Parameters Computation

In order to deduce the parameters, we consider the “rated” condition, i.e. considering the maximum possible acceleration at the rated speed 60km/h, when the maximum torque is required. In the following we denote the parameters in this condition with a subscript “n”. Thus

$$v_n = 60\text{km/h} = \frac{50}{3}\text{m/s} \cong 16.67\text{m/s}$$
$$a_n = a_{max} = \frac{16.67}{25} = \frac{2}{3}\ \text{m/s}^2 \cong 0.67\text{m/s}^2$$

The total mass is given by

$$M = 10\times10^3 + 200\times80 = 26\times10^3\ \text{kg}$$

So the maximum traction power is

$$P_{tr,n} = F_{tr,n}v_n = (M\cdot a_{max})\cdot v_n \cong 289\ \text{kW}$$

Considering the fact that the friction is at this time 1/3 of traction force, we have the total mechanical power and the torque provided by the machine:

$$P_{e,n} = \left(F_{tr,n} + F_f\right)\cdot v_n = \left(F_{tr,n} + \frac{1}{3}F_{tr,n}\right)\cdot v_n \cong 385\ \text{kW}$$
$$T_{e,n} = \frac{P_{e,n}}{\omega_n} = \frac{385\text{kW}}{314\text{rad/s}} \cong 1226\ \text{N}\cdot\text{m}$$

Recalling the energy balance,

$$v_a i_a = R_a {i_a}^2 + i_a p\psi_a + E i_a$$

where the mechanical power $\mathrm{P_e} = \mathrm{Ei_a}$ and the efficiency of the machine is defined as $\eta = \frac{P_e}{v_a i_a} = 0.9$

$$\Rightarrow i_{a,n} = \frac{P_{e,n}}{v_{a,n}} = \frac{385\text{kW}}{0.9\times600} \cong 713\ \text{A}$$

In steady state we have the term $i_a p\psi_a = 0$, so

$$R_a {i_{a,n}}^2 = (1-\eta)\cdot v_a i_a = \frac{1-\eta}{\eta}\cdot P_{e,n}$$
$$\Rightarrow R_a = \frac{1-\eta}{\eta}\cdot\frac{P_{e,n}}{{i_{a,n}}^2} \cong 0.084\ \Omega$$
$$\Rightarrow L_a = R_a\cdot\tau_a = 0.084\Omega\ \times 10\text{ms} \cong 8.4\times10^{-4}\ \text{H}$$

Recall that in DC machines, we have $T_e = k_c\psi_{ae}i_a$ where $\psi_{ae} = \psi_{ae}(i_e)$. By assuming linearity between ψ_{ae} and i_e, we can then write the expression

$$T_e = K_{eq}\cdot i_e\cdot i_a$$

$$\Rightarrow K_{eq} = \frac{T_{e,n}}{i_{e,n} \cdot i_{a,n}} \cong 1.7195$$

Mechanical Load Parameters

Since $F_f \propto v$, we can define a ratio between the friction force and the speed as k_f such that $F_f = k_f \cdot v$. As is described in the exercise, $\frac{1}{3} F_{tr,n} = k_f \cdot v_n$

$$\Rightarrow k_f \cong 346.67$$

Also, we have the corresponding resistant torque $T_f \propto \omega$, so similarly $T_f = k_r \cdot \omega$

$$\frac{k_r}{k_f} = \frac{T_r}{F_f} \cdot \frac{v}{\omega}$$

$$\Rightarrow k_r \cong 0.9767$$

The equivalent moment of inertia is given by

$$J_{eq} = \frac{T_{tr,n}}{\dot{\omega}_n} = \frac{\frac{3}{4} \times 1226}{314/_{25}} \cong 73.21$$

Since the moment balance is

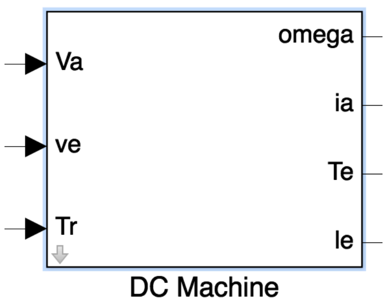
$$\dot{\omega} = \frac{T_{tr}}{J_{eq}} = \frac{T_e - k_r \cdot \omega}{J_{eq}}$$

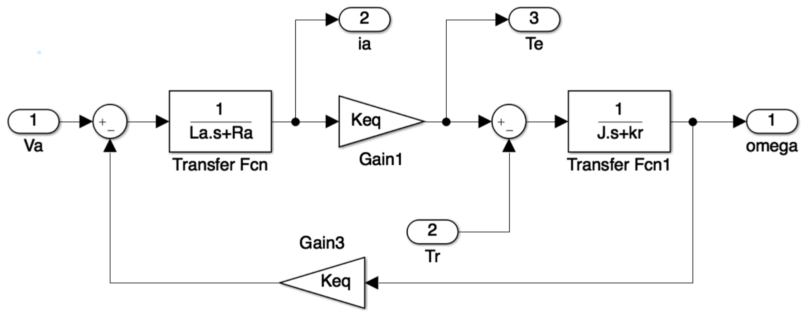
we have the transfer function from T_e to ω as

$$\frac{1}{s \cdot J_{eq} + k_r}$$

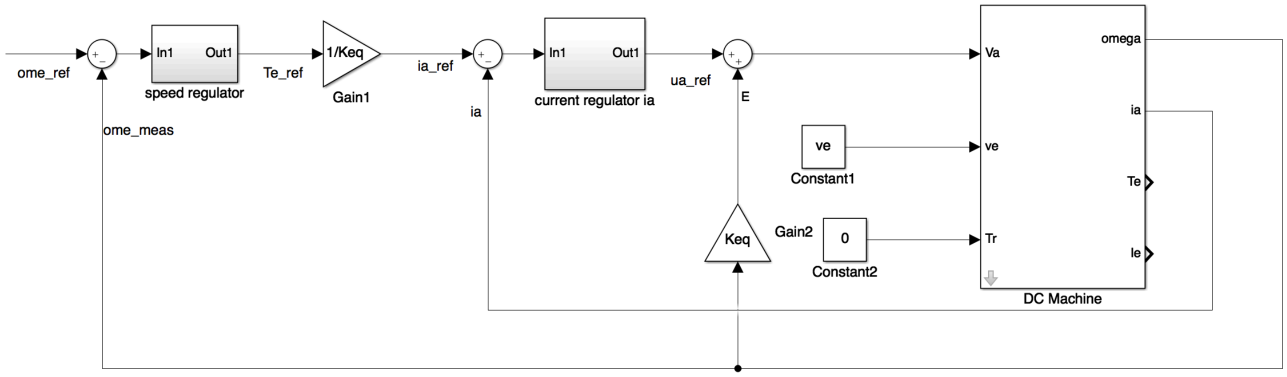
Simulink: Speed Control Loop

First we design a "simple" model for the DC machine (including the mechanical loads) for the speed control (neglecting flux control part, i.e. focus on i_a but not i_e):



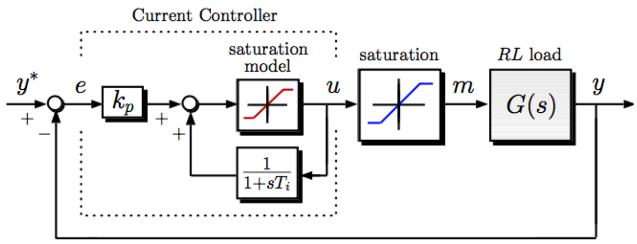


The speed control loop is given in the notes, basing on which we built (assuming an ideal voltage power supply):



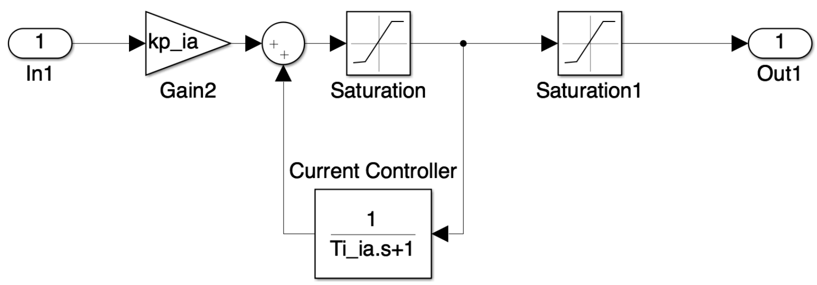
As was tutored, a PI controller for such a second order system ($\frac{1}{R+s\cdot L}$) can be designed according to the following steps:

1) Specify a settling time $T \Rightarrow$ time constant $\tau = T/5 \Rightarrow$ critical frequency $\omega_c = 2\pi/\tau$
2) $k_i = -\omega_c{}^2 L + \omega_c\sqrt{2\omega_c{}^2 L^2 - k_p{}^2 + R^2 + 2k_p R}$
3) $k_p = 0.9k_{p,max} = 0.9\left[R + \sqrt{2R^2 + \omega_c L^2}\right]$
4) implement the controller with the anti-windup technique as following



where $T_i = {k_p}/{k_i}$

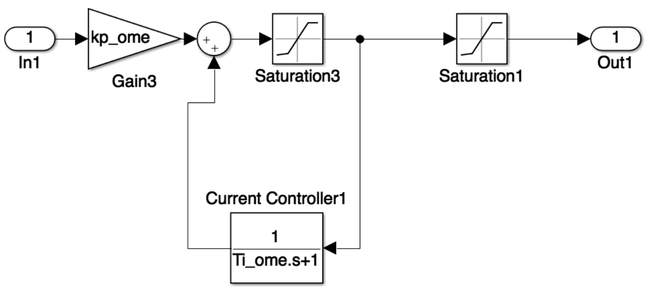
The armature current regulator is designed according to the block $\frac{1}{R_a+s\cdot L_a}$



To have a settling time equaling 100ms, we have
kp_ia = 0.1746
ki_ia = 34.3924
Ti_ia = 0.0051

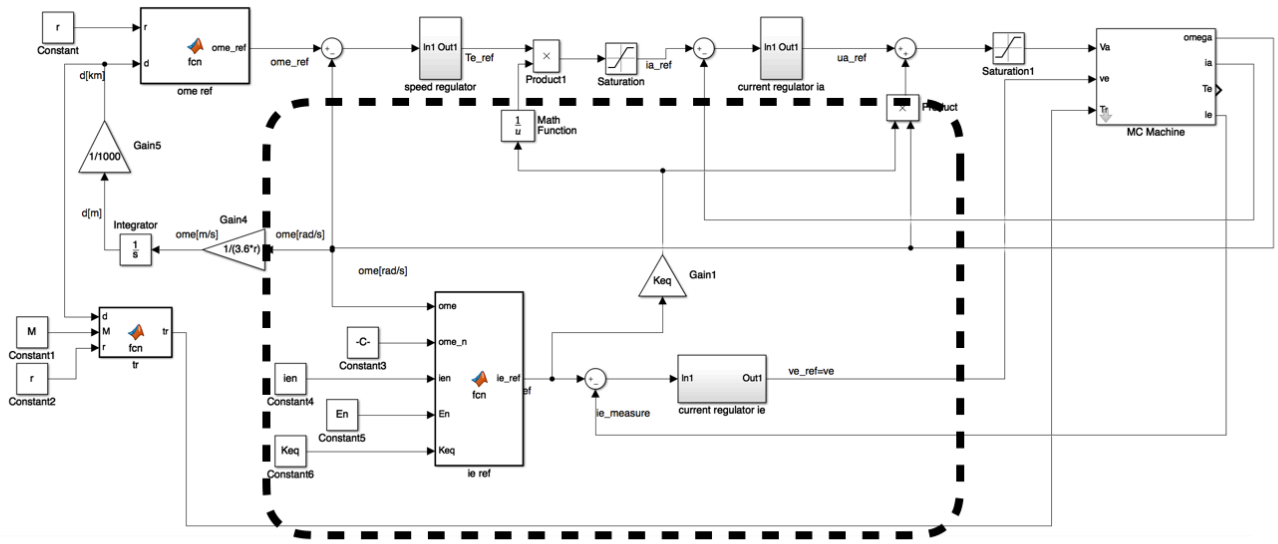
Since the dynamics of armature current regulator is very fast (bandwidth enough big), according to the notes, one can consider only the block $\frac{1}{s \cdot J_{eq} + k_r}$ when designing the speed regulator.

Thus similarly we have:



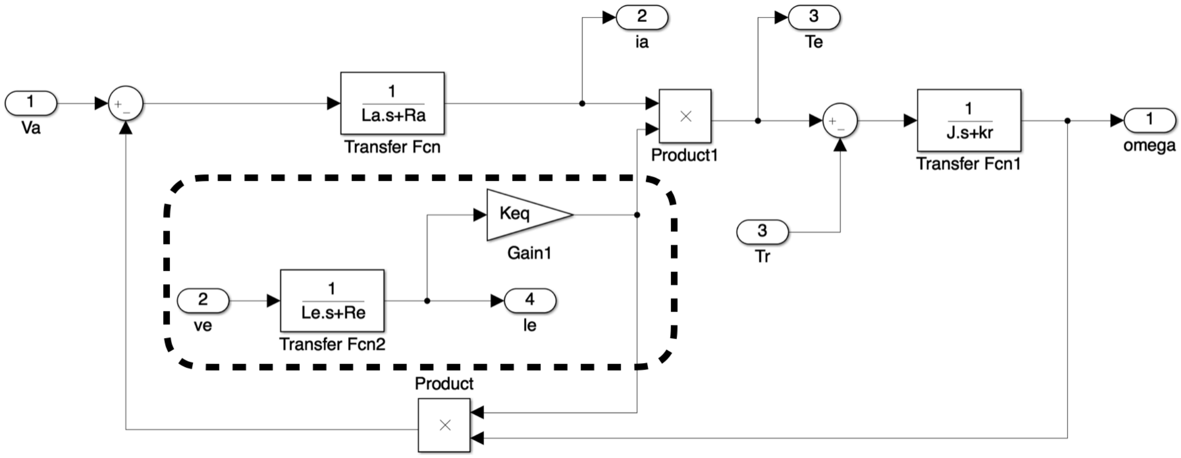
With the settling time set to be 25s,
kp_ome =74.7509
ki_ome =19.0726
Ti_ome =3.9193

Simulink: Flux Control Loop and Field Weakening



The above figure shows the complete control loop with the added flux control part highlighted.

Also the model of DC Machine is modified as following:



As is tutored in the lessons, the following approach is employed:

- if $\omega < \omega_b$

$$i_e = i_e^n = \text{cost} \quad \rightarrow \quad e = \underbrace{K_s i_e^n}_{K} \omega$$

similar to the coefficient K in the PM case

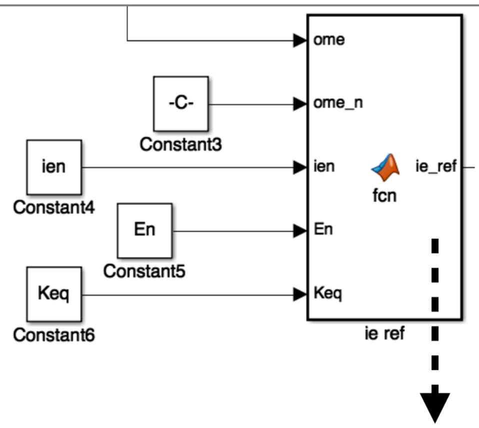
.

- if $\omega > \omega_b$

$$e = e^n = \text{cost} \quad \rightarrow \quad e^n = K_s i_e \omega$$

then we can isolate the excitation current as

$$i_e = \frac{e^n}{K_s \omega}$$

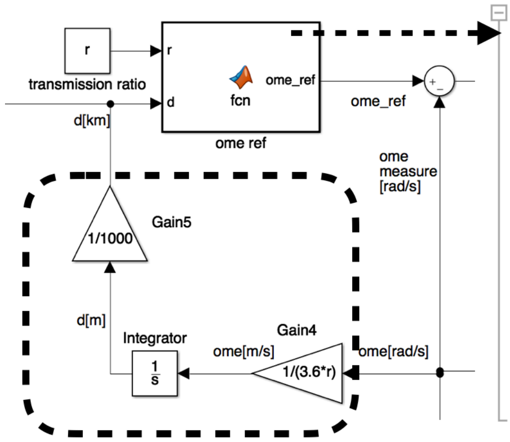



```
function ie_ref = fcn(ome,ome_n,ien,En,Keq)
if ome<=ome_n
    ie_ref=ien;
else
    ie_ref=En/(Keq*ome);
end
```

according to which the Matlab function for reference excitation current (i_e) generation is designed as above.

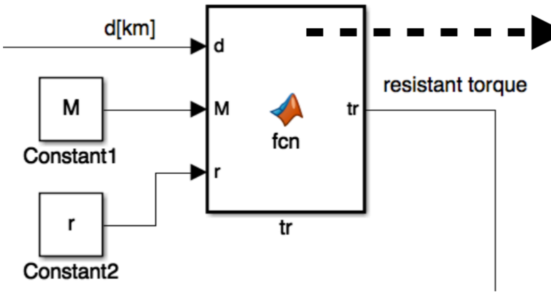
Simulink: Reference Speed and Road Slope Profiles

Both the profiles are built using Matlab functions. For the reference speed profile is shown as following, where the highlighted part is to transfer the rotation speed in [rad/s] into distance in [km].



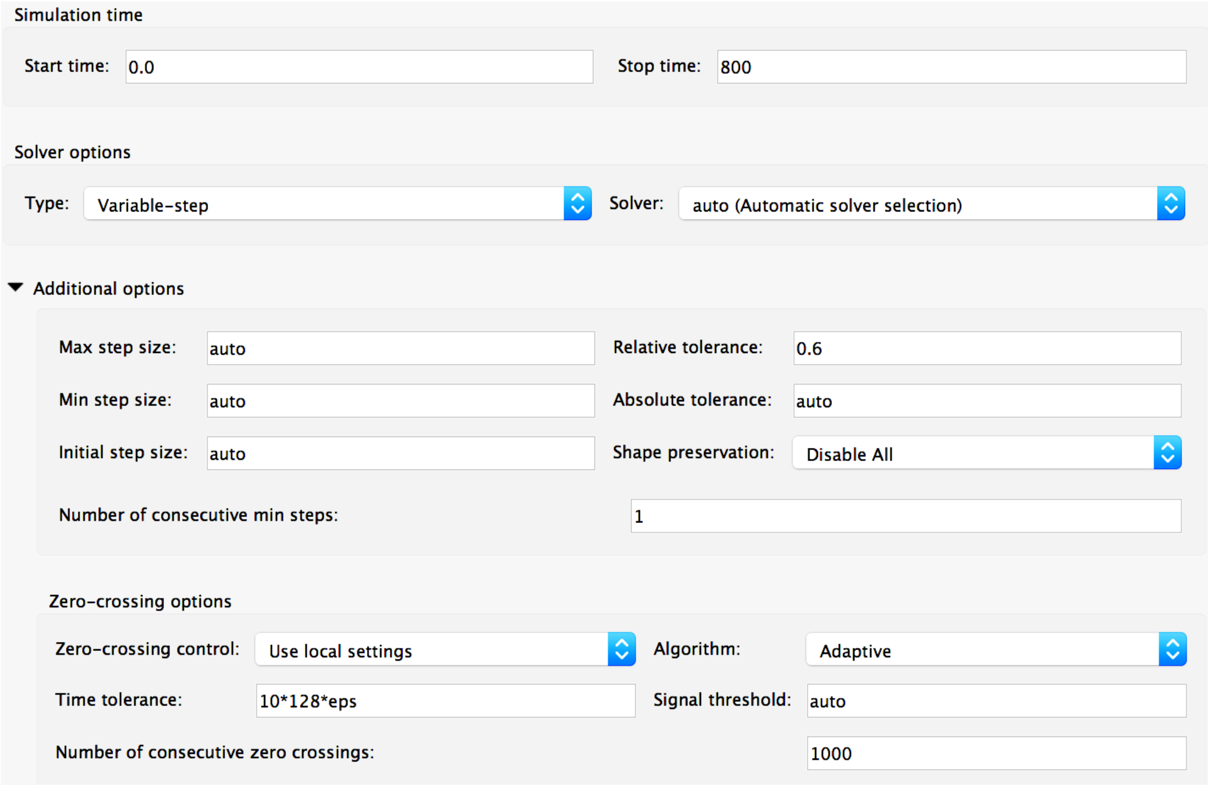

```
function ome_ref = fcn(r,d)
if d<=1
    ome_ref=r*35;
elseif d>1 && d<=4
    ome_ref=r*60;
elseif d>4 && d<=6
    ome_ref=r*75;
elseif d>6 && d<=9
    ome_ref=r*60;
elseif d>9 && d<=10
    ome_ref=r*35;
else
    ome_ref=0;
end
```

Similar is the profile for the equivalent resistant torque caused by the slope. To be noticed that a slope can be interpreted as a constant resistant or traction force.




```
function tr = fcn(d,M,r)
if d>3 && d<=4
    tr=M*9.8*0.0005/r;
elseif d>8 && d<=9
    tr=-M*9.8*0.0005/r;
else
    tr=0;
end
```

Simulation Results



Simulation time

Start time: 0.0
Stop time: 800

Solver options

Type: Variable-step
Solver: auto (Automatic solver selection)

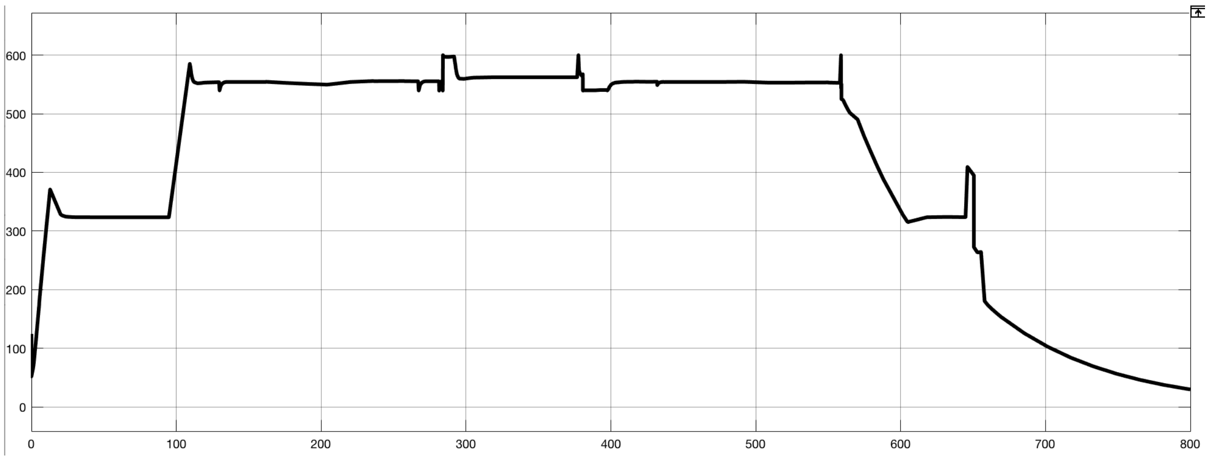
Additional options

Max step size: auto
Relative tolerance: 0.6
Min step size: auto
Absolute tolerance: auto
Initial step size: auto
Shape preservation: Disable All
Number of consecutive min steps: 1

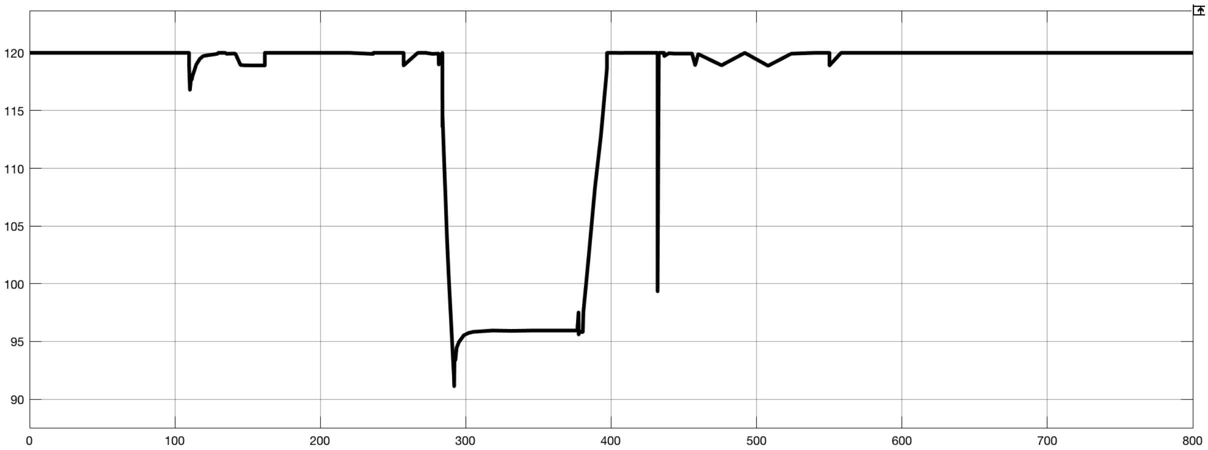
Zero-crossing options

Zero-crossing control: Use local settings
Algorithm: Adaptive
Time tolerance: 10*128*eps
Signal threshold: auto
Number of consecutive zero crossings: 1000

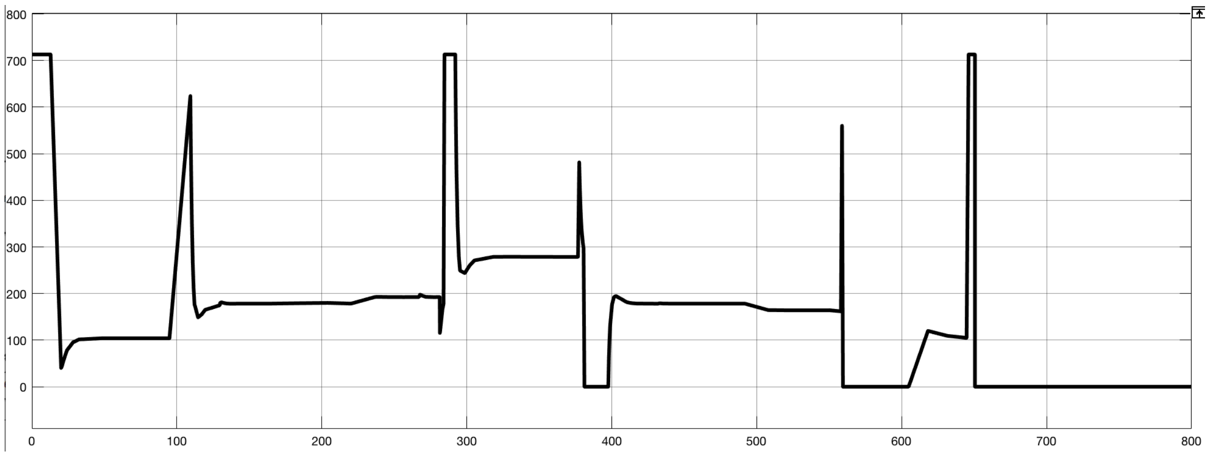
Simulation settings



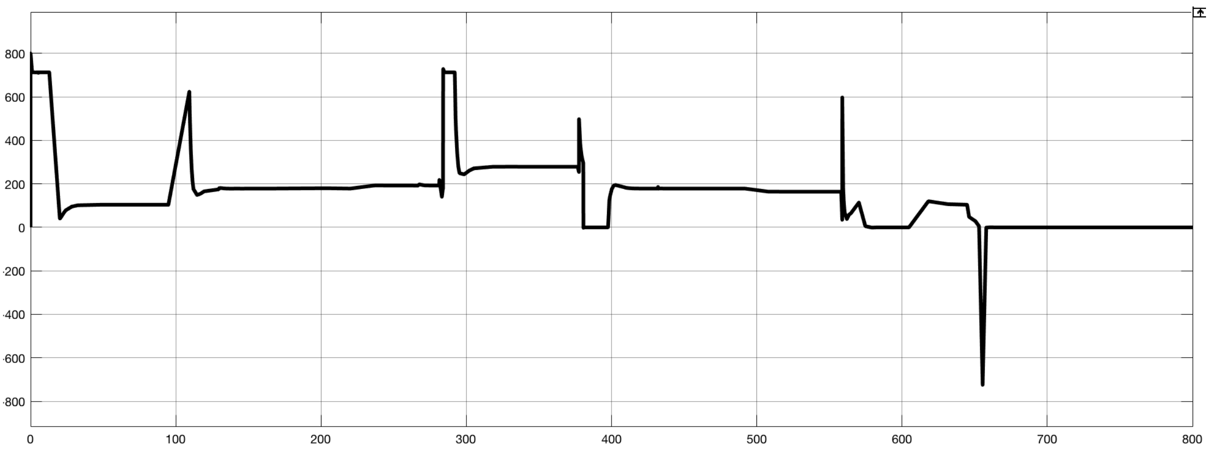
$v_a = v_{a,ref}$ [V] (by assuming ideal power converter)



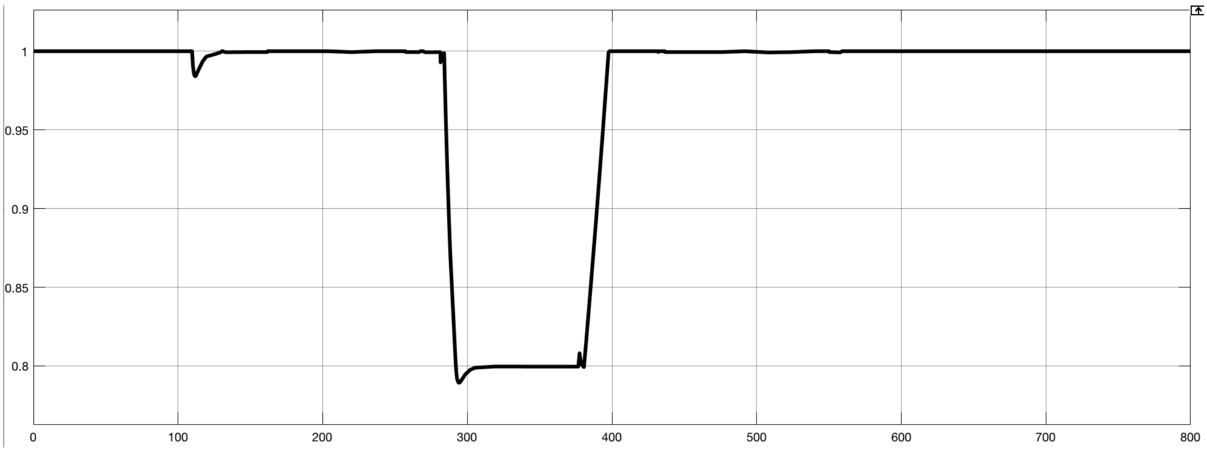
$v_e = v_{e,ref}$ [V] (by assuming ideal power converter)



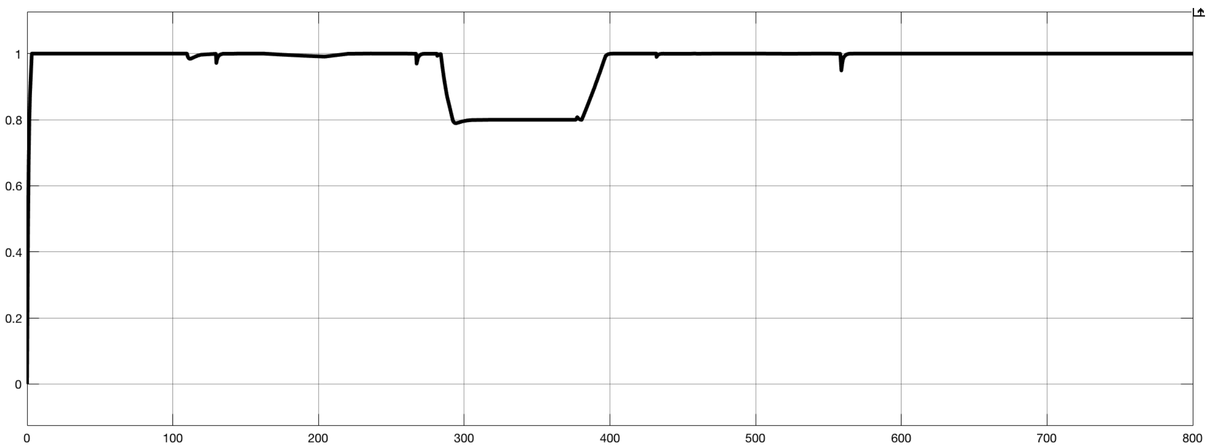
$i_{a,ref}$ [A]



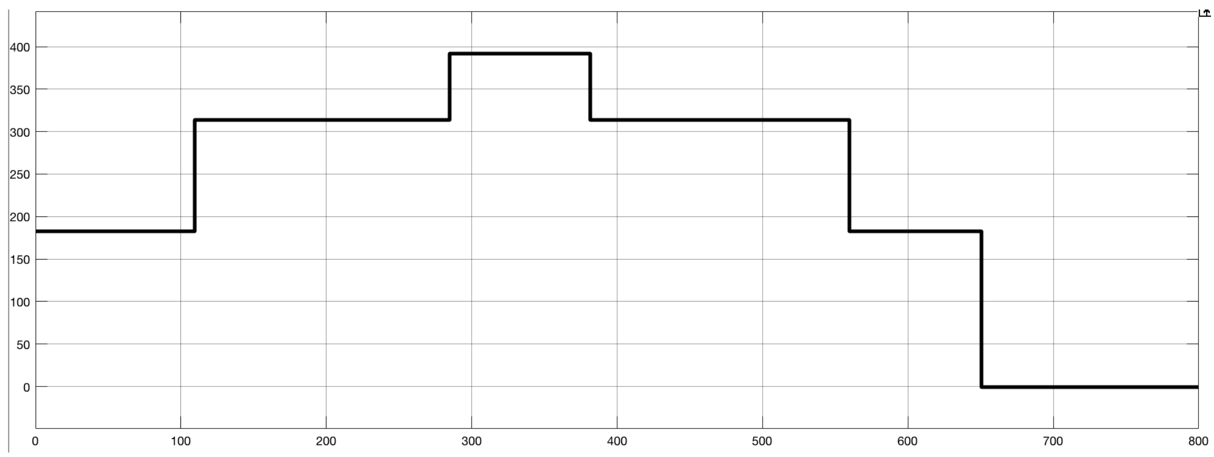
i_a [A]



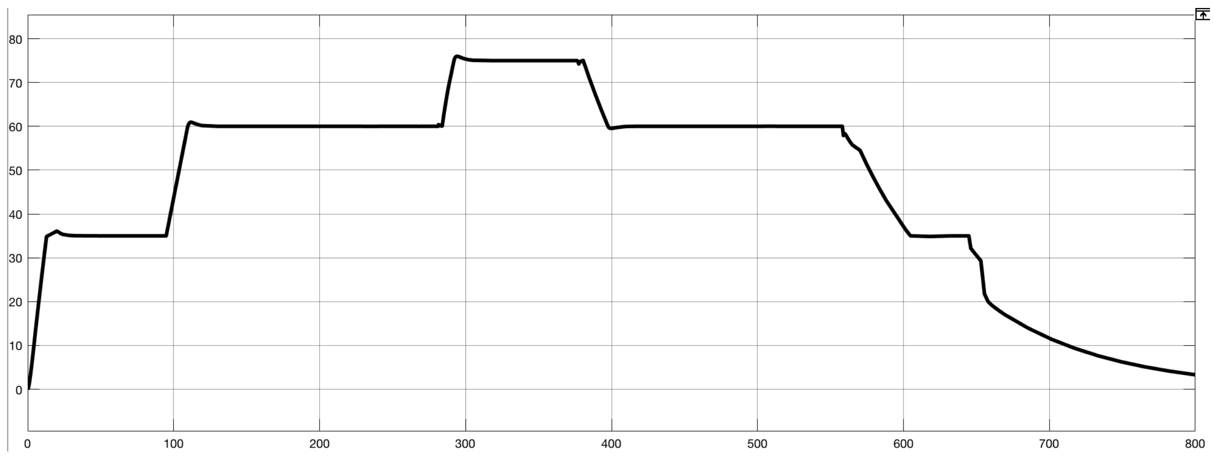
$i_{e,ref}$ [A]



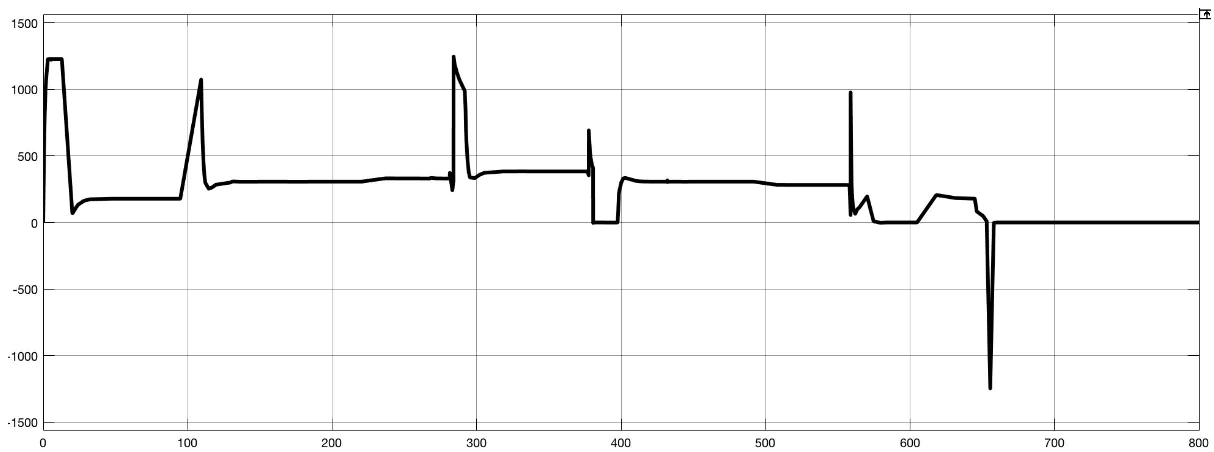
i_e [A]



ω_{ref} [rad/s]



v [km/h]



T_e [Nm]

Conclusion

From the above diagrams we find that the results turn out to be desirable and the field weakening performs well in high speed region. In additional tests (not shown here) it was found that if field weakening was neglected, the 75km/h reference speed could never be reached.