Dynamic of Electrical Machine and Drives

Speed control of a Separately Excited DC Motor

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PROBLEM STATEMENT

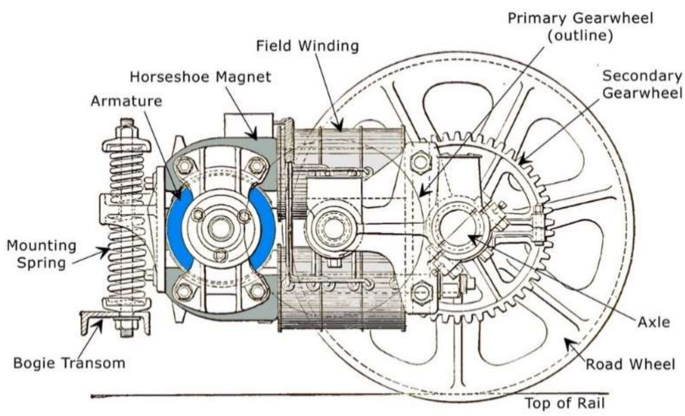
A DC (separately excited) motor is used to move an ATM trailway vehicle “Carrelli 1928” with the following characteristics:

- Line Voltage: V_n = 600V
- Efficiency: η = 0.9 (neglecting excitation losses and iron losses)
- Motor rated speed [rad/s]: ω_n = 314 rad/s
- Motor rated speed [km/h]: v_n = 60 km/h
- Armature circuit time constant: $\tau_a = 10\text{ms}$
- Excitation circuit rated voltage: $V_{e,n} = 120$ V
- Excitation circuit rated current : $I_{e,n}$ = 1 A
- Excitation circuit time constant: $\tau_e = 1\text{s}$
- Tram mass: M_t = 10000 Kg
- Number of passengers: N_p = 200
- Single passenger weight: m_p = 80 Kg
- Time of acceleration: Dt_a = 25s

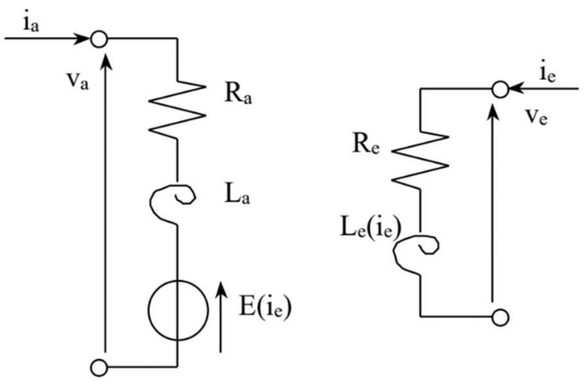
track	slope %	speed
$0-1\,km$	0	$35\ km/h$
$1-3\,km$	0	$60\ km/h$
$3-4\,km$	5%	$60\ km/h$
$4-6\,km$	0	$75\ km/h$
$6-8\,km$	0	$60\ km/h$
$8-9\,km$	-5%	$60\ km/h$
$9-10\,km$	0	$35\ km/h$

REQUESTS:

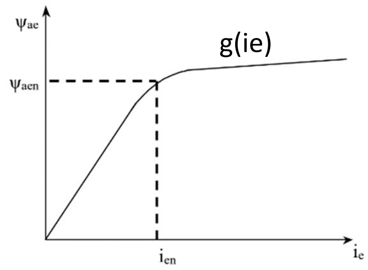
- Find the design parameters of the DC motor according to the data
- Design and simulate speed and current control in order to cover a 10km track considering the Table above (the slope is s%=100tan(ϑ))



DC MOTOR DESIGN PARAMETERS



$$
\begin{cases}
Va = Ra*ia + p\,\Psi a + E \\
Ve = Re*ie + p\,\Psi e \\
\Psi a = La*ia \\
\Psi e = f(ie) \\
\Psi ae = g(ie) \\
E = K*\Psi ae*\Omega m \\
Te = K*\Psi ae*ia \\
Te - Tr = J*\dot{\Omega} m + beta*\Omega m
\end{cases}
$$



We compute it directly on Matlab, so we have all the parameters for the tuning of the controllers and the implementation of the complete Simulink control Scheme:

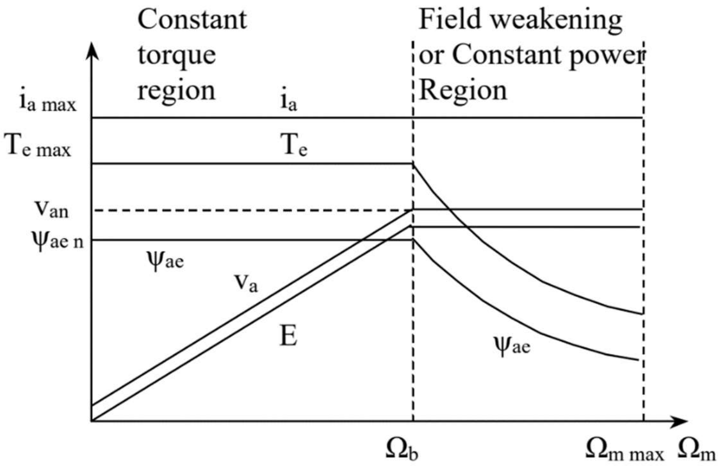
```
%*Data*
Vn=600;       % Line voltage
eta=0.9;      % Efficiency
wn=314;       % Rated speed [rad/s]
vn=60;        % Rated speed [km/h]
tau_a=10e-3;  % Armature time constant
tau_e=1;      % Excitation time constant
Ven=120;      % Excitation rated voltage
Ien=1;        % Excitation rated current
mp=80;        % Mass of std passenger
Np=200;       % Number of passengers
Mt=10000;     % Tramway mass
Dta=25;       % time of acceleration

%*Motor parameters Design*
M=Mt+mp*Np;            % Total mass
v_max=vn*1000/3600;    % Rated speed [m/s]
a=v_max/Dta;           % acceleration
Ftrac=M*a;             % Traction force
Ptrac=Ftrac*v_max;     % Traction power
Ptot=Ptrac + Ptrac/3;  % Total power (friction power 1/3*traction)
Pel=Ptot/eta;          % Electrical power
Tn=Ptot/wn;            % Rated torque
In=Pel/Vn;             % Rated current
K=Tn/(In*Ien);         % DC machine coefficient for Torque and Emf
Ra=(Pel-Ptot)/In^2;    % Armature resistance
La=Ra*tau_a;           % Armature inductance, from time constant
En=eta*Vn;             % Rated emf, from Vn=Ra*In+En and Pel=Vn*In
Re=Ven/Ien;             % Excitation resistance
Le=Re*tau_e;           % Excitation inductance, again from time constant
J=M*v_max^2/wn^2;      % Equivalent inertia of the motor
beta=Ptrac/3/wn^2;     % Damping factor, from Tfric=Pfric/wn=beta*wn
```

a	0.6667
beta	0.9767
Dta	25
En	540
eta	0.9000
Ftrac	1.7333...
Ien	1
In	713.3059
J	73.2507
K	1.7197
La	8.4115...
Le	120
M	26000
mp	80
Mt	10000
Np	200
Pel	4.2798...
Ptot	3.8519...
Ptrac	2.8889...
Ra	0.0841
Re	120
tau_a	0.0100
tau_e	1
Tn	1.2267...
v_max	16.6667
Ven	120
vn	60
Vn	600
wn	314

Before discussing about modelling and control of the system, let’s discuss about the Operating regions of the machine:

It is a representation of the machine limitation in steady state condition, very helpful to understand our feasible control region. In particular for this application we can notice a **problem in 4-6 Km part of the track: the speed is above the rated one** (wn, usually near the so called wb base speed, corresponding to the max reachable speed due to power supply limitations or rated working condition of the machine)

DC OPERATING REGIONS:



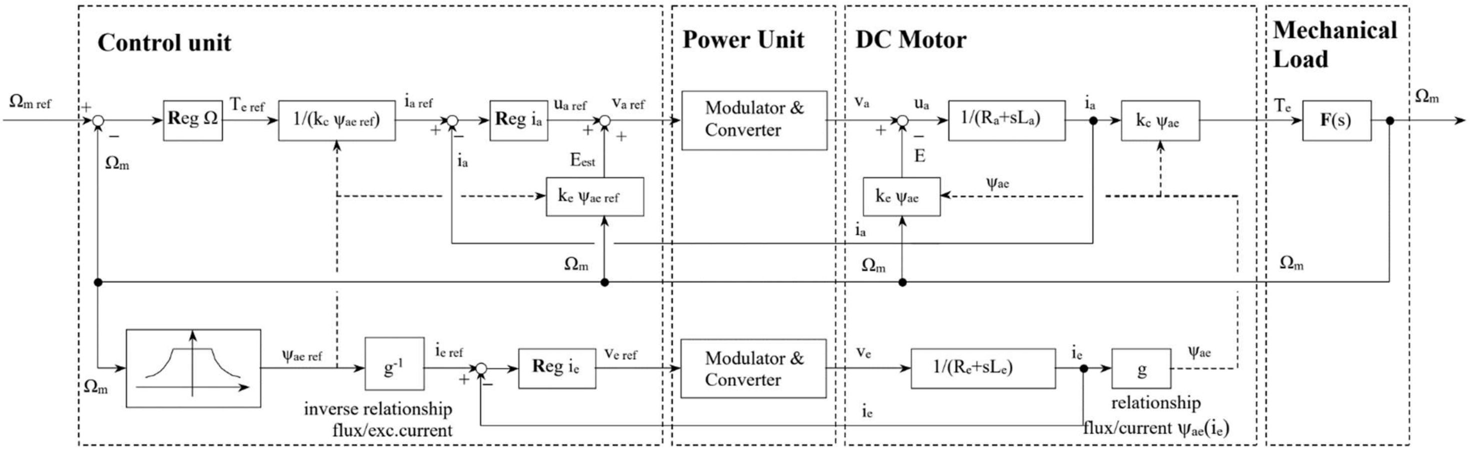
As we can see, it is possible to **work above the base speed** by means of the "Flux weakening" procedure. Obtained with a flux control, which through the control variable (ie) reduce the flux and so limit the e.m.f (not exceeding va limitations),this allow to increase the speed above its limit! If instead we work **below the base speed:** the flux controller maintain Ψae on its rated value (best fe material usage)
(We can manage it in a simplified way)

CONTROL TUNING AND SCHEME

Separately excited DC machine is based on two control schemes acting in parallel with the feedback data:

- Speed/Torque control (based on speed reference, cascade structure)
- Flux control (based on a flux reference managed as explained before)

Overall control scheme:



For our case study we know the speed reference from the table, and we can easily model armature and excitation windings, but also the mechanical load (from J, beta and Tr as gravitational resistive torque using the track slope and total tram mass). We will discuss other implementation issues (like the flux dynamic g inversion) later on when we will have to model it on Simulink.
Now we focus on the tuning of the PI Regulators for speed, armature current and excitation current, that can be computed using usual PI tuning procedure, with some assumptions to make the tuning affordable in a simple way.

An easy PI tuning approach is by cancellation, using the regulator zero to cancel the downstream system TF pole, and add a useful integral action. The relevant aspect of it is the "downstream" system seen by each regulator:

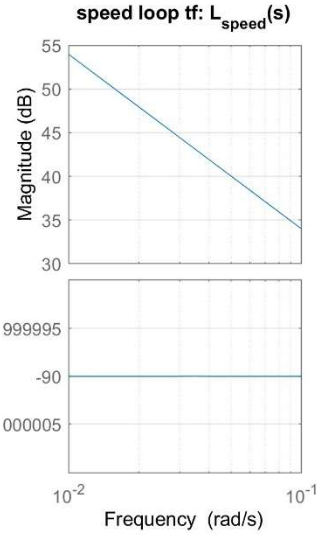
- Reg(ia): inner loop (must be 10 times faster than the outer one, this information helps us on the choice of the cut off frequency), assuming good compensation, fast power supply and good sensors with negligible delay. This can be tuned on armature windings TF, Ga(s) = 1/(Ra+s*La)
- Reg(Ω): much slower than inner loop, that can be considered as a unitary gain (if weel tuned), so neglected. Tuned on the mechanical load TF F(s) = 1/(beta+J*s)
- Reg(ie): tuned on the excitation windings TF Ge(s) = 1/(Re+s*Le)

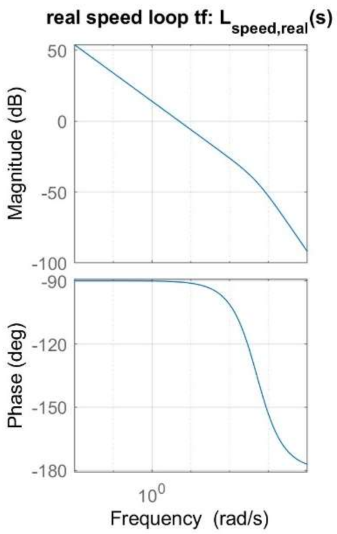
Once discussed the general aspect, let's make the computations in Matlab:

```
%*CONTROL TUNING*
%TF (if we need some testing on bode diagram)
s=tf('s');
Ga = 1/(Ra + s*La);  % Armature winding tf (ia responce)
F  = 1/(beta + s*J); % mechanical load (speed responce)
Ge = 1/(Re + s*Le);  % excitation winding tf (ie response)
tauF = J/beta;       % time constant of mechanical load
%TUNING:

% Aramture current controller:
% notice,all PI tuned by cancellation, imposing the cut off frequency
% according to our design choice and obtaining approximatively 90
% deg of phase margin!
new_tau = tau_a/5;   % make 5 times faster than electric dynamic
wc_i = 1/new_tau;     % current loop cut off frequency
kp_a = wc_i*La;
ki_a = wc_i*Ra;
Reg_ia = kp_a + ki_a/s;

% Speed controller:
wc_o = wc_i/100;  % nested loop thumb rule, inner loop at least 10 times faster
kp_speed = wc_o*J;
ki_speed = wc_o*beta;
Reg_speed = kp_speed + ki_speed/s;

% Excitation current controller:
wc_e = wc_i/10; % make it 10 times slower than armature winding
kp_e = wc_e*Le;
ki_e= wc_e*Re;
Reg_ie = kp_e + ki_e/s;

%*CONVERSION CONSTANT*
C1=v_max/wn; %from [rad/s] to [m/s]
C2=wn/vn;  % from [km/h] to [rad/s]
```

Useful later on for the Simulink scheme. C1 to go from Force to Torque while C2 to convert from linear to angular speed

SOME COMMENTS ON THE TUNING RESULTS:





Comparing the resultant speed loop transfer function (used to check performance):

Approximated) with inner loop considered as unitary gain

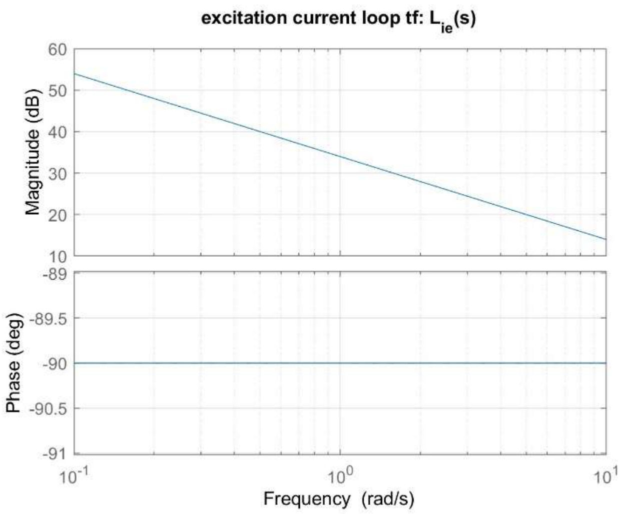
```
L_speed = F*Reg_speed;
```

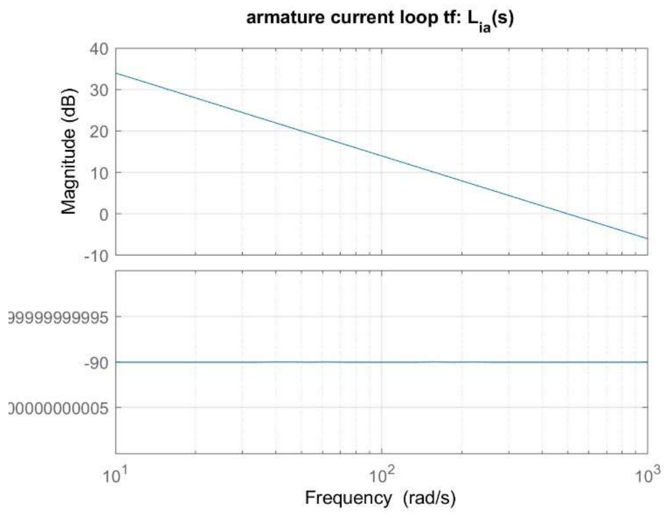
“Real”) including the inner loop

```
L_speed_real = F*Reg_speed*(L_ia/(1+L_ia));
```

As we can see, in the bandwidth of our interest for the mechanical world (we set up an wc_o = 5Hz) the real one behaves like the approximated one.

Checking the resultant loop transfer function obtained by the current controllers, the performance are as we expected

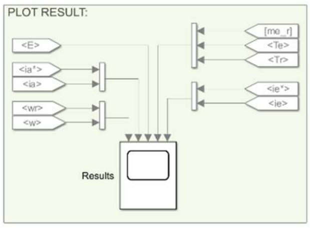


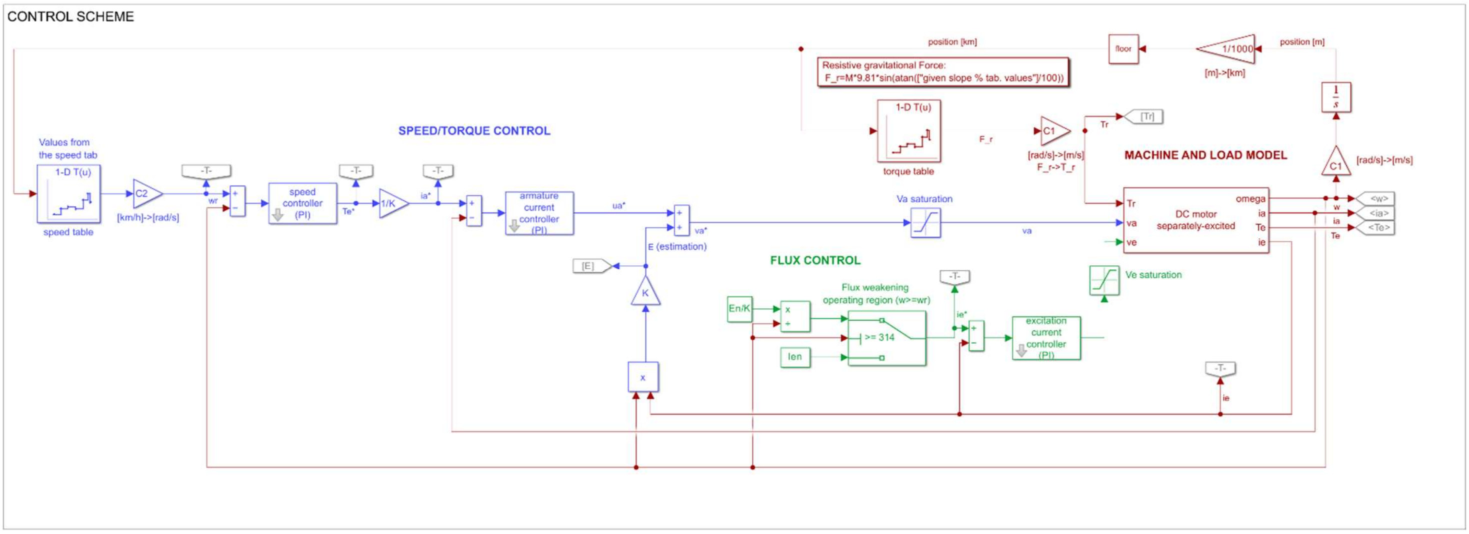


Now that we have all the necessary parameters in terms of system model and controllers, we can finally implement the Simulink scheme to simulate our result!

SIMULINK SCHEME IMPLEMENTATION

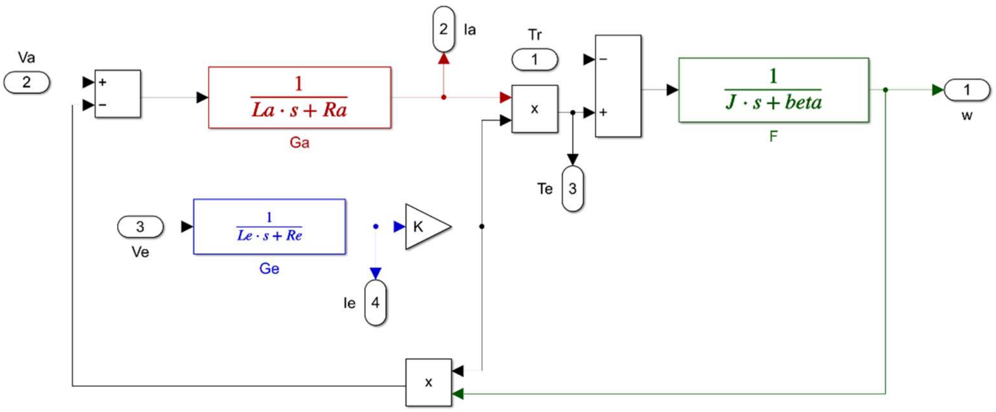
First, the overall scheme is :





Now Let's zoom in on the most interesting blocks:

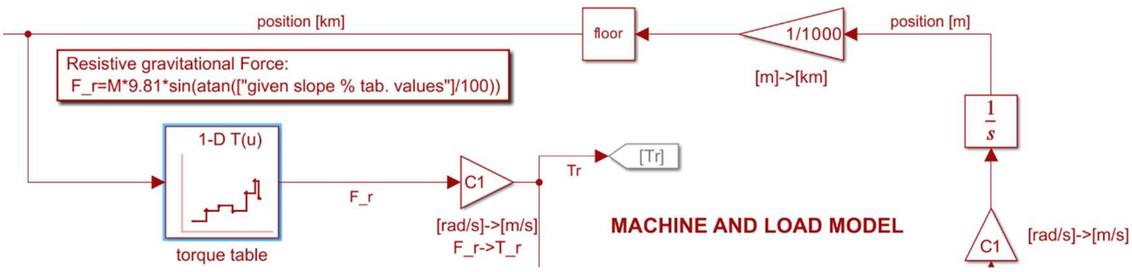
SYSTEM AND LOAD MODEL:



Laplace domain of the dynamical model of the system, including the Resistive torque (acting as a disturbance to compensate) and the mechanical load model

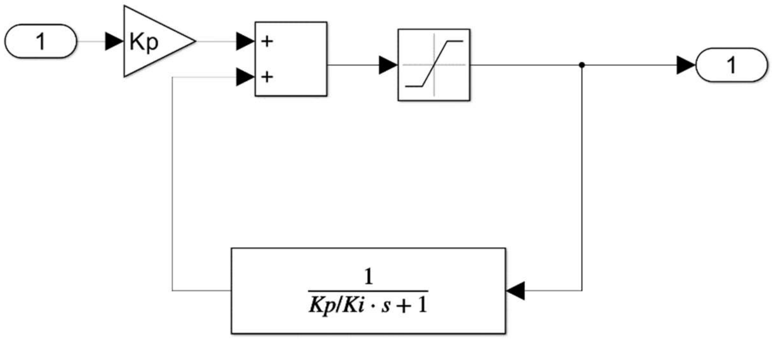
Where the resistive torque is purely resistive and it is given by the resistive force multiplied by a proper scaling factor (C1):

Fr = M*9.81*sin(theta) is the only resistive force, found as force parallel to the ground due to the overall weight of the tram, where the values of theta is taken from the slope of the current track, properly identified by speed integration.



(Resistive torque computation)

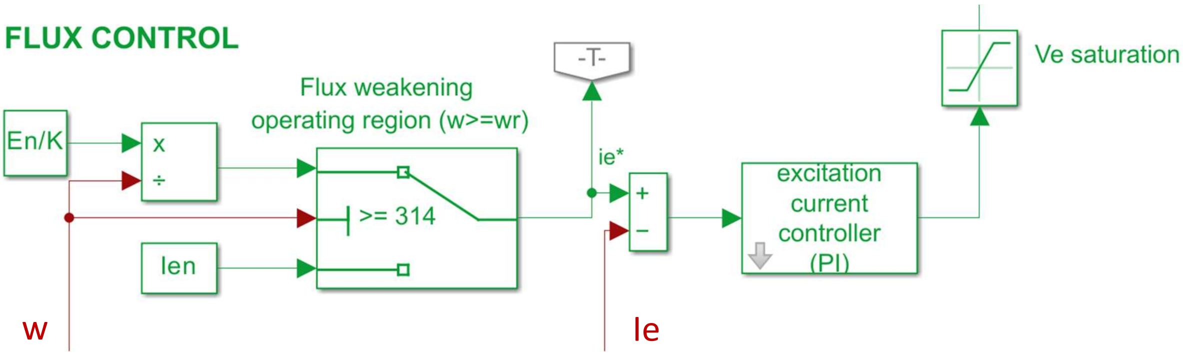
PI CONTROLLERS: ANTI-WINDUP AND SATURATIONS



Each PI regulator internally is made with an anti-windup strategy (using the control parameters found) where the SATURATION block is limited on the control variable limits, for example:
Reg_ia acts on ua, which is limited in between [-(Vn-En);Vn-En]

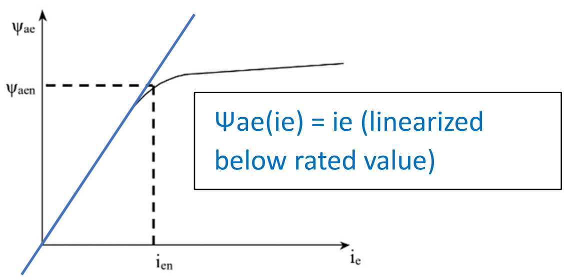
And we also need to add additional saturation to model the Power Supply limitations in for Ve and Va.

EXCITATION CONTORL, FLUX WEAKENING AND OPERATING REGIONS:

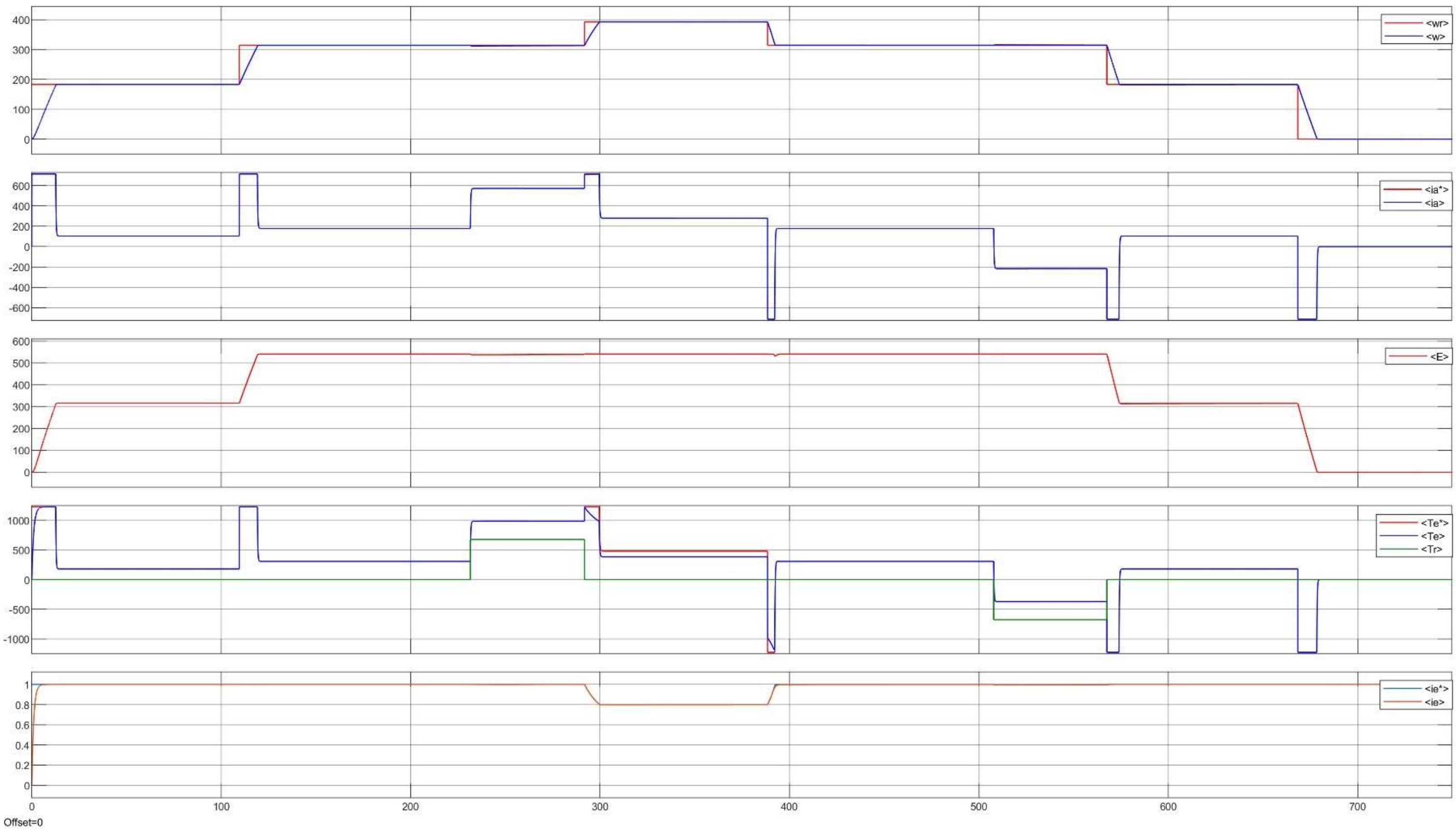


As discussed before, we need to manage the possibility to have a speed request higher than the rated one (in our case coincide with the base speed, because we compute the parameters in such a way that Vamax coincide with Van).
We identify the working region with a simple condition based selector, which decide between

$$\begin{cases} Ie = Ie_n & w < w_n \\ Ie = \frac{E_n}{K*w} & w > w_n \end{cases}$$

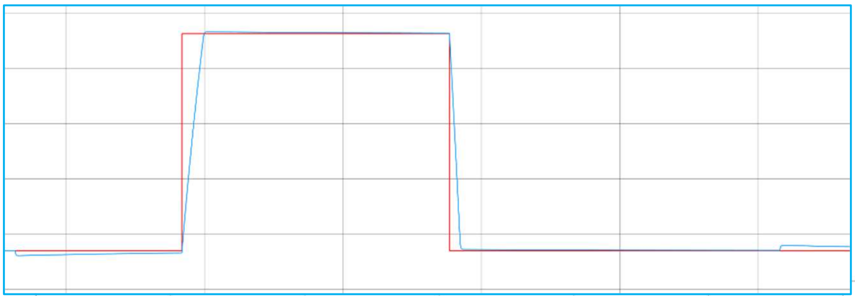


RESULTS OF SIMULATION

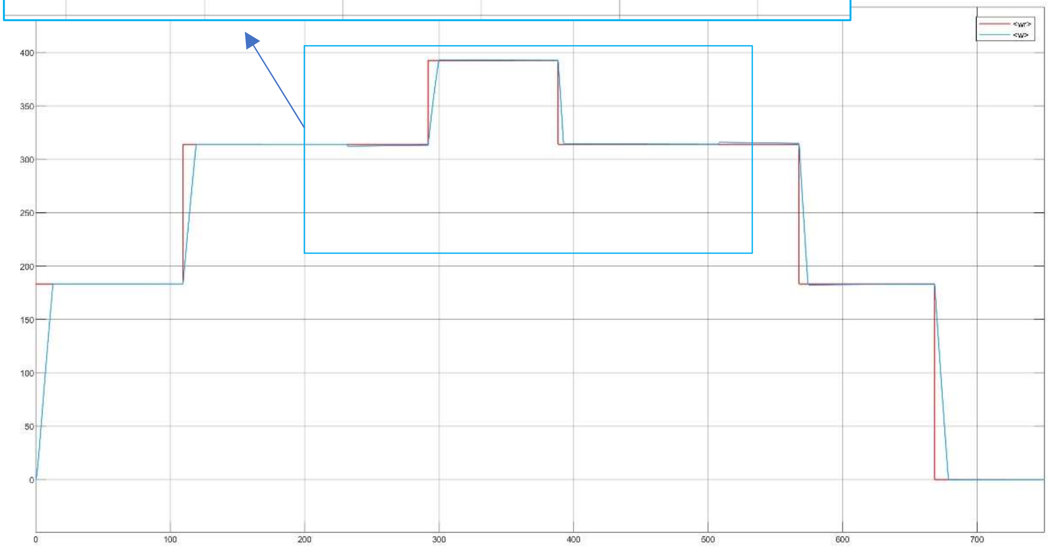


From a first check the results seems very good!
We can make some comments on this final results:

- **SPEED**

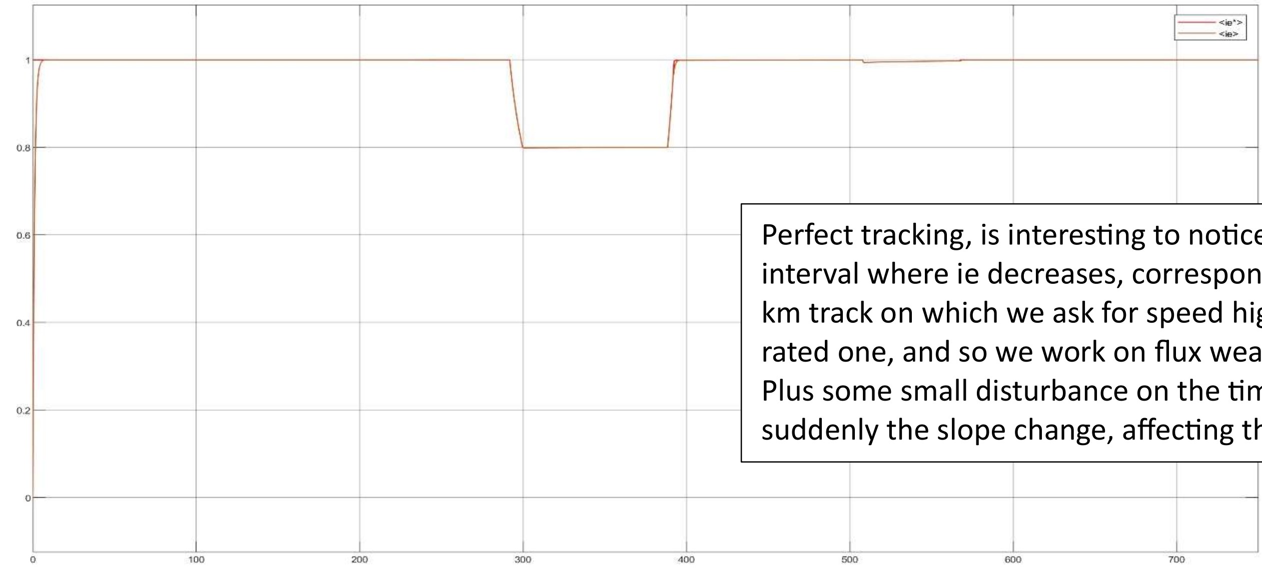


We can see a good tracking (with some delay due to the real mechanical dynamic modelled, so a real slope on the signal instead of a step)



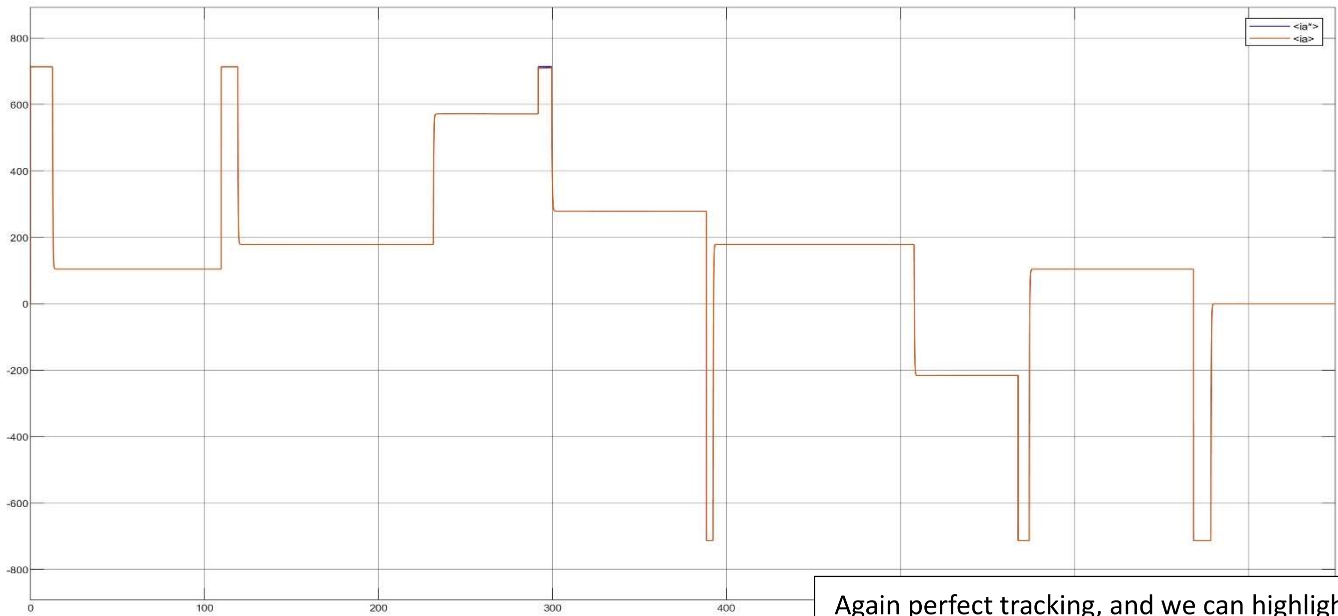
the only “Strange” behaviors appear on this points where we zoom in, where we can perceive some overshoot which are obvious due to the slope change, so the resistive torque disturbance, that we kill rapidly

- **EXCITATION CURRENT**



Perfect tracking, is interesting to notice the time interval where ie decreases, corresponding to the 4-6 km track on which we ask for speed higher than the rated one, and so we work on flux weakening region. Plus some small disturbance on the time instant where suddenly the slope change, affecting the system.

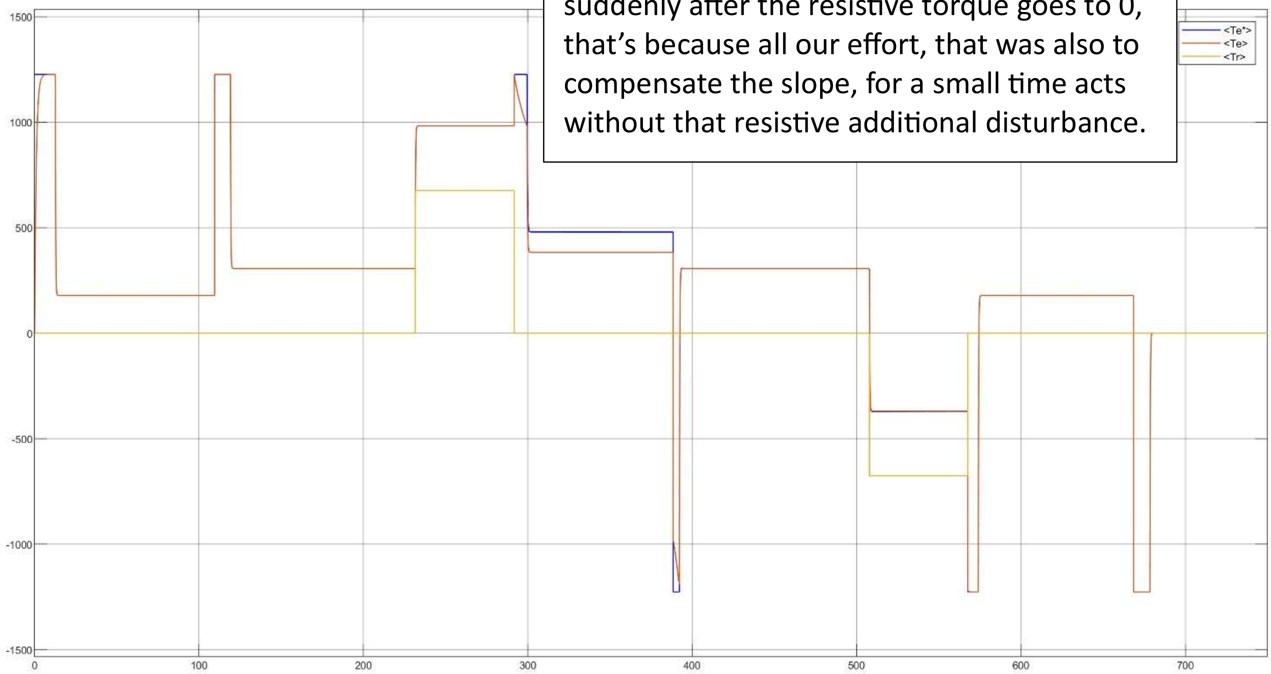
- **ARMATURE CURRENT**



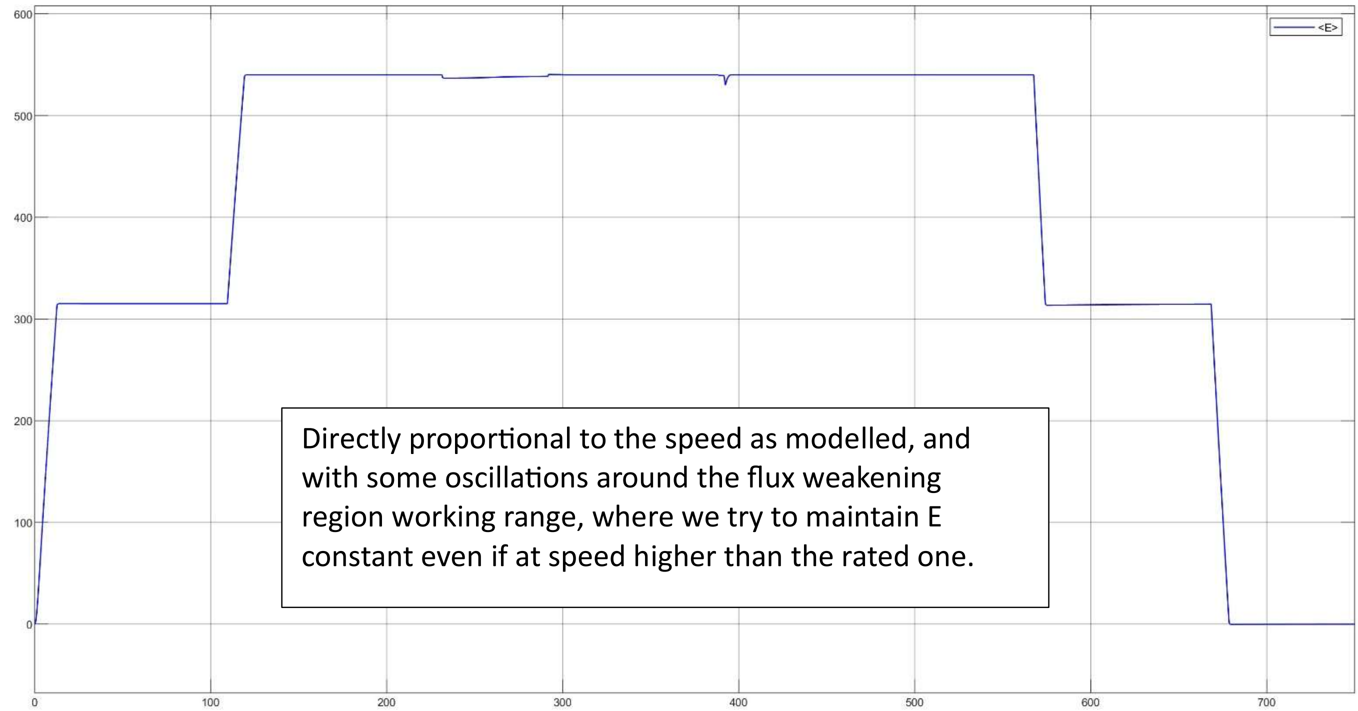
Again perfect tracking, and we can highlight that whenever we ask for an higher speed, the system accelerate (increase the torque) by applying max current (rated one). And drops negative when we need to decrease rapidly the torque (decelerate)

- **TORQUE**

This match the armature current behavior as discussed before. Negative when we need to decelerate. We can notice a torque pick suddenly after the resistive torque goes to 0, that's because all our effort, that was also to compensate the slope, for a small time acts without that resistive additional disturbance.



- **ELECTROMOTIVE FORCE**



Directly proportional to the speed as modelled, and with some oscillations around the flux weakening region working range, where we try to maintain E constant even if at speed higher than the rated one.