VHDL-AMS MODELING AND SIMULATION OF A PMSM CONTROL SYSTEM FOR AUTOMOTIVE APPLICATIONS

Master thesis

Source: www.forococheselectricos.com

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Motivation: Why electric cars?

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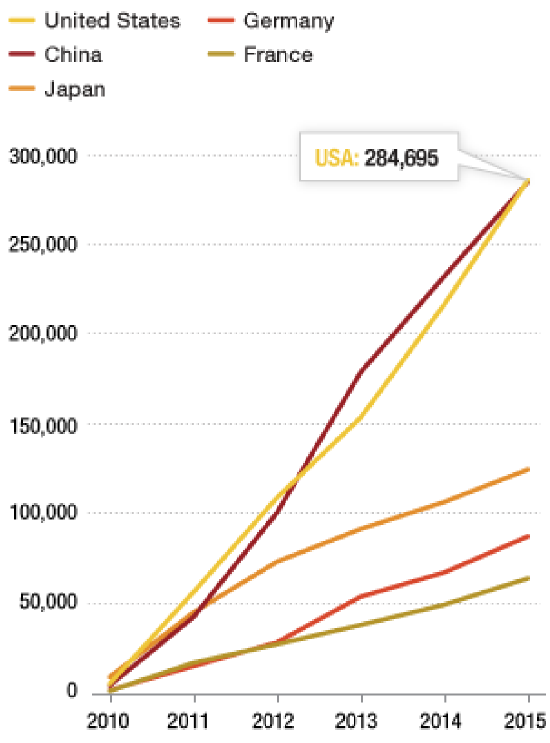
Transportation solution

- Energy efficient
- Environmentally friendly
- Reduce energy dependence

Engineering "toy"

- Performance benefits
- Easy and revolutionary



Projected electric vehicle and plug-in hybrid sales
Source : Pike research

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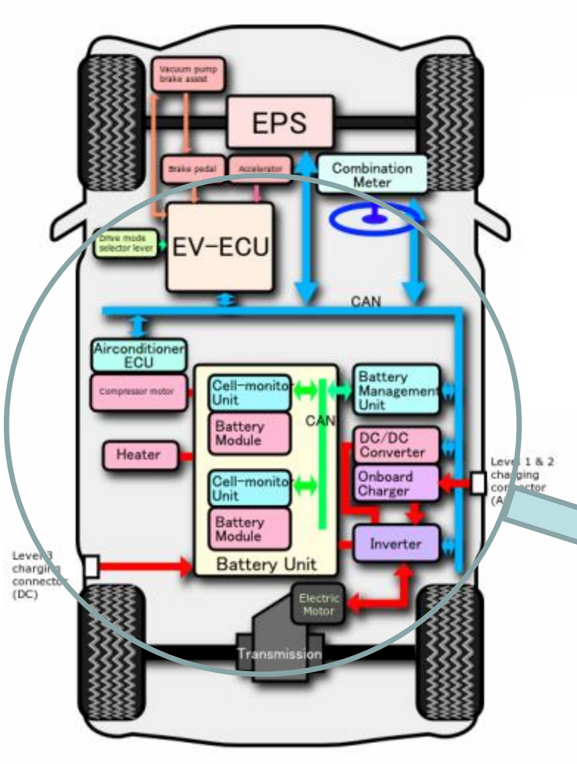
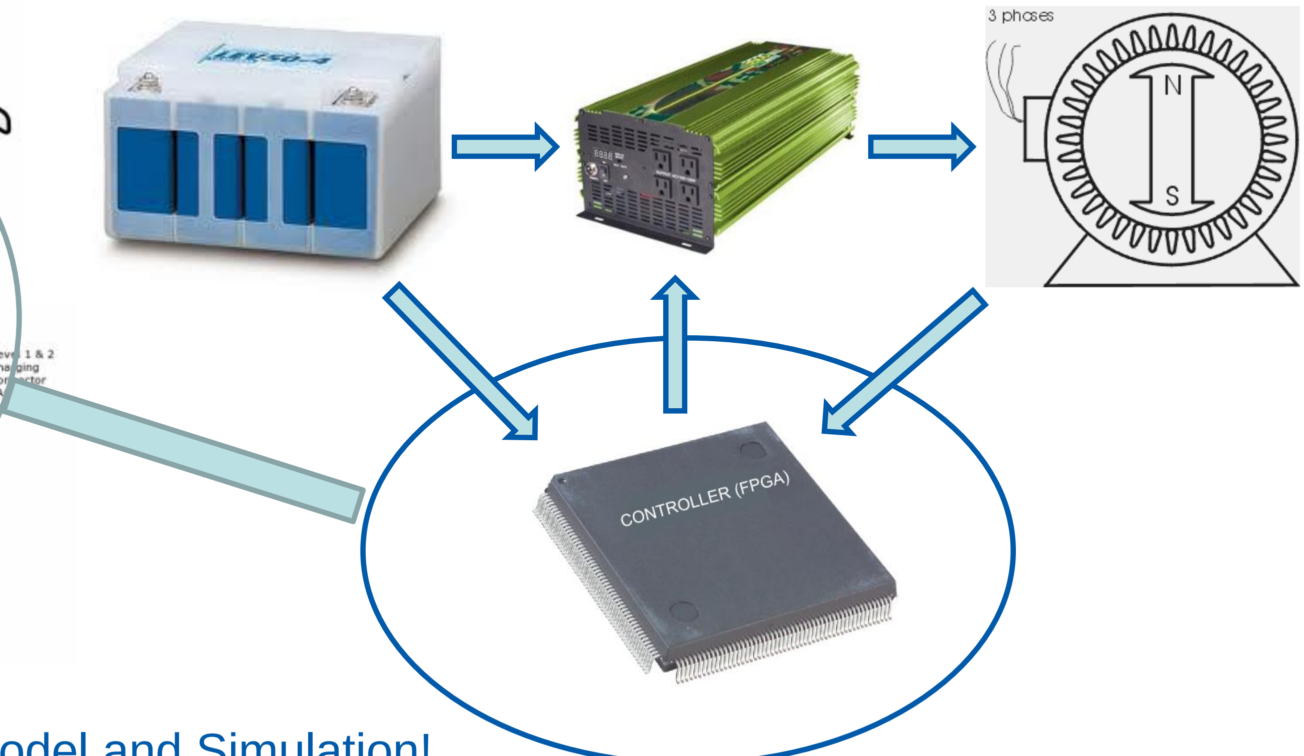
Scope of the thesis



Source : Wikipedia



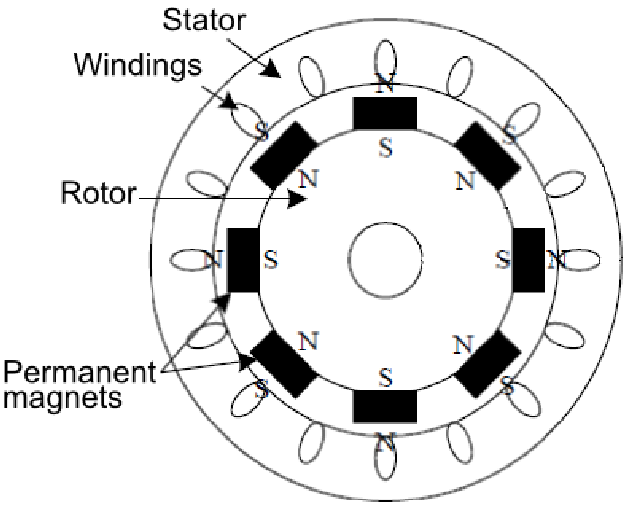
First step: Model and Simulation!

General concepts: PMSM

- Main problem: Non-linear model, difficult to control

$$\begin{bmatrix} v_{as} \\ v_{bs} \\ v_{cs} \end{bmatrix} = \begin{bmatrix} r_s & 0 & 0 \\ 0 & r_s & 0 \\ 0 & 0 & r_s \end{bmatrix} \cdot \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \frac{d}{dt}\left(\begin{bmatrix} L_{aas} & L_{abs} & L_{acs} \\ L_{bas} & L_{bbs} & L_{bcs} \\ L_{cas} & L_{cbs} & L_{ccs} \end{bmatrix} \cdot \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix} + \lambda_m \begin{bmatrix} \sin(\theta_r) \\ \sin\left(\theta_r - 2\pi/3\right) \\ \sin\left(\theta_r + 2\pi/3\right) \end{bmatrix} \right)$$

Park transformation



SPMSM

- Solved: Easy model, easy to control.

$$v_{ds}^r = r_s i_{ds}^r + L_d \frac{d}{dt} i_{ds}^r - \omega_r L_q i_{qs}^r$$

$$v_{qs}^r = r_s i_{qs}^r + L_q \frac{d}{dt} i_{qs}^r + \omega_r L_d i_{ds}^r + \omega_r \lambda_m$$

SPMSM advantage: Ld = Lq

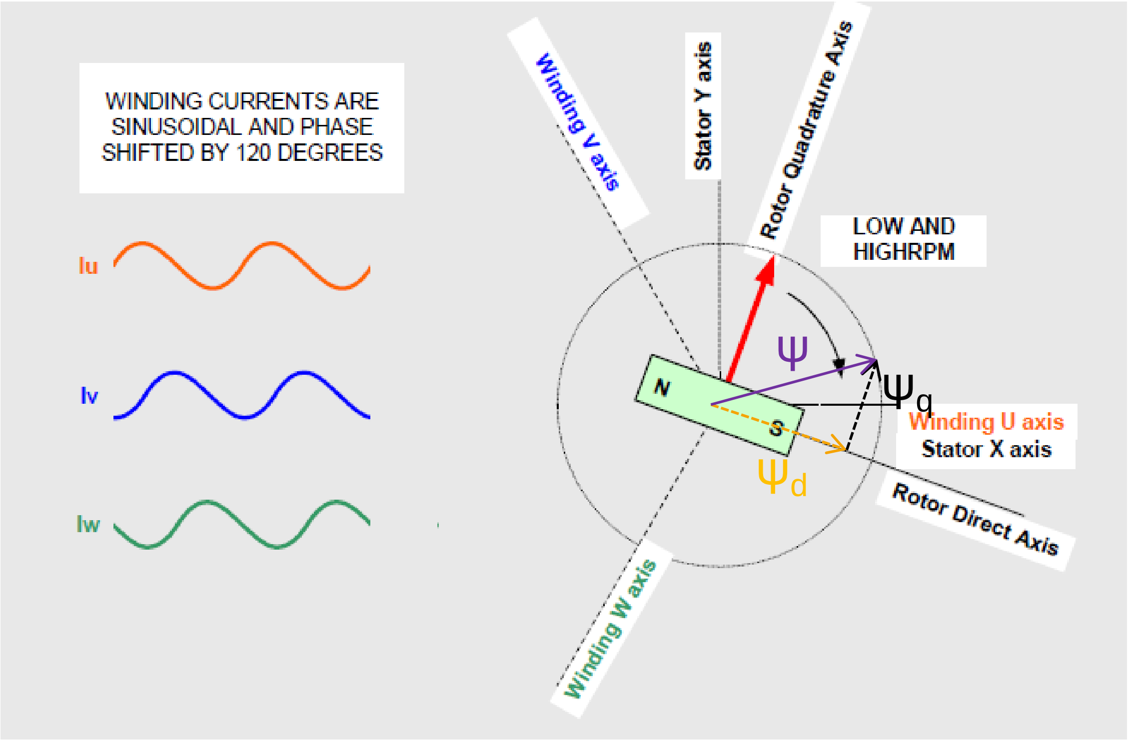
$$T_e = \frac{3}{2}\frac{n}{2}\lambda_m i_{qs}^r$$

Reminds DC motor controls!

General concepts: FOC

- Stator currents create a rotating flux
- Rotor (perm. Mag) presents a field, too
- Interaction between fields: movement!
- GOAL OF CONTROL:

Maximum torque, decoupling currents in d, q - reference



Source: Copey controls corporation – Article: What is Field Oriented Control and what good is it

General concepts: Control scheme

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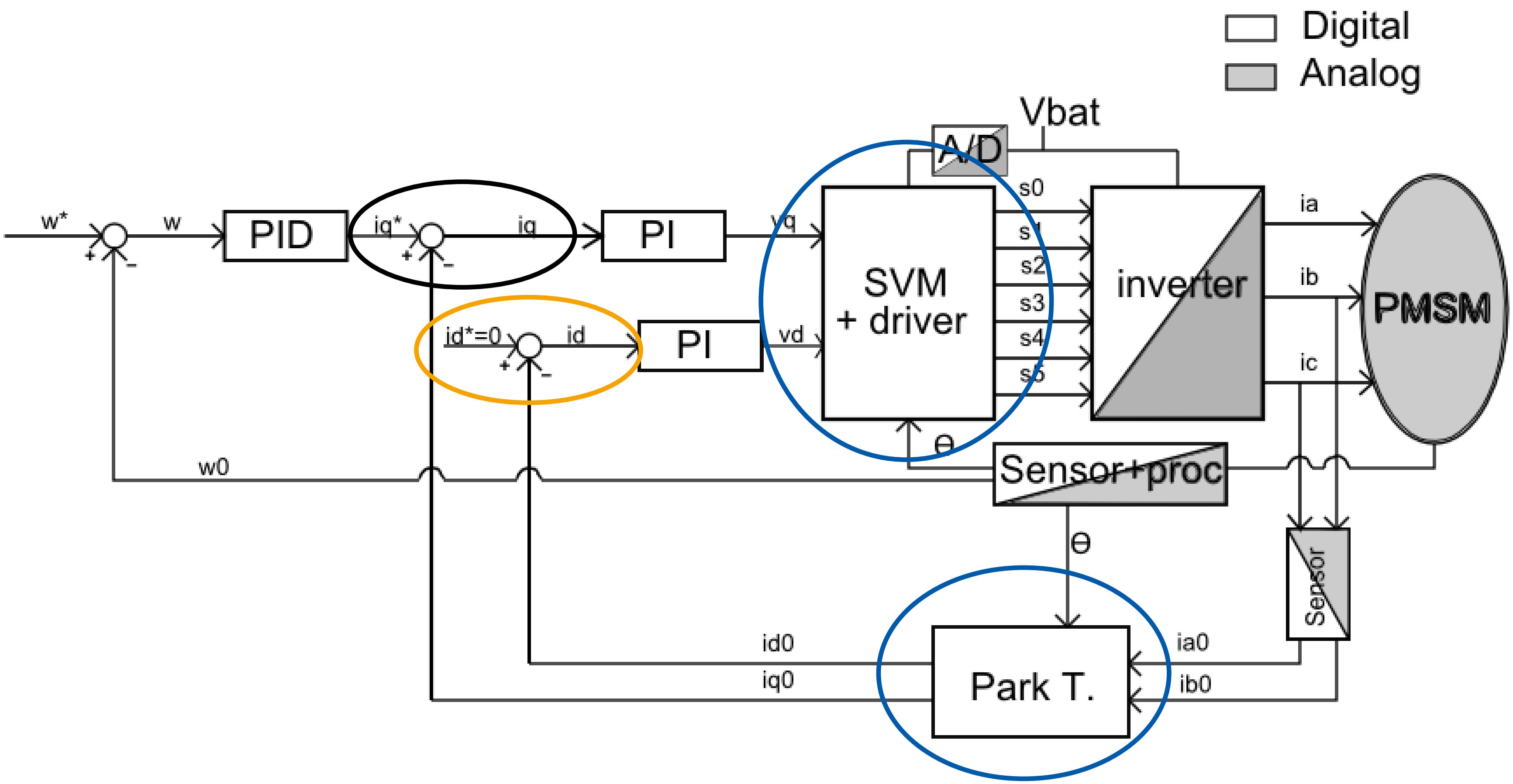

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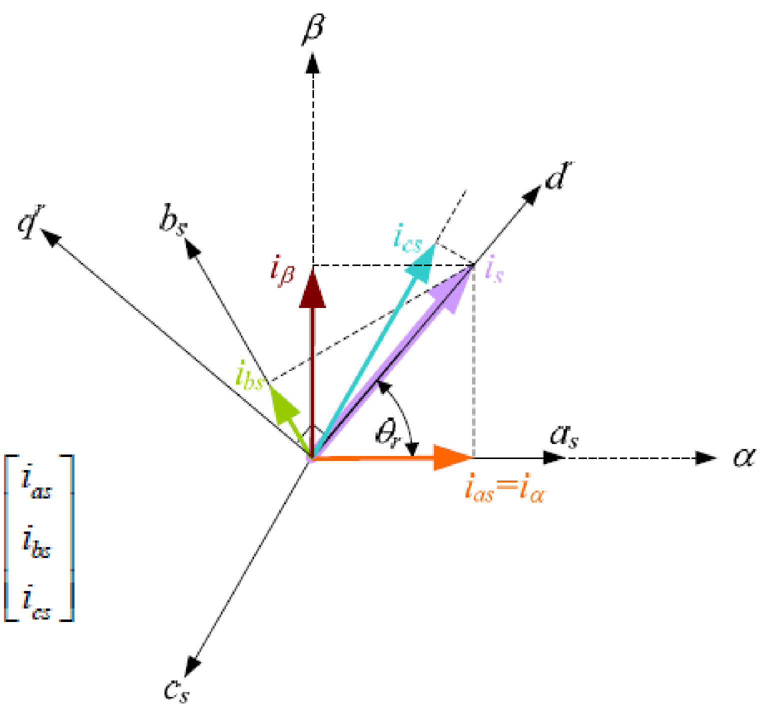
General concepts: Park transformations

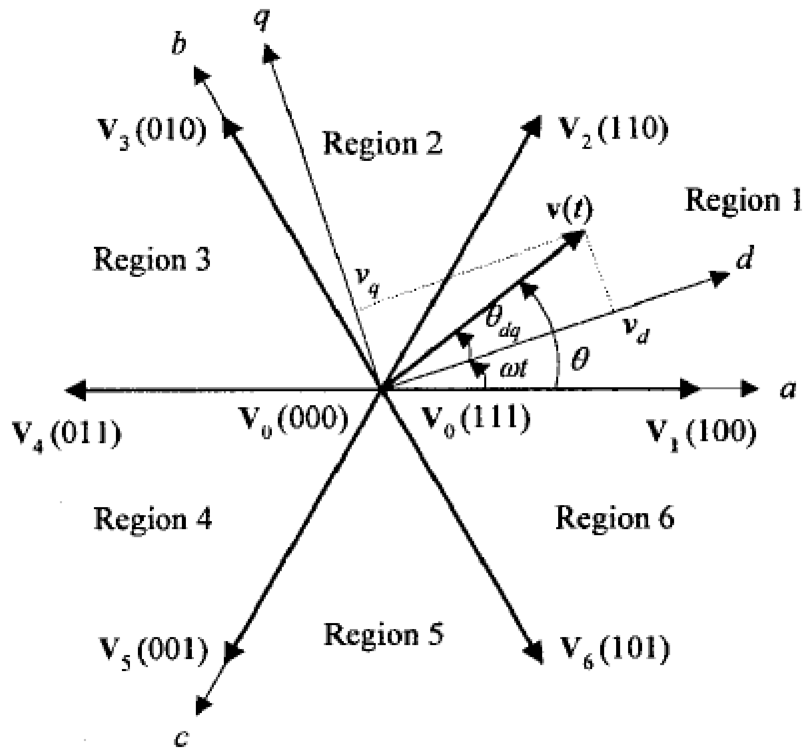
- Park = Clarke+ Rotation
- Clarke = Orthogonal system

$$\begin{bmatrix} i_0 \\ i_d \\ i_q \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1/2 & 1/2 & 1/2 \\ \cos\theta_r & \cos(\theta_r - 2\pi/3) & \cos(\theta_r + 2\pi/3) \\ -\sin\theta_r & -\sin(\theta_r - 2\pi/3) & -\sin(\theta_r + 2\pi/3) \end{bmatrix} \cdot \begin{bmatrix} i_{as} \\ i_{bs} \\ i_{cs} \end{bmatrix}$$



General concepts: Space vector modulation (I)

- Controls the switches of the driver
- Uses Vbat, Vd, Vq and the angle of rotation to calculate the conducting time of each transistor
- Depending on the zero vectors selected, different THD and losses



Source: "An Effective Software Implementation of the Space-Vector Modulation", Jang-Hyoun Youm and Bong-Hwan Kwon

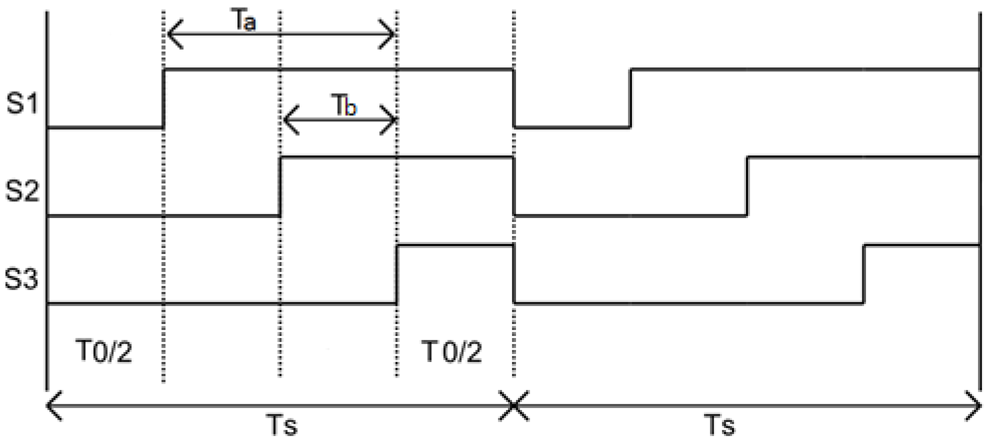
General concepts: Space vector modulation (II)

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \cos \omega t & -\sin \omega t \\ \sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

$$v_{\min} = \min(v_{ao}, v_{bo}, v_{co})$$
$$v_{\max} = \max(v_{ao}, v_{bo}, v_{co})$$

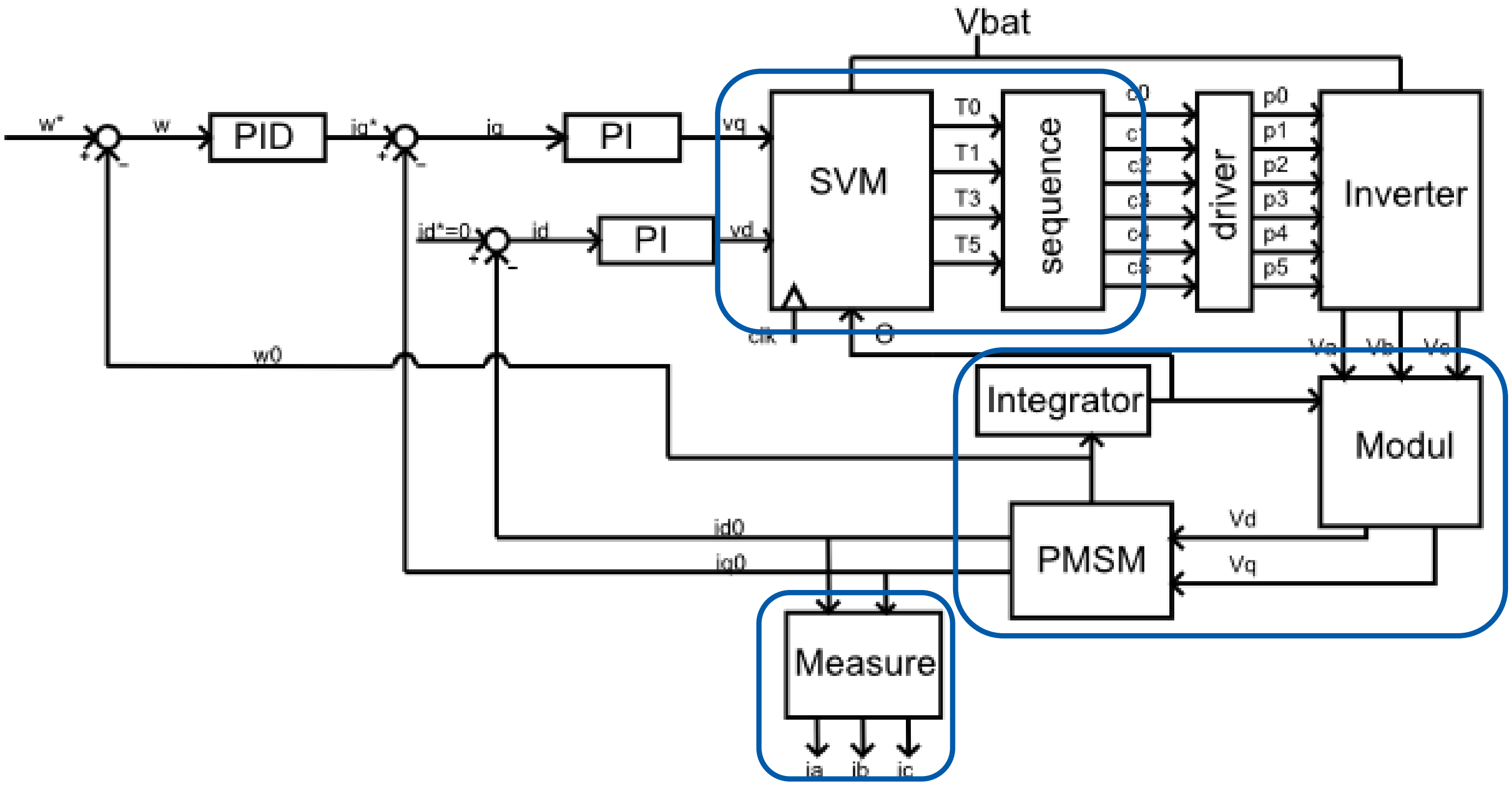
$$\begin{bmatrix} T_a \\ T_b \\ T_c \end{bmatrix} = \frac{T_s}{V_d} \begin{bmatrix} v_{ao} - v_{\min} \\ v_{bo} - v_{\min} \\ v_{co} - v_{\min} \end{bmatrix}$$

$$T_0 = T_s - \frac{T_s}{V_d}(v_{\max} - v_{\min}).$$



Right aligned scheme. (000) and (111) share T0

Solution: Simplifications in control scheme



Solution: Implementation SVM

```
  calcul: process is

   variable va, vb, vc, vmax, vmin: real;

  begin

  va := calcul_va(Vd, Vq, wt);
  vb := calcul_vb(Vd, Vq, wt);
  vc := calcul_vc(Vd, Vq, wt);

  vmax := max(va,vb,vc);
  vmin := minim(va, vb, vc);

  T0 <= Ts - Ts*(vmax-vmin)/Vdc;
  T1 <= Ts*(va-vmin)/Vdc  ;
  T3 <= Ts*(vb-vmin)/Vdc  ;
  T5 <= Ts*(vc-vmin)/Vdc  ;

  wait on clk;

 end process calcul;

end architecture PMSM;
```

$$\begin{bmatrix} v_{ao} \\ v_{bo} \\ v_{co} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \cos \omega t & -\sin \omega t \\ \sin \omega t & \cos \omega t \end{bmatrix} \begin{bmatrix} v_d \\ v_q \end{bmatrix}$$

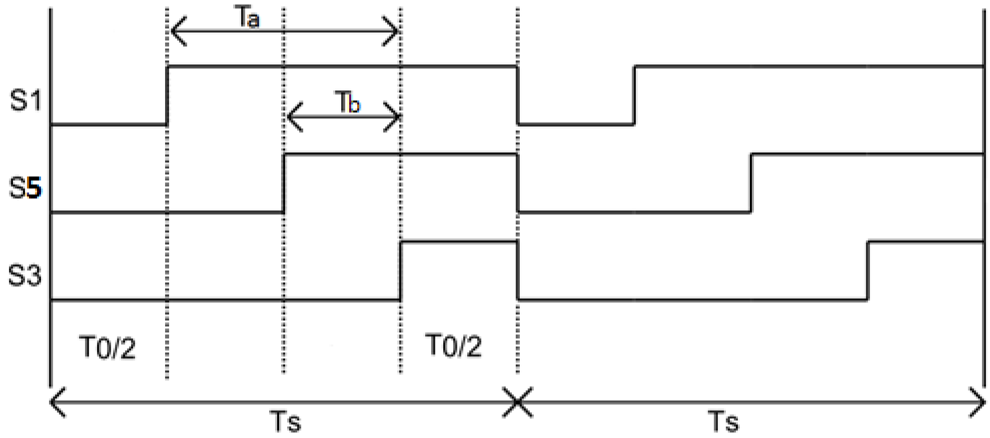
$$v_{\max} = \max(v_{ao}, v_{bo}, v_{co})$$
$$v_{\min} = \min(v_{ao}, v_{bo}, v_{co})$$

$$T_0 = T_s - \frac{T_s}{V_d}(v_{\max} - v_{\min}).$$

$$\begin{bmatrix} T_a \\ T_b \\ T_c \end{bmatrix} = \frac{T_s}{V_d} \begin{bmatrix} v_{ao} - v_{\min} \\ v_{bo} - v_{\min} \\ v_{co} - v_{\min} \end{bmatrix}$$

Solution: Implementation sequence

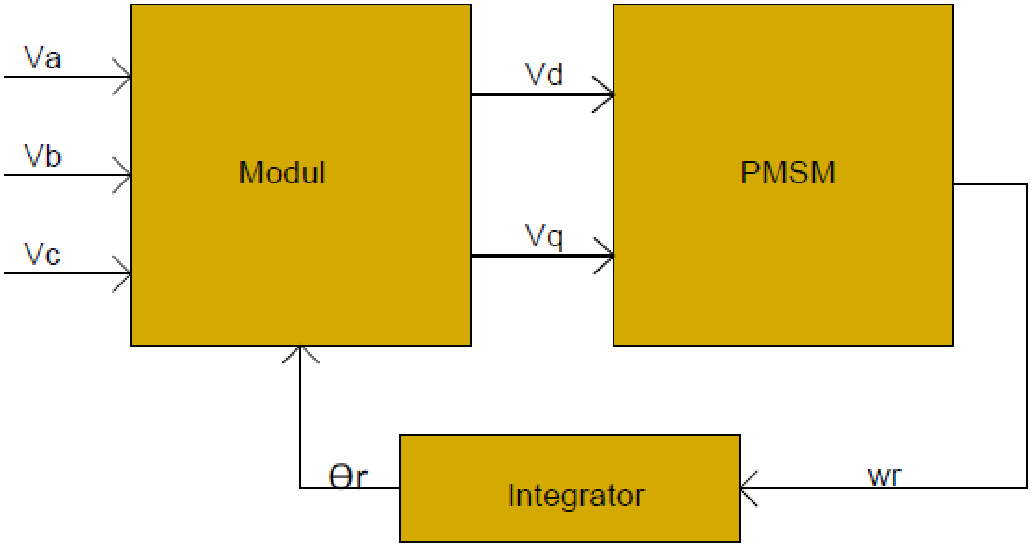
```
maxim := max (T1, T3, T5);
min := minim (T1, T3, T5);

c1 <= '0'; c3 <= '0'; c5 <= '0';
c0 <= '1'; c2 <= '1'; c4 <= '1';
wait for T0/2.0;

if maxim = T1 and min = T3 then

  c1 <= '1'; c3 <= '0'; c5 <= '0';
  c0 <= '0'; c2 <= '1'; c4 <= '1';
   wait for (T1-T5);
  c1 <= '1'; c3 <= '0'; c5 <= '1';
  c0 <= '0'; c2 <= '1'; c4 <= '0';
   wait for T5;
  c1 <= '1'; c3 <= '1'; c5 <= '1';
  c0 <= '0'; c2 <= '0'; c4 <= '0';
  wait for T0/2.0;
```



Solution: Motor model (I)

- Integrator:

```
theta_e == we'integ ;
```



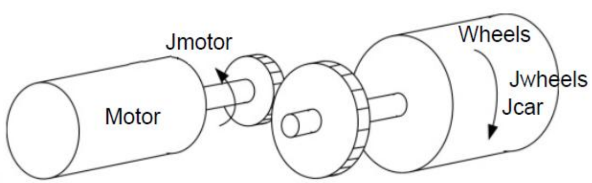
- Modul

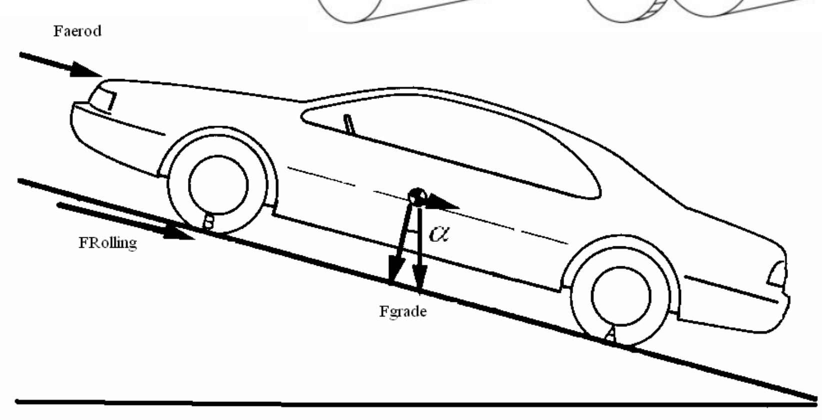
```
Vq == (2.0/3.0)* (cos(theta_e)*Va + cos(theta_e-math_2_pi/3.0)*Vb + cos(theta_e+math_2_pi/3.0)*Vc);
Vd == (2.0/3.0)* (sin(theta_e)*Va + sin(theta_e-math_2_pi/3.0)*Vb + sin(theta_e+math_2_pi/3.0)*Vc);
```

Solution: Motor model (II)

- PMSM:

```
 IF domain = quiescent_domain USE
  wm == 0.0;
ELSE
  tau_e == tau_load + J*(wm'dot);
END USE;
```





$$\tau_e = \tau_{load} + J\frac{dw_m}{dt}$$

$$w_r = \frac{p}{2}\cdot w_m$$

$$F_{rolling} = f\cdot M\cdot g$$

$$F_{grade} = M\cdot g\cdot \sin(\alpha)$$

$$F_{aerod} = \frac{1}{2}\cdot Cx\cdot S\cdot ls\cdot v^2$$

$$\tau_{load} = R_{wheels}\cdot(F_{rolling} + F_{grade} + F_{aerod})$$

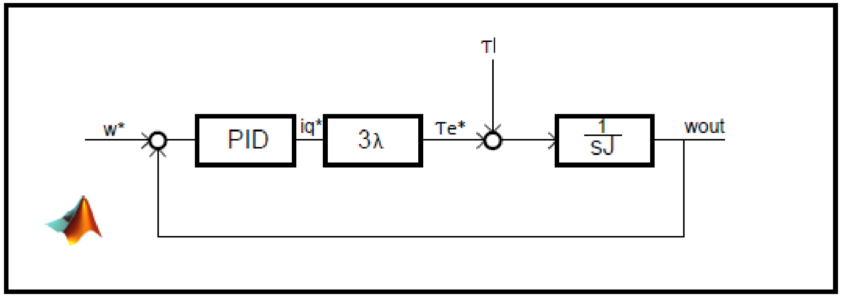
$$Vd = r_s i_d + L_d\frac{d}{dt}i_d - w_r L_q i_q$$

$$Vq = r_s i_q + L_q\frac{d}{dt}i_q + w_r L_d i_d + w_r\lambda_m$$

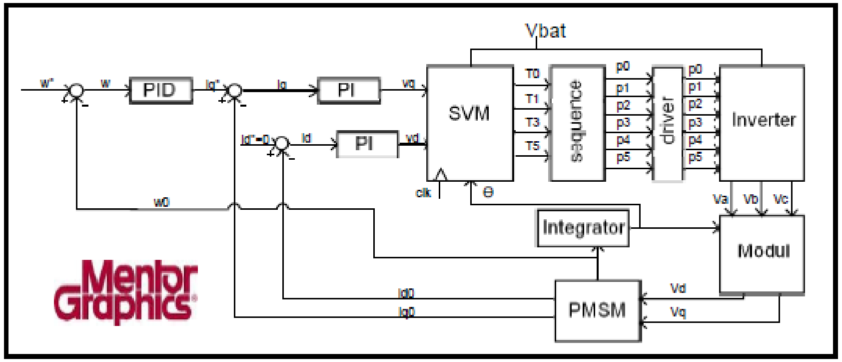
$$\tau_e = \frac{3}{2}\frac{p}{2}\lambda\cdot iq$$

Solution: PID tuning

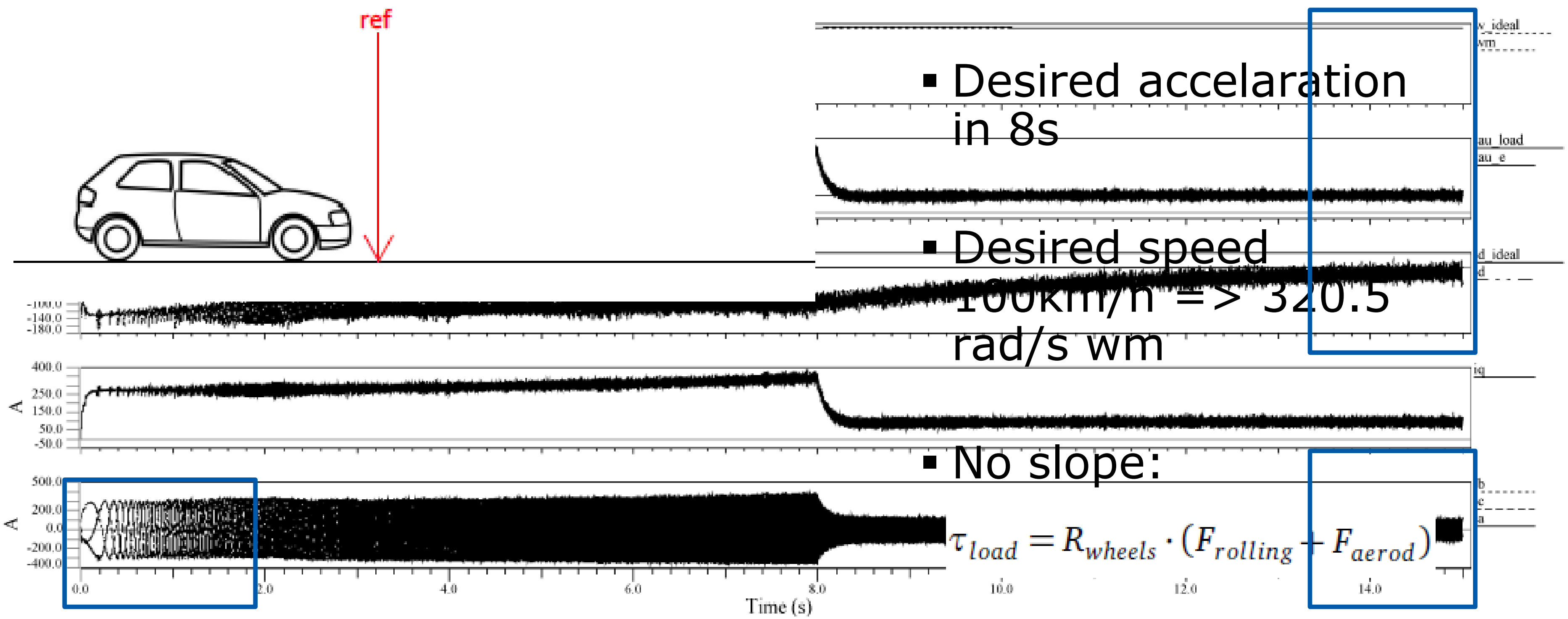
Linearization and Simulink simulation



Simulation with Questa ADMS



Results: Situation1, 0-100km/h



- Desired accelaration in 8s
- Desired speed 100km/h => 320.5 rad/s wm
- No slope:

$$\tau_{load} = R_{wheels} \cdot (F_{rolling} + F_{aerod})$$

$$\tau_e = \tau_{load} + J \frac{dw_m}{dt}$$

Results: Situation2, parking slope

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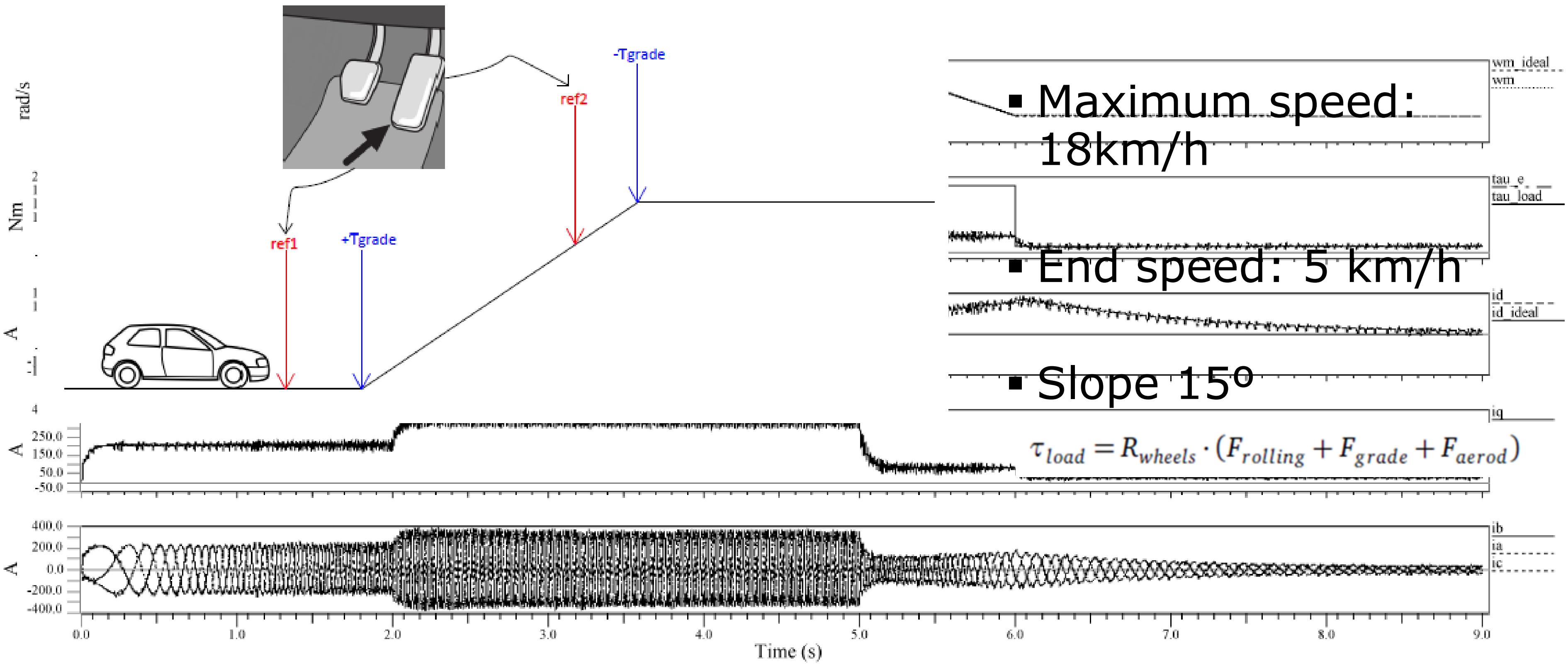

- Maximum speed: 18km/h
- End speed: 5 km/h
- Slope 15º

$$\tau_{load} = R_{wheels} \cdot (F_{rolling} + F_{grade} + F_{aerod})$$

$$\tau_e = \tau_{load} + J\frac{dw_m}{dt}$$

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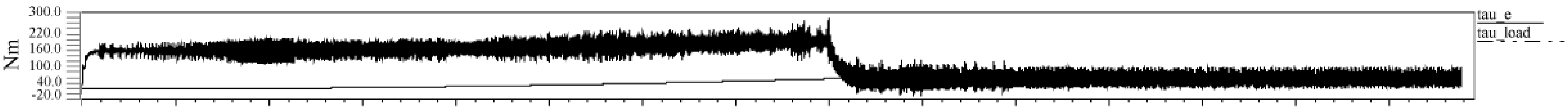
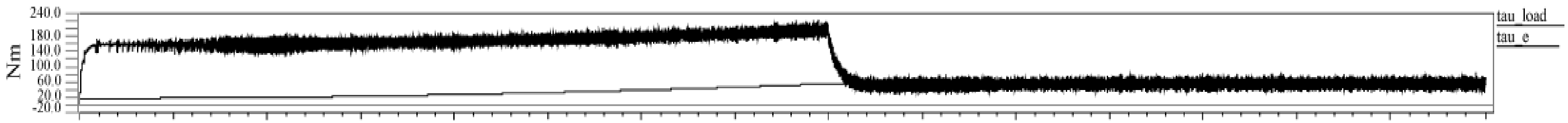
Results: Switching frequency effect on response





Simulation nr	Frequency (kHz)	Ripple between 14:00 and 14:50 (Nm)	Simulation time
1	1	error	error
2	3	84.996	1h 7min
3	6	48.095	2h 30min
4	12	15.42	4h 47min

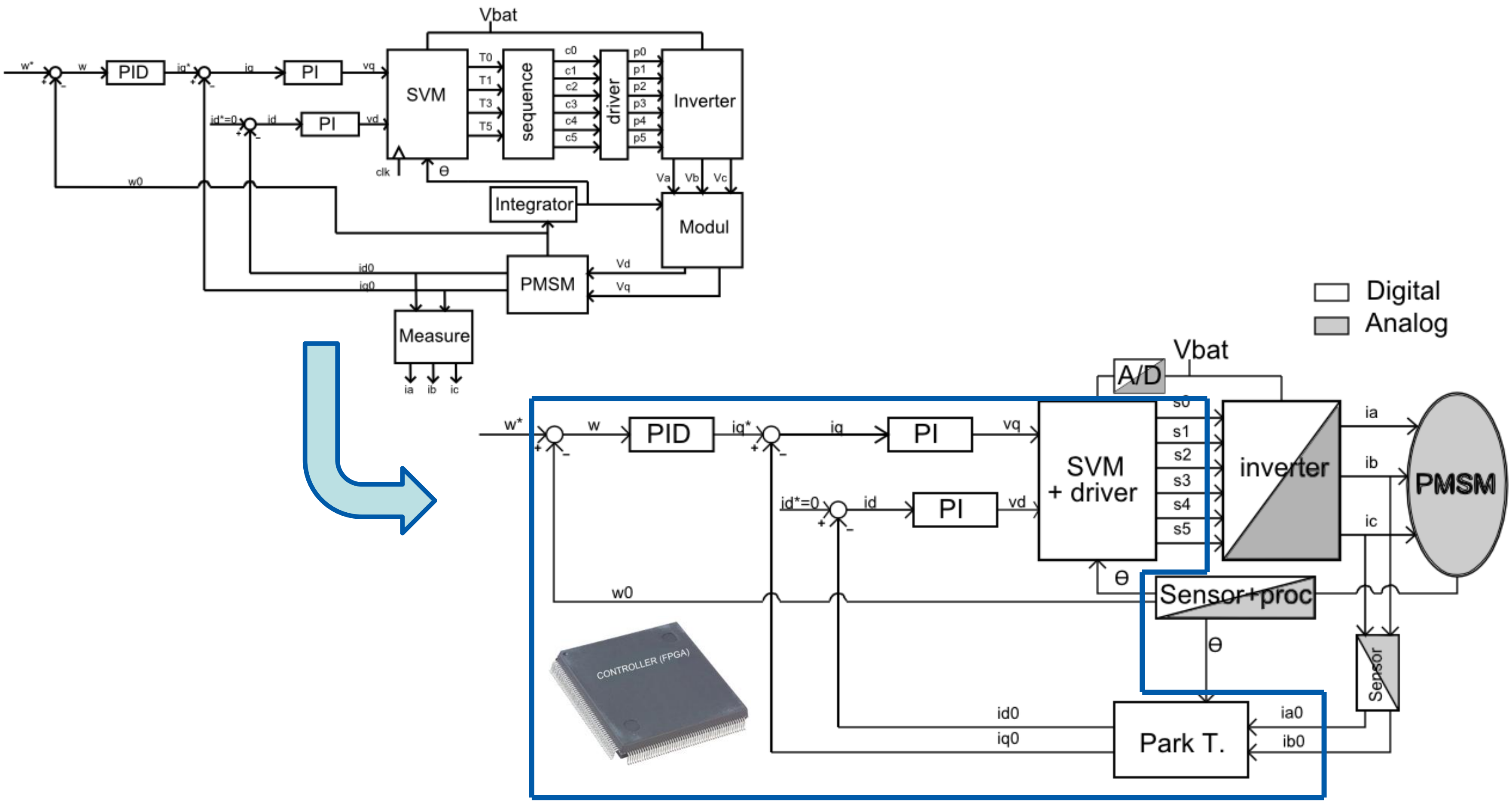
Conclusions & Further works

- Simulations evidence that the complex model works as expected
- Switching frequency as a crutial parameter
- Powerful combination: Simulink + Questa (VHDL AMS)

Further works…

- Quantities => signals (Block by block)
- Cordic for Park transformation

Further works...



Sources

- **Slide nr 3:**

FPGA : http://www.elenilsonvieira.com.br/wp-content/uploads/2011/12/fpga.jpg
Battery: http://www.centralcontracts.com/news/wp-content/uploads/electric-car-battery1.jpg
Inverter: http://static.ddmcdn.com/gif/dc-ac-power-inverter-3.jpg
Motor: http://www.coolmagnetman.com/images/sm1.gif

- **Slide nr4 & nr7**:

Metodología para la docencia del control vectorial de la máquina síncrona de imanes permanentes. Master thesis: Carlos Montes Chacón

- **Slide nr14:**

CAR: “Modeling and Simulation of Electrical Vehicle in VHDL-AMS” ,K. Jaber, B.Ben Saleh ,A. Fakhfakh ,R. Neji
Transmission: ”Modeling and Control of a Superimposed Steering System”, Bjoern Avak

- **Slide nr15:**

Faucet: http://img.compradiccion.com/2012/01/temji.jpg

Ende

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Danke für Ihre Aufmerksamkeit !

Frage ?

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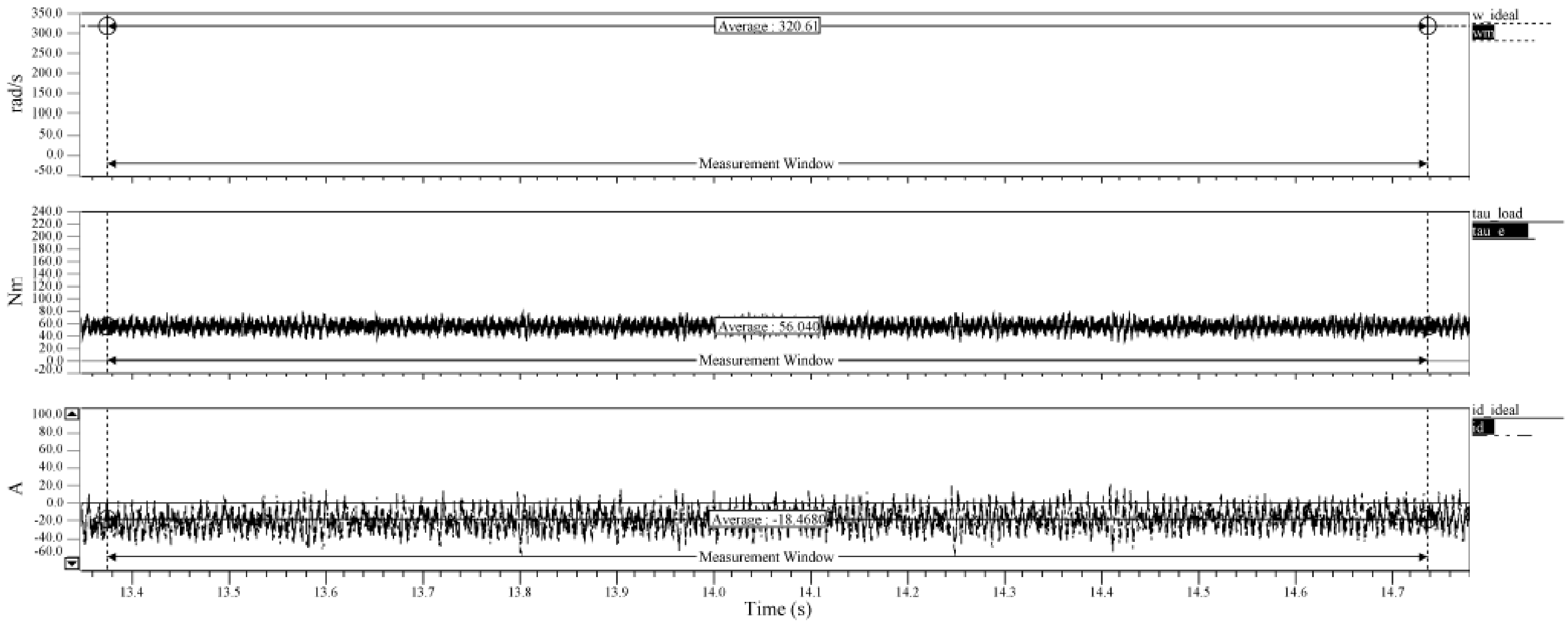
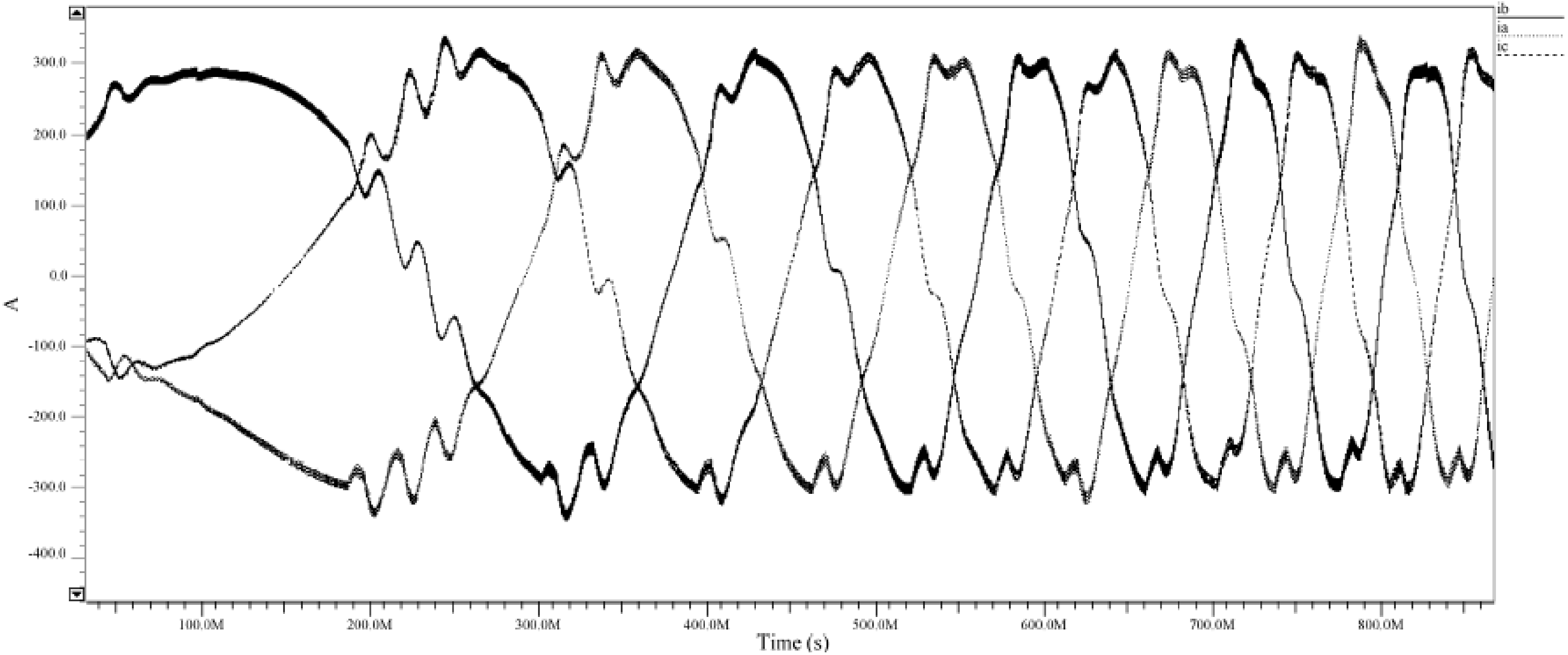
Results: Situation1, 0-100km/h



Results: Situation1, 0-100km/h



Results: Situation1, 0-100km/h