MODELLING AND SIMULATION OF ELECTRIC VEHICLES

Part 1

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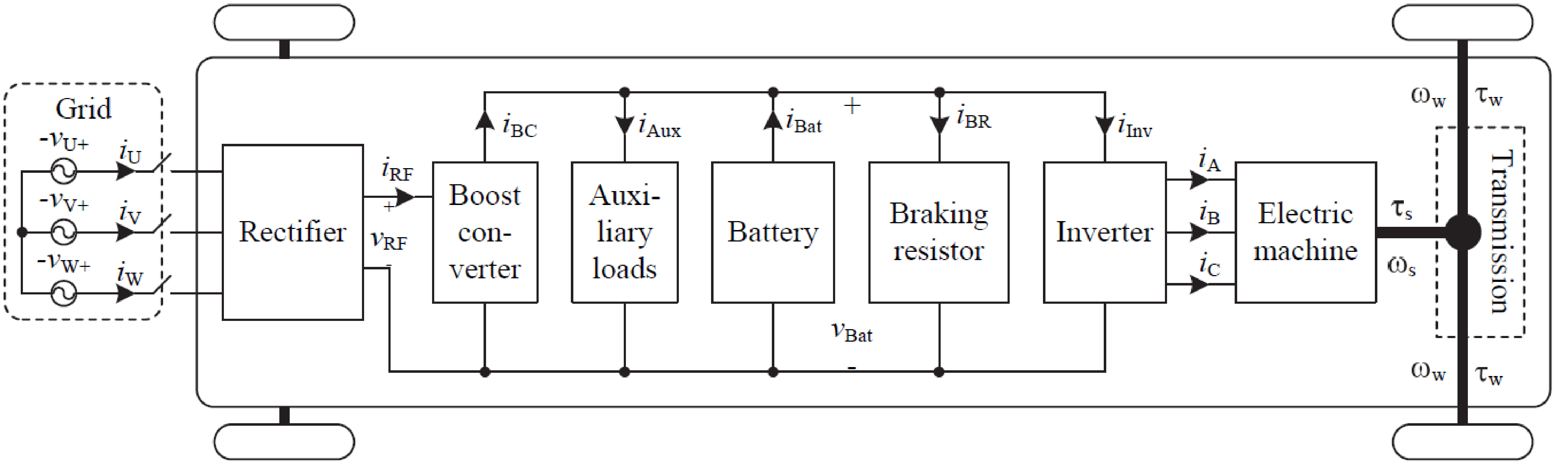
Introduction

- Electric vehicles (EVs) are by many seen as the cars of the future as they are highly efficient, produce no local pollution, are silent, and can be used for power regulation by the grid operator.
- EVs still have critical issues which need to be solved. The three main challenges are limited driving range, long charging time, and high cost. These challenges are all related to the battery package of the car.
- In order to be able to estimate the energy consumption of the EV, and to test its features, it is very important to have a proper model (often called a digital twin) of the EV.
- The model of the EV is very complex as it contains many different components, e.g., transmission, electric machine, power electronics, and battery.

Vehicle modeling - architecture

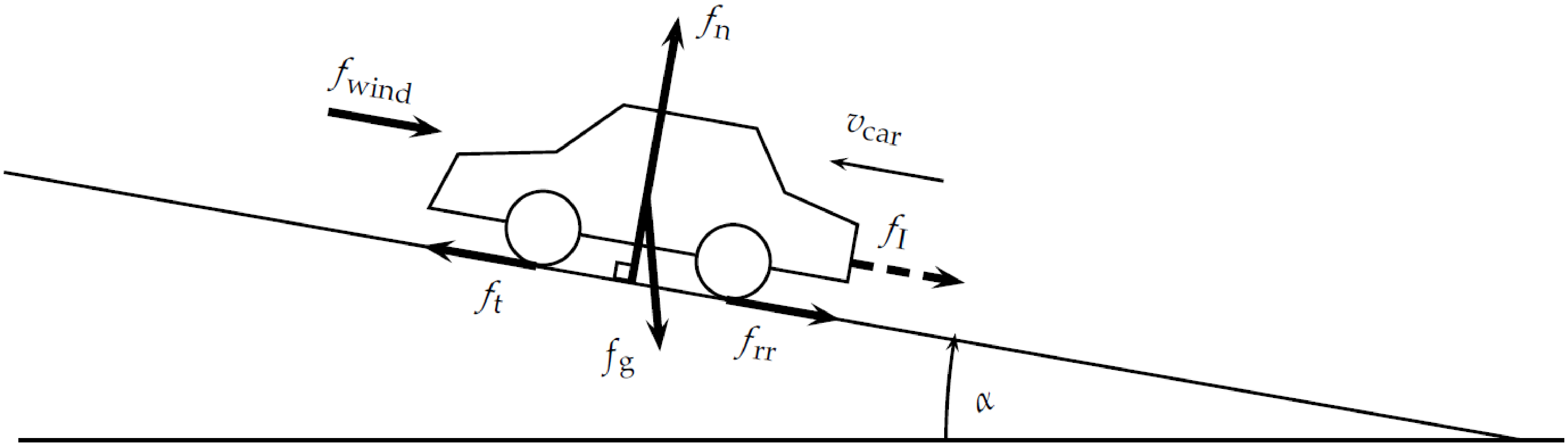
- Many different architectures of the EV exist, as there are many possibilities, e.g., 1 to 4 electric machines, DC or AC machines, gearbox/no gearbox, high or low battery voltage, one or three phase charging, etc.



Example of architecture of the battery electric vehicle

Vehicle modeling - force model

- The forces which the electric machine of the vehicle must overcome are the forces due to gravity, wind, rolling resistance, and inertial effect.



Free body diagram of the forces (thick arrows) acting on the car

Vehicle modeling - force model

- The traction force of a vehicle can be described by the following two equations:

$$f_t = \underbrace{M_{car}\dot{v}_{car}}_{f_I} + \underbrace{M_{car} \cdot g}_{f_g} \cdot \sin(\alpha) + \text{sign}(v_{car}) \underbrace{\overbrace{M_{car} \cdot g \cdot \cos(\alpha)}^{f_n} \cdot c_{rr}}_{f_{rr}}$$
$$+ \text{sign}(v_{car} + v_{wind}) \underbrace{\frac{1}{2}\rho_{air} C_{drag} A_{front} \left(v_{car} + v_{wind}\right)^2}_{f_{wind}} \qquad (1)$$

$$c_{rr} = 0.01 \left(1 + \frac{3.6}{100} v_{car}\right), \qquad (2)$$

Vehicle modeling - force model

where	f_t	[N]	Traction force of the vehicle
	f_I	[N]	Inertial force of the vehicle
	f_{rr}	[N]	Rolling resistance force of the wheels
	f_g	[N]	Gravitational force of the vehicle
	f_n	[N]	Normal force of the vehicle
	f_{wind}	[N]	Force due to wind resistance
	α	[rad]	Angle of the driving surface
	M_{car}	[kg]	Mass of the vehicle
	v_{car}	[m/s]	Velocity of the vehicle
	$\dot{v}_{car}$	[m/s²]	Acceleration of the vehicle
	$g = 9.81$	[m/s²]	Free fall acceleration
	$\rho_{air} = 1.2041$	[kg/m³]	Air density of dry air at 20 °C
	c_{rr}	[−]	Tire rolling resistance coefficient
	C_{drag}	[−]	Aerodynamic drag coefficient
	A_{front}	[m²]	Front area
	v_{wind}	[m/s]	Headwind speed

Vehicle modeling - auxiliary loads

- A modern car have also other loads which the battery should supply. These loads are either due to safety, e.g., light, wipers, horn, etc. and/or comfort, e.g., radio, heating, air conditioning, etc.

Radio	52 W
Heating Ventilation Air Condition (HVAC)	489 W
Lights	316 W
Total p_{Aux}	857 W

Example of average power level of the auxiliary loads of the vehicle

Vehicle modeling - transmission

- Torque, angular velocity, and power of the transmission system are given by the following equations:

$$\tau_{t} = f_{t} r_{w} \tag{3}$$

$$\tau_{w} = \frac{\tau_{t}}{2} \tag{4}$$

$$\omega_{w} = \frac{v_{car}}{r_{w}} \tag{5}$$

$$p_{t} = f_{t} v_{car}, \tag{6}$$

Vehicle modeling - transmission

where	τ_t	[Nm]	Traction torque
	τ_w	[Nm]	Torque of each driving wheel
	r_w	[m]	Wheel radius
	ω_w	[rad/s]	Angular velocity of the wheels
	p_t	[W]	Traction power

$$\tau_s = \begin{cases} \eta_{TS} \frac{\tau_t}{G} & , p_t < 0 \\ \frac{\tau_t}{\eta_{TS} G} & , p_t \geq 0 \end{cases} \tag{7}$$

$$\omega_s = G \omega_w \tag{8}$$

$$p_s = \tau_s \omega_s , \tag{9}$$

where	τ_s	[Nm]	Shaft torque of electric machine
	ω_s	[rad/s]	Shaft angular velocity of electric machine
	p_s	[W]	Shaft power of electric machine
	G	[−]	Gear ratio of differential

Vehicle modeling - electric machine

- For propulsion usually the induction machine (IM), permanent magnet synchronous machine (PMSM), and switched reluctance machine (SRM) are considered.
- The "best" choice is like many other components a trade off between cost, mass, volume, efficiency, reliability, maintenance, etc.
- Due to its high power density and high efficiency, the PMSM is selected as an example.
- The electric machine is divided into an electric part and mechanic part.
- The electric part of the PMSM is modeled in the DQ-frame:

Vehicle modeling - electric machine

$$v_\mathrm{d} = R_\mathrm{s} i_\mathrm{d} + L_\mathrm{d} \frac{di_\mathrm{d}}{dt} - \omega_e L_\mathrm{q} i_\mathrm{q} \tag{10}$$

$$v_\mathrm{q} = R_\mathrm{s} i_\mathrm{q} + L_\mathrm{q} \frac{di_\mathrm{q}}{dt} + \omega_e L_\mathrm{d} i_\mathrm{d} + \omega_\mathrm{e} \lambda_{pm} \tag{11}$$

$$p_\mathrm{EM} = \frac{3}{2} \left(v_\mathrm{d} i_\mathrm{d} + v_\mathrm{q} i_\mathrm{q} \right), \tag{12}$$

Vehicle modeling - electric machine

where	v_{d}	[V]	D-axis voltage
	v_{q}	[V]	Q-axis voltage
	i_{d}	[A]	D-axis current
	i_{q}	[A]	Q-axis current
	R_{s}	[Ω]	Stator phase resistance
	L_{d}	[H]	D-axis inductance
	L_{q}	[H]	Q-axis inductance
	λ_{pm}	[Wb]	Permanent magnet flux linkage
	ω_{e}	[rad/s]	Angular frequency of the stator
	λ_{pm}	[Wb]	Permanent magnet flux linkage
	p_{EM}	[W]	Electric input power

Vehicle modeling - electric machine

- The mechanical part of the PMSM can be modeled as follows:

$$\tau_e = J_s \frac{d\omega_s}{dt} + B_v \omega_s + \tau_c + \tau_s \tag{13}$$

$$p_s = \tau_s \omega_s, \tag{14}$$

where	J_s	[kgm^2]	Shaft moment of inertia
	τ_e	[Nm]	Electromechanical torque
	τ_c	[Nm]	Coulomb torque
	B_v	[Nms/rad]	Viscous friction coefficient

Vehicle modeling - electric machine

- The coupling between the electric and mechanic part is given by:

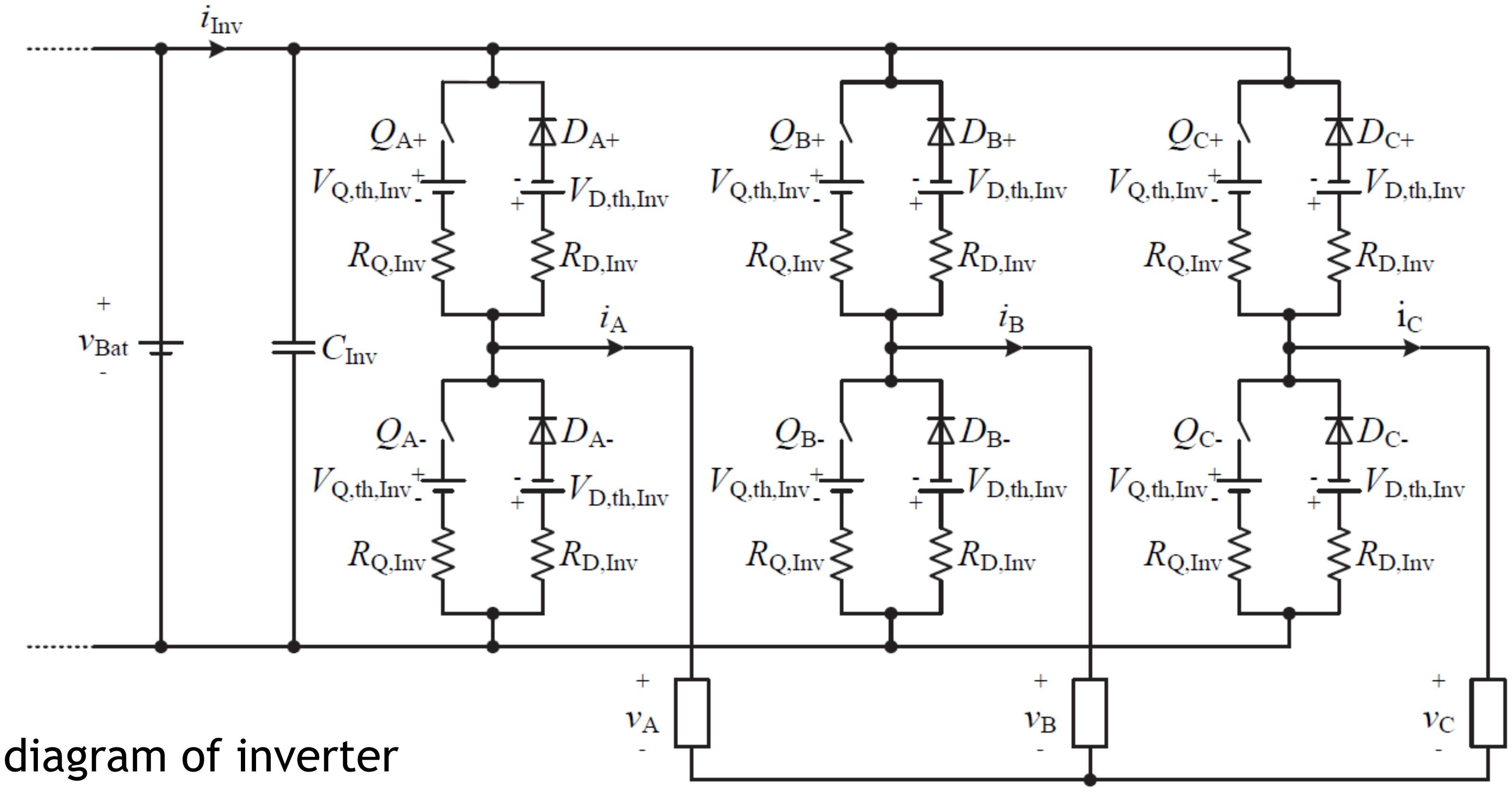
$$\tau_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{pm} i_q + \left(L_d - L_q\right) i_d i_q\right) \tag{15}$$

$$\omega_e = \frac{P}{2}\omega_s, \tag{16}$$

where P $[-]$ Number of poles

Vehicle modeling - inverter

- The inverter transmits power between the electric machine (with phase voltages *v*A, *v*B, and *v*C) and the battery by turning on and off the switches *Q*A+, *Q*A-, *Q*B+, *Q*B-, *Q*C+, and *Q*C-.



Circuit diagram of inverter

Vehicle modeling - inverter

- The average power losses of one switch *p*Q,Inv and diode *p*D,Inv during one fundamental period are:

$$p_{\mathrm{Q,Inv}} = \left(\frac{1}{8} + \frac{m_{\mathrm{i}}}{3\pi}\right) R_{\mathrm{Q,Inv}} \hat{I}_{\mathrm{p}}^{2} + \left(\frac{1}{2\pi} + \frac{m_{\mathrm{i}}}{8}\cos(\phi_{\mathrm{EM}})\right) V_{\mathrm{Q,th,Inv}} \hat{I}_{\mathrm{p}} \tag{17}$$

$$p_{\mathrm{D,Inv}} = \left(\frac{1}{8} - \frac{m_{\mathrm{i}}}{3\pi}\right) R_{\mathrm{D,Inv}} \hat{I}_{\mathrm{p}}^{2} + \left(\frac{1}{2\pi} - \frac{m_{\mathrm{i}}}{8}\cos(\phi_{\mathrm{EM}})\right) V_{\mathrm{D,th,Inv}} \hat{I}_{\mathrm{p}} \tag{18}$$

$$m_{\mathrm{i}} = \frac{2\hat{V}_{\mathrm{p}}}{V_{\mathrm{Bat}}}, \tag{19}$$

Vehicle modeling - inverter

where	$p_{\mathrm{Q,Inv}}$	[W]	Power loss of one switch
	$p_{\mathrm{D,Inv}}$	[W]	Power loss of one diode
	ϕ_{EM}	[rad]	Power factor angle
	$\hat{I}_{\mathrm{p}}$	[A]	Peak phase current
	$\hat{V}_{\mathrm{p}}$	[V]	Peak phase voltage
	m_{i}	[−]	Modulation index
	V_{Bat}	[V]	Battery voltage
	$R_{\mathrm{Q,Inv}}$	[Ω]	Inverter switch resistance
	$R_{\mathrm{D,Inv}}$	[Ω]	Inverter diode resistance
	$V_{\mathrm{Q,th,Inv}}$	[V]	Inverter switch threshold voltage
	$V_{\mathrm{D,th,Inv}}$	[V]	Inverter diode threshold voltage

Vehicle modeling - inverter

- The total power loss of the inverter is given by:

$$P_{\text{Inv,loss}} = 6\left(P_{\text{Q,Inv}} + P_{\text{D,Inv}}\right) = \frac{3}{2} R_{\text{Inv}} \hat{I}_{\text{p}}^2 + \frac{6}{\pi} V_{\text{th,Inv}} \hat{I}_{\text{p}}. \quad (20)$$

- The inverter input power and efficiency are:

$$p_{\text{Inv}} = v_{\text{Bat}} i_{\text{Inv}} = p_{\text{EM}} + p_{\text{Inv,loss}} \quad (21)$$

$$\eta_{\text{Inv}} = \begin{cases} \frac{p_{\text{EM}}}{p_{\text{Inv}}}, & p_{\text{EM}} \geq 0 \\ \frac{p_{\text{Inv}}}{p_{\text{EM}}}, & p_{\text{EM}} < 0, \end{cases} \quad (22)$$

where i_{Inv} [A] Inverter input current
p_{Inv} [W] Inverter input power
η_{Inv} [–] Inverter efficiency

Vehicle modeling - battery

- The battery pack is the heart of an electric vehicle.
- Many different battery types exist, e.g., lead-acid, nickel-metal hydride, lithium-ion, etc.
- Today, the lithium-ion is the preferred choice due to its relatively high specific energy and power.
- As an example, the battery model will be based on a Saft VL 37570 lithium-ion cell.
- Both electric and capacity battery models will be presented.

Vehicle modeling - battery

Maximum voltage	$V_{Bat,max,cell}$	4.2 V
Nominal voltage	$V_{Bat,nom,cell}$	3.7 V
Minimum voltage	$V_{Bat,min,cell}$	2.5 V
1 h capacity	$Q_{1,cell}$	7 Ah
Nominal 1 h discharge current	$I_{Bat,1,cell}$	7 A
Maximum pulse discharge current	$I_{Bat,max,cell}$	28 A

Data sheet specifications of Saft VL 37570 Li-Ion battery