MODELLING AND SIMULATION OF ELECTRIC VEHICLES

Part 2

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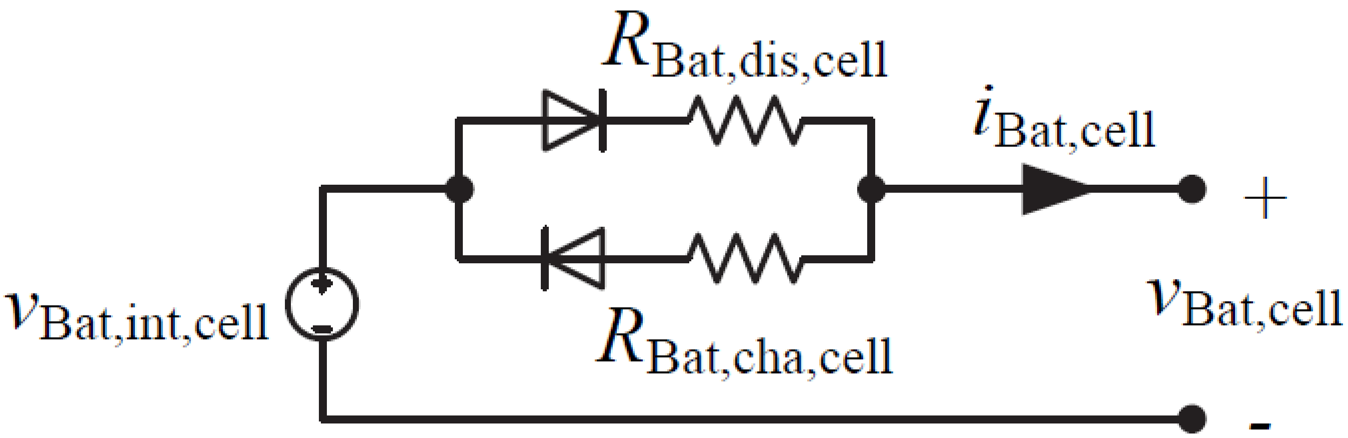
Vehicle modeling - battery electric model

- The battery electric model consists of an internal voltage source and two inner resistances used for charging and discharging. The two diodes are ideal and have only symbolics meaning, i.e., to be able to shift between the charging and discharging resistances. Discharging currents are treated as positive currents, i.e., charging currents are then negative.



Electric equivalent circuit diagram of a battery cell

Vehicle modeling - battery electric model

$$v_{\text{Bat,cell}} = \begin{cases} v_{\text{Bat,int,cell}} - R_{\text{Bat,cell,dis}} i_{\text{Bat,cell}} & , i_{\text{Bat,cell}} \geq 0 \\ v_{\text{Bat,int,cell}} - R_{\text{Bat,cell,cha}} i_{\text{Bat,cell}} & , i_{\text{Bat,cell}} < 0, \end{cases} \tag{23}$$

where $v_{\text{Bat,cell}}$ [V] Battery cell voltage
$v_{\text{Bat,int,cell}}$ [V] Internal battery cell voltage
$i_{\text{Bat,cell}}$ [A] Battery cell current
$R_{\text{Bat,cell,dis}}$ [Ω] Inner battery cell resistance during discharge mode
$R_{\text{Bat,cell,cha}}$ [Ω] Inner battery cell resistance during charge mode

$$\begin{aligned} R_{\text{Bat,cell,dis}} = {} & a_{10} DoD_{\text{Bat}}^{10} + a_9 DoD_{\text{Bat}}^{9} + a_8 DoD_{\text{Bat}}^{8} + a_7 DoD_{\text{Bat}}^{7} + a_6 DoD_{\text{Bat}}^{6} \\ & + a_5 DoD_{\text{Bat}}^{5} + a_4 DoD_{\text{Bat}}^{4} + a_3 DoD_{\text{Bat}}^{3} + a_2 DoD_{\text{Bat}}^{2} + a_1 DoD_{\text{Bat}} + a_0 \end{aligned} \tag{24}$$

Vehicle modeling - battery electric model

$$v_{\text{Bat,int,cell}} = b_{10}DoD_{\text{Bat}}^{10} + b_9DoD_{\text{Bat}}^{9} + b_8DoD_{\text{Bat}}^{8} + b_7DoD_{\text{Bat}}^{7} + b_6DoD_{\text{Bat}}^{6} + b_5DoD_{\text{Bat}}^{5} + b_4DoD_{\text{Bat}}^{4} + b_3DoD_{\text{Bat}}^{3} + b_2DoD_{\text{Bat}}^{2} + b_1DoD_{\text{Bat}} + b_0 \quad (25)$$

$$R_{\text{Bat,cell,cha}} = c_{10}DoD_{\text{Bat}}^{10} + c_9DoD_{\text{Bat}}^{9} + c_8DoD_{\text{Bat}}^{8} + c_7DoD_{\text{Bat}}^{7} + c_6DoD_{\text{Bat}}^{6} + c_5DoD_{\text{Bat}}^{5} + c_4DoD_{\text{Bat}}^{4} + c_3DoD_{\text{Bat}}^{3} + c_2DoD_{\text{Bat}}^{2} + c_1DoD_{\text{Bat}} + c_0 \quad (26)$$

where a_{10} = -634.0, a_9 = 2942.1, a_8 = -5790.6, a_7 = 6297.4, a_6 = -4132.1, a_5 = 1677.7
a_4 = -416.4, a_3 = 60.5, a_2 = -4.8, a_1 = 0.2, a_0 = 0.0
b_{10} = -8848, b_9 = 40727, b_8 = -79586, b_7 = 86018, b_6 = -56135, b_5 = -5565
b_4 = 784, b_3 = -25, b_2 = 55, b_1 = 0, b_0 = 4
c_{10} = 2056, c_9 = -9176, c_8 = 17147, c_7 = -17330, c_6 = 10168, c_5 = -3415
c_4 = 578, c_3 = 25, c_2 = 3, c_1 = 0, c_0 = 0

Vehicle modeling - battery capacity model

- The inner voltage source, charging resistance, and discharge resistance all depend on the depth-of-discharge. The state-of-charge and depth-of-discharge depend on the integral of the current drawn or delivered to the battery, i.e.,

$$DoD_{\mathrm{Bat}} = DoD_{\mathrm{Bat,ini}} + \int \frac{i_{\mathrm{Bat,eq,cell}}}{Q_{\mathrm{Bat,1,cell}}} dt \tag{27}$$

$$SoC_{\mathrm{Bat}} = 1 - DoD_{\mathrm{Bat}} \tag{28}$$

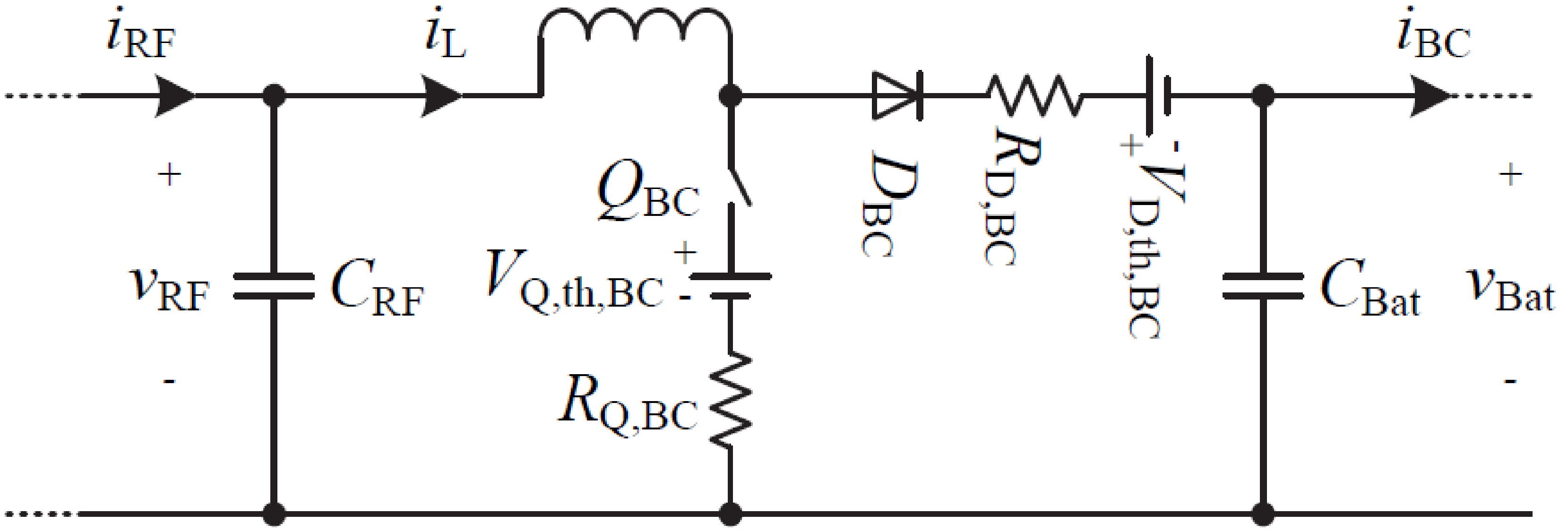
where DoD_{Bat} [−] Depth-of-discharge
$DoD_{\mathrm{Bat,ini}}$ [−] Initial depth-of-discharge
SoC_{Bat} [−] Battery state-of-charge
$i_{\mathrm{Bat,eq,cell}}$ [A] Equivalent battery cell current

$$i_{\mathrm{Bat,eq,cell}} = \begin{cases} I_{\mathrm{Bat,1,cell}} \left(\frac{i_{\mathrm{Bat,cell}}}{I_{\mathrm{Bat,1,cell}}} \right)^k & , i_{\mathrm{Bat,cell}} \geq 0 \\ \eta_{\mathrm{Bat,cha}} i_{\mathrm{Bat,cell}} & , i_{\mathrm{Bat,cell}} < 0 \end{cases} \tag{29}$$

$$k = \begin{cases} 1 & , i_{\mathrm{Bat,cell}} \leq I_{\mathrm{Bat,1,cell}} \\ 1.125 & , i_{\mathrm{Bat,cell}} > I_{\mathrm{Bat,1,cell}}, \end{cases} \tag{30}$$

where k [−] Peukert number
$\eta_{\mathrm{Bat,cha}} = 0.95$ [−] Charging efficiency

Vehicle modeling - boost converter



Electric circuit diagram of the boost converter

Vehicle modeling - boost converter

- The power equations of the boost converter are given by:

$$P_{\mathrm{RF}} = V_{\mathrm{RF}} i_{\mathrm{RF}} = P_{\mathrm{BC}} + P_{\mathrm{Loss,BC}} \quad (31)$$

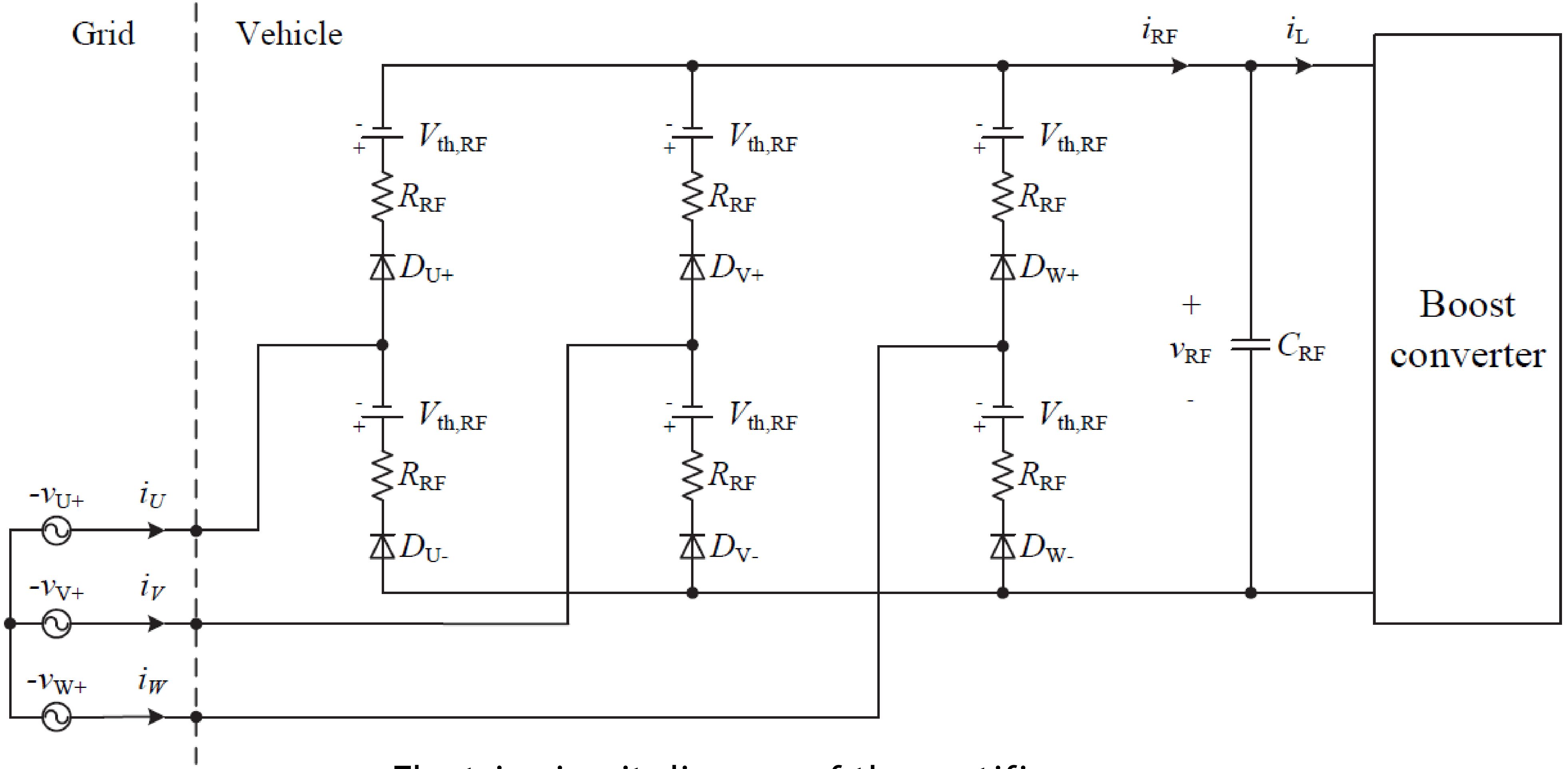
$$P_{\mathrm{BC}} = V_{\mathrm{Bat}} i_{\mathrm{BC}} \quad (32)$$

$$P_{\mathrm{Loss,BC}} = R_{\mathrm{BC}} i_{\mathrm{RF}}^2 + V_{\mathrm{th,BC}} i_{\mathrm{RF}}, \quad (33)$$

where

P_{RF}	[W]	Input power of boost converter
P_{BC}	[W]	Output power of boost converter
$P_{\mathrm{Loss,BC}}$	[W]	Power loss of boost converter
V_{RF}	[V]	Input voltage of boost converter
$V_{\mathrm{th,BC}}$	[V]	Threshold voltage of switch and diode
R_{BC}	[Ω]	Resistance of switch and diode
i_{RF}	[A]	Input current of boost converter
i_{BC}	[A]	Output current of boost converter

Vehicle modeling - rectifier



Electric circuit diagram of the rectifier

Vehicle modeling - rectifier

$$i_{\mathrm{RF}} = I_{\mathrm{Grid}}\sqrt{\frac{3}{2}} \tag{34}$$

$$V_{\mathrm{RF}} = \frac{3\sqrt{2}}{\pi}V_{\mathrm{LL}} - 2R_{\mathrm{RF}}i_{\mathrm{RF}} - 2V_{\mathrm{th,RF}} \tag{35}$$

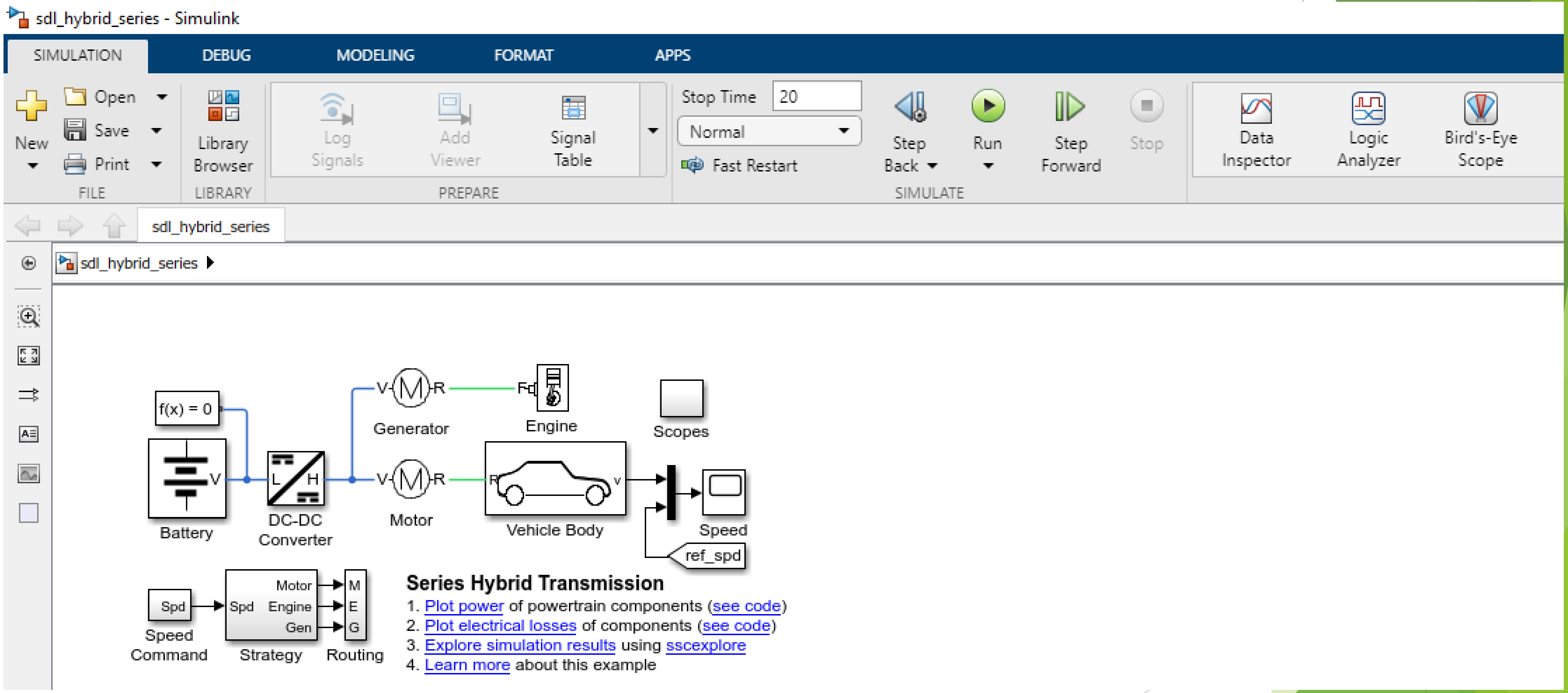
$$P_{\mathrm{RF}} = V_{\mathrm{RF}}i_{\mathrm{RF}} = P_{\mathrm{Grid}} - P_{\mathrm{RF,loss}} \tag{36}$$

$$P_{\mathrm{Grid}} = \frac{3\sqrt{2}}{\pi}V_{\mathrm{LL}}I_{\mathrm{RF}} \tag{37}$$

$$P_{\mathrm{RF,loss}} = 2R_{\mathrm{RF}}i_{\mathrm{RF}}^2 + 2V_{\mathrm{th,RF}}i_{\mathrm{RF}}, \tag{38}$$

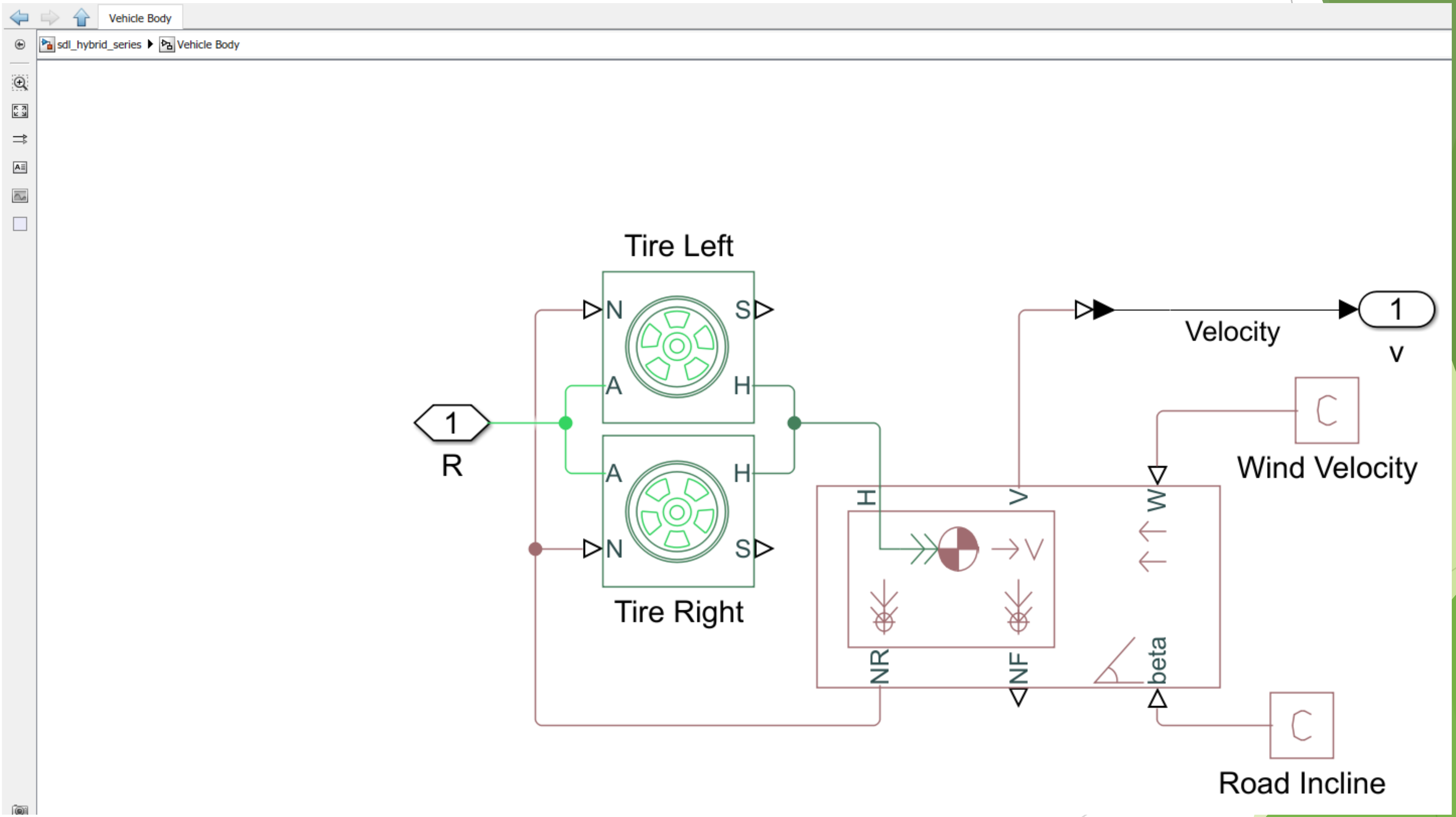
where	I_{Grid}	[A]	Grid RMS-current
	P_{Grid}	[W]	Power of three phase grid
	$P_{\mathrm{loss,RF}}$	[W]	Total loss of the rectifier
	R_{RF}	[Ω]	Resistance of switch and diode
	$V_{\mathrm{th,RF}}$	[V]	Threshold voltage of switch and diode

Simulation of electric vehicles



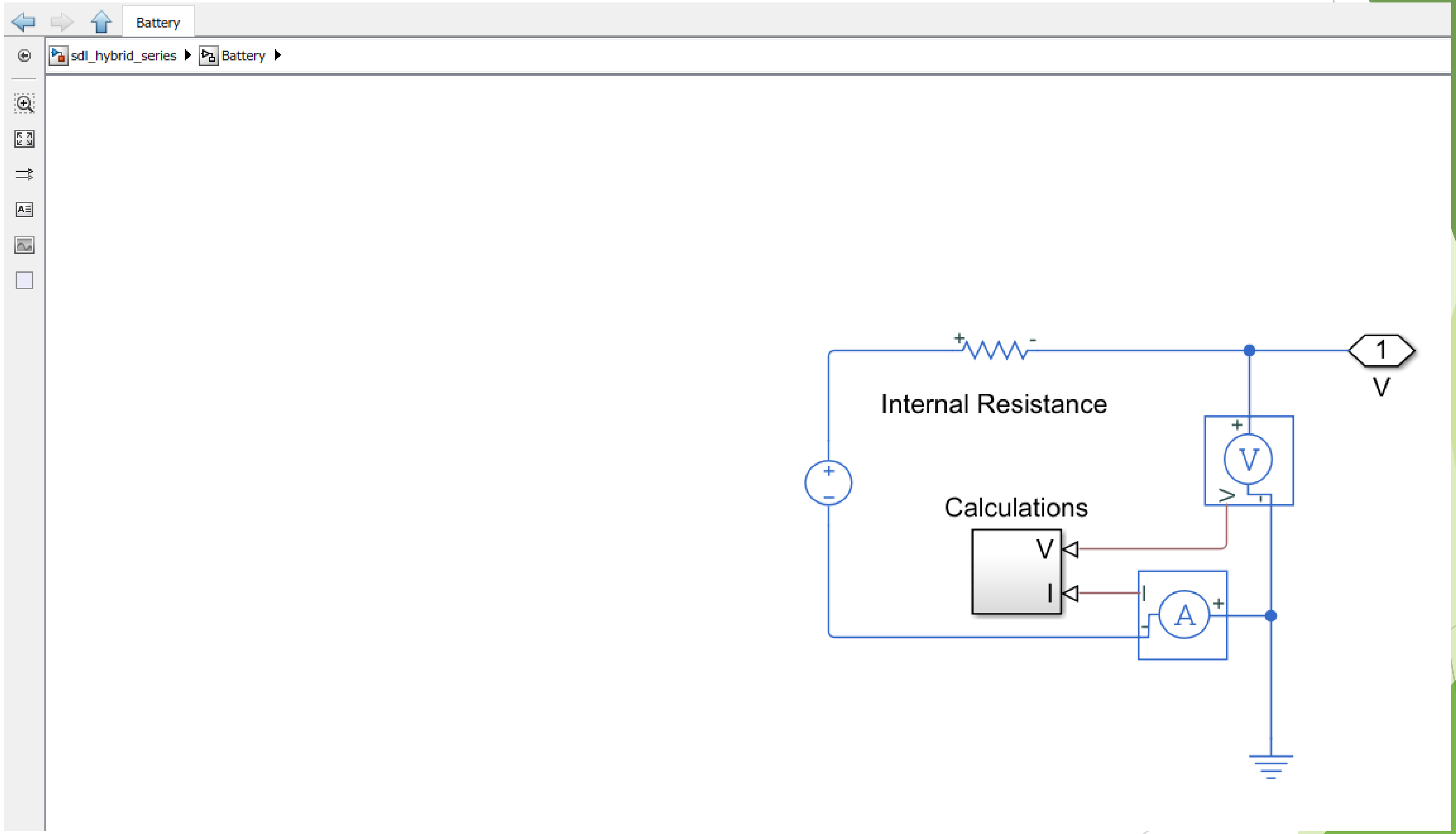
Series Hybrid Transmission – Matlab/Simulink demo

Simulation of electric vehicles



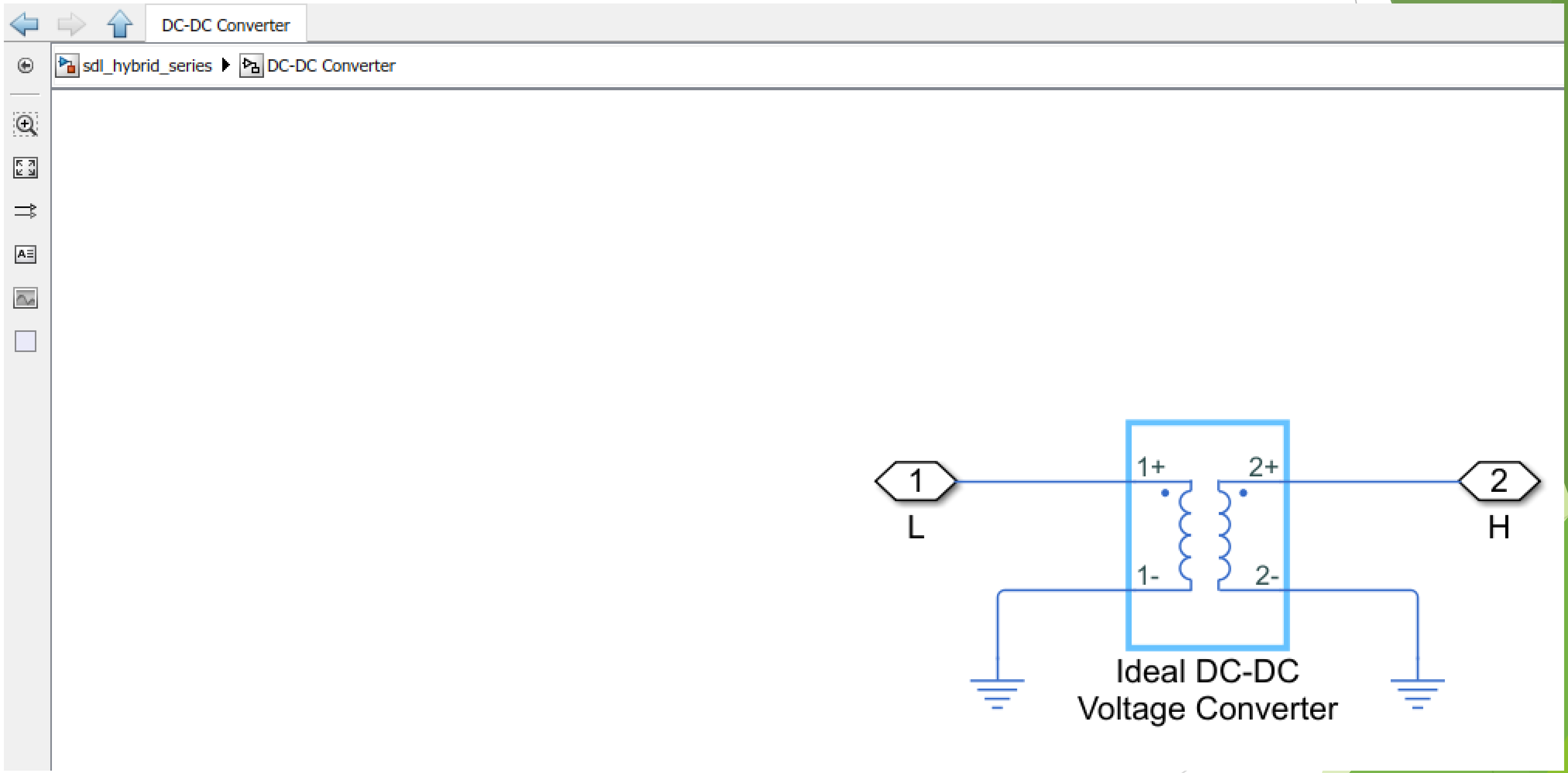
Series Hybrid Transmission – Matlab/Simulink demo (Vehicle Body subsystem)

Simulation of electric vehicles



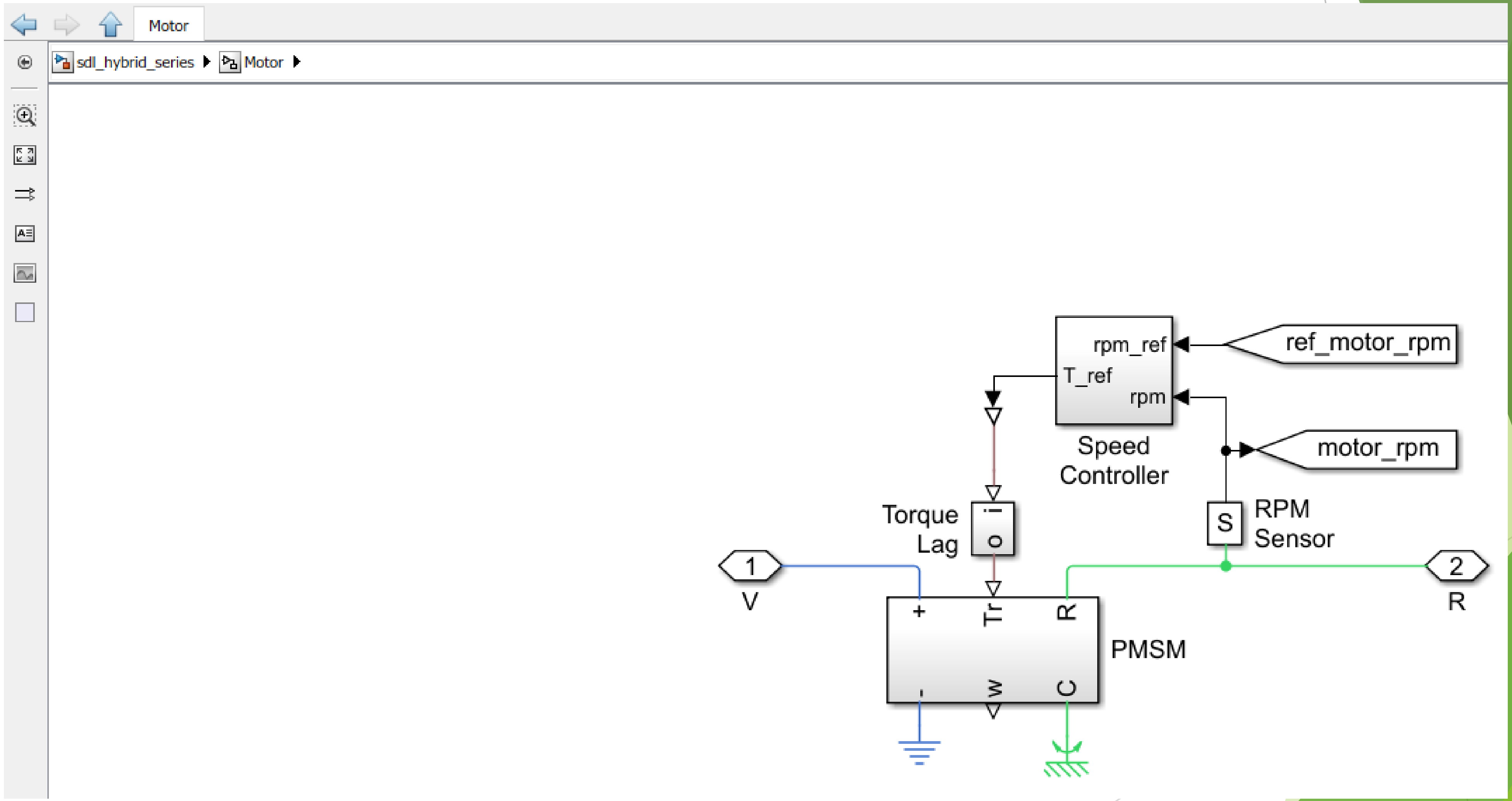
Series Hybrid Transmission – Matlab/Simulink demo (Battery subsystem)

Simulation of electric vehicles



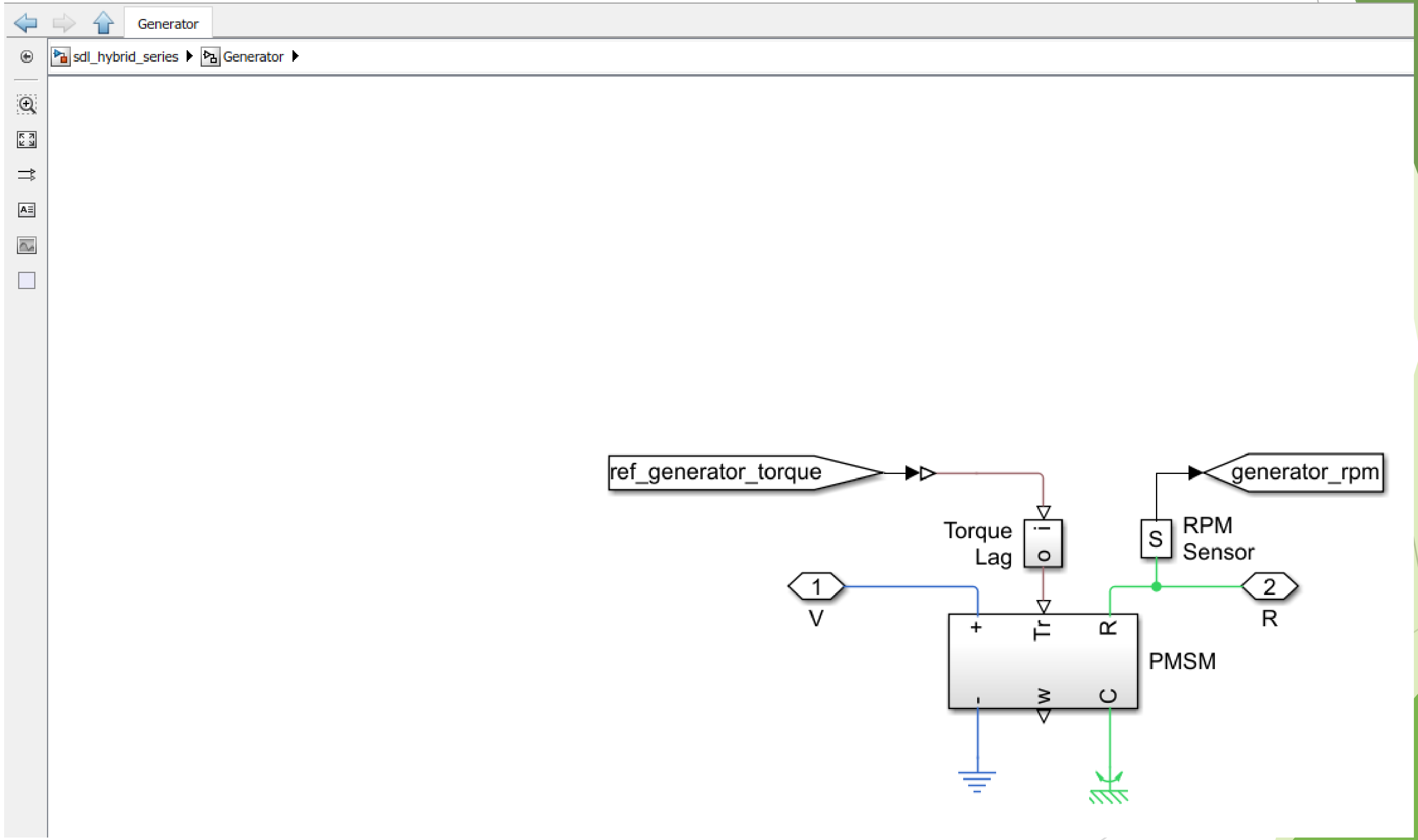
Series Hybrid Transmission – Matlab/Simulink demo (DC-DC Converter subsystem)

Simulation of electric vehicles



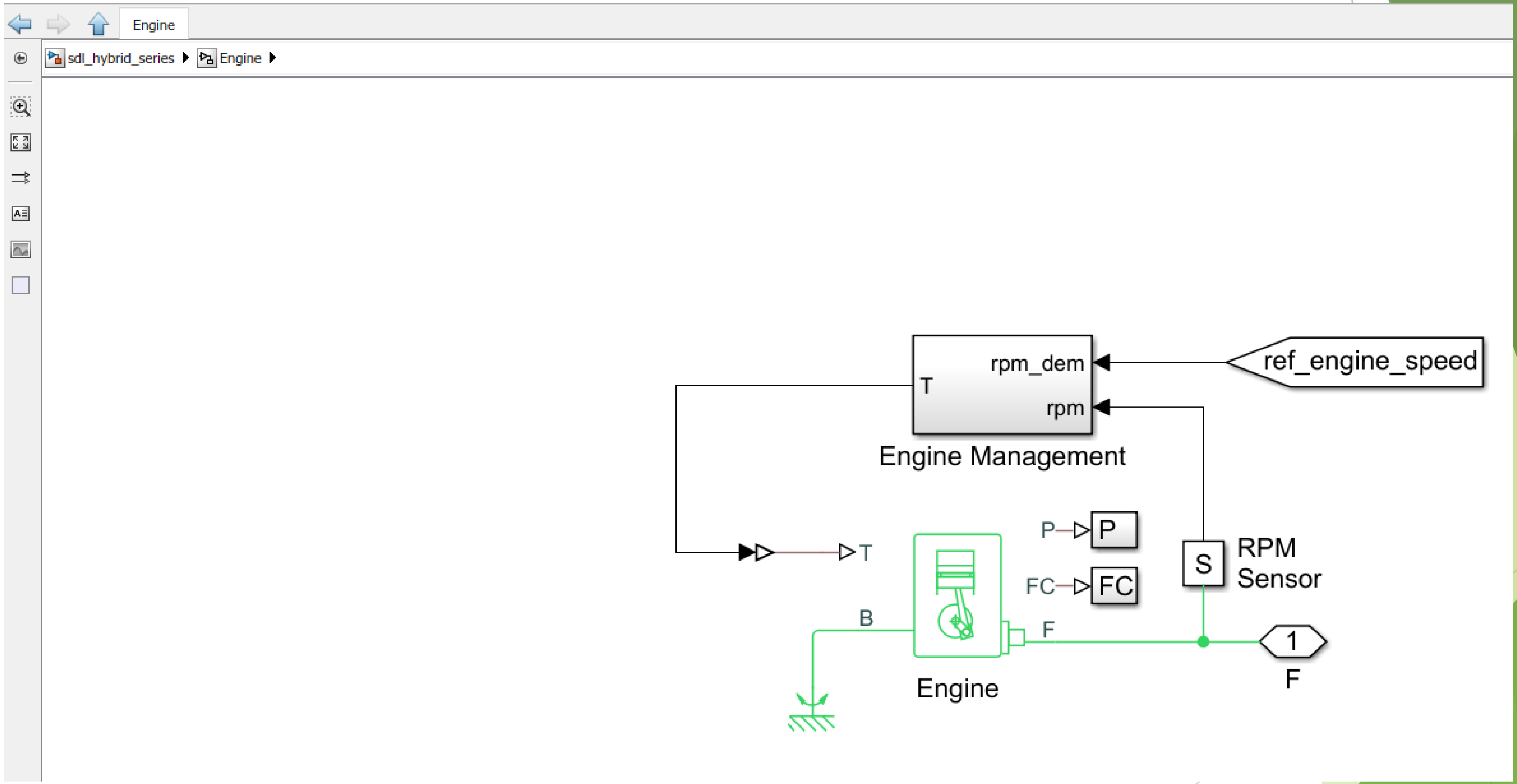
Series Hybrid Transmission – Matlab/Simulink demo (Motor subsystem)

Simulation of electric vehicles



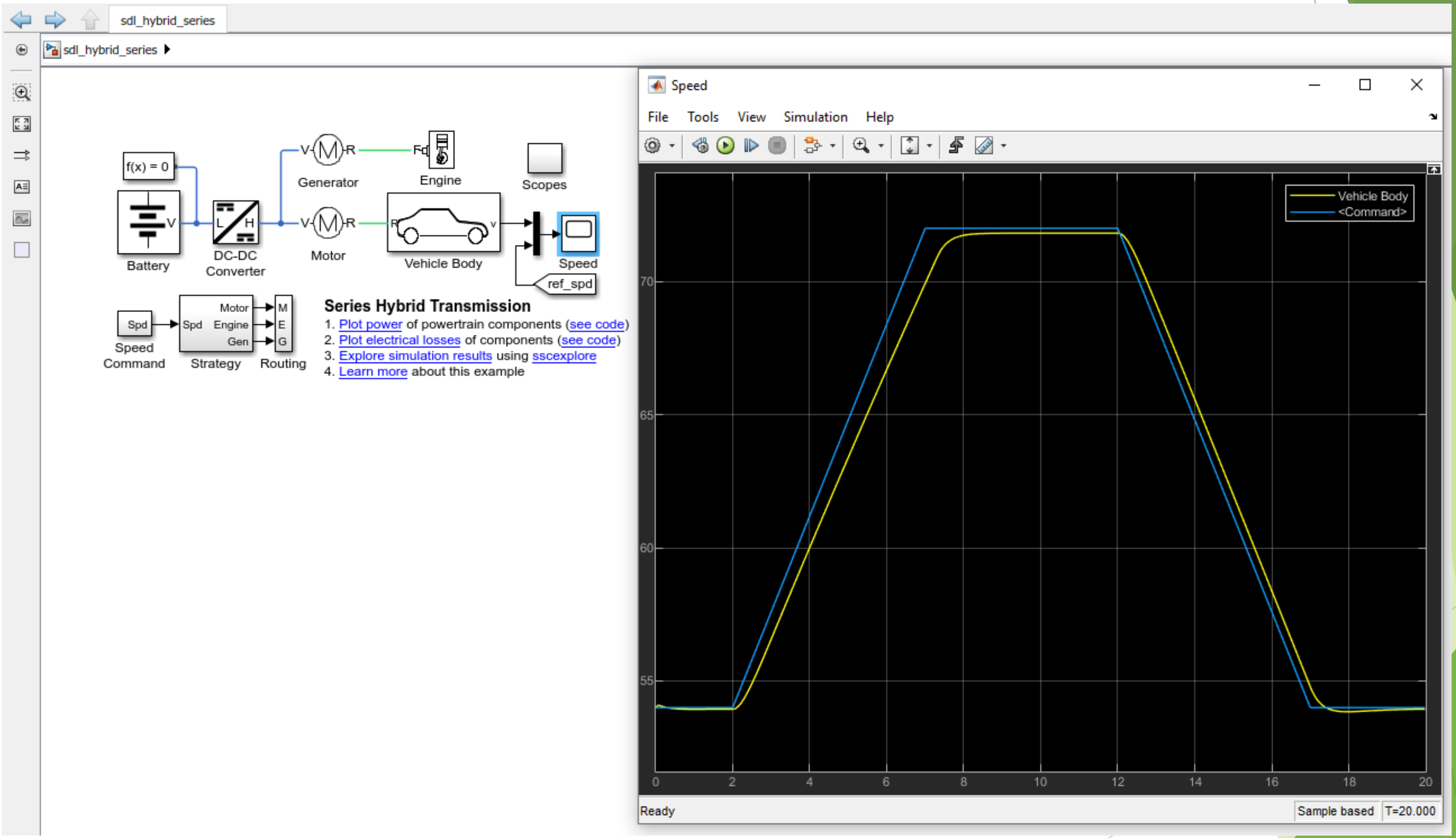
Series Hybrid Transmission – Matlab/Simulink demo (Generator subsystem)

Simulation of electric vehicles



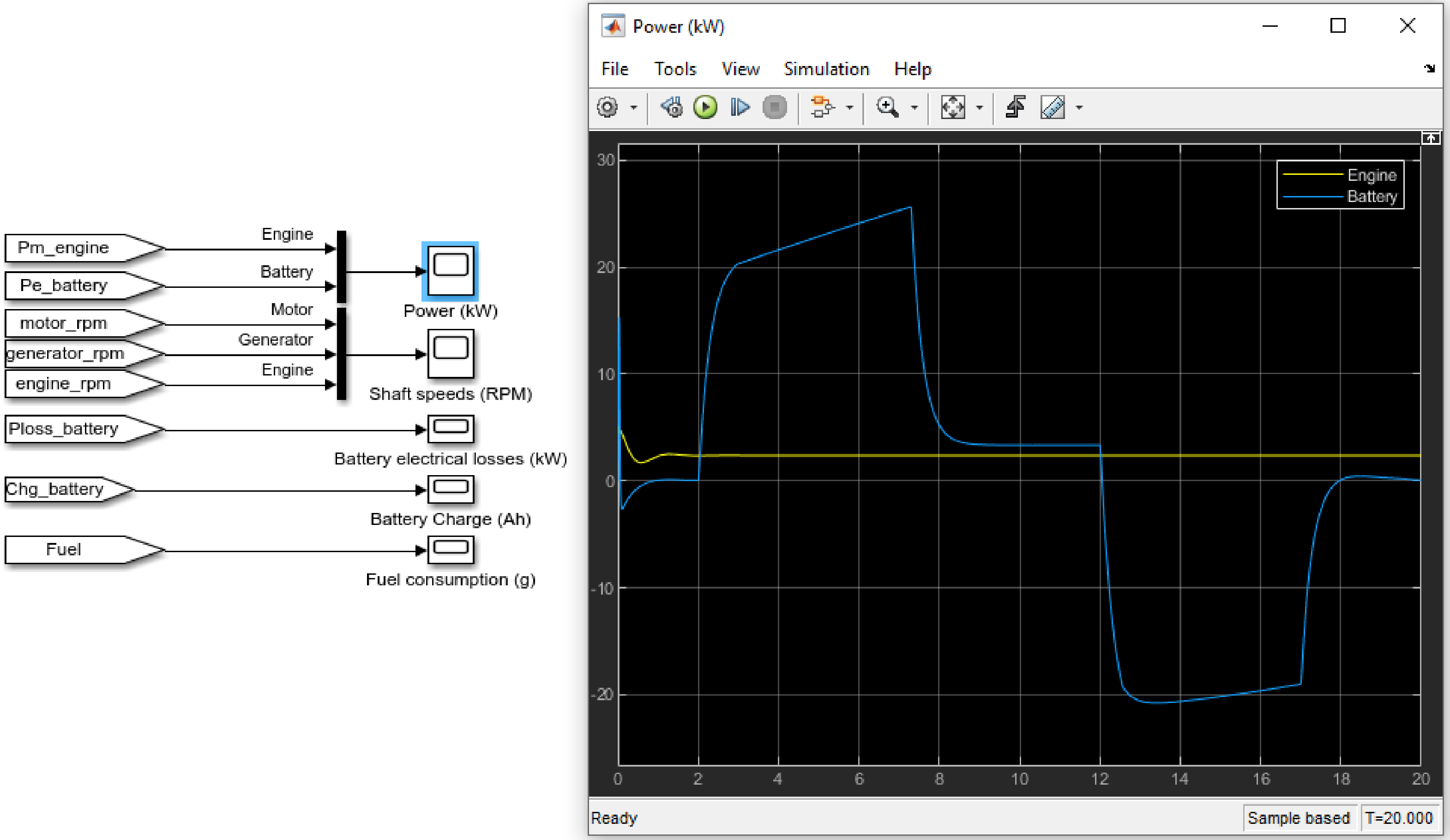
Series Hybrid Transmission – Matlab/Simulink demo (Engine subsystem)

Simulation of electric vehicles



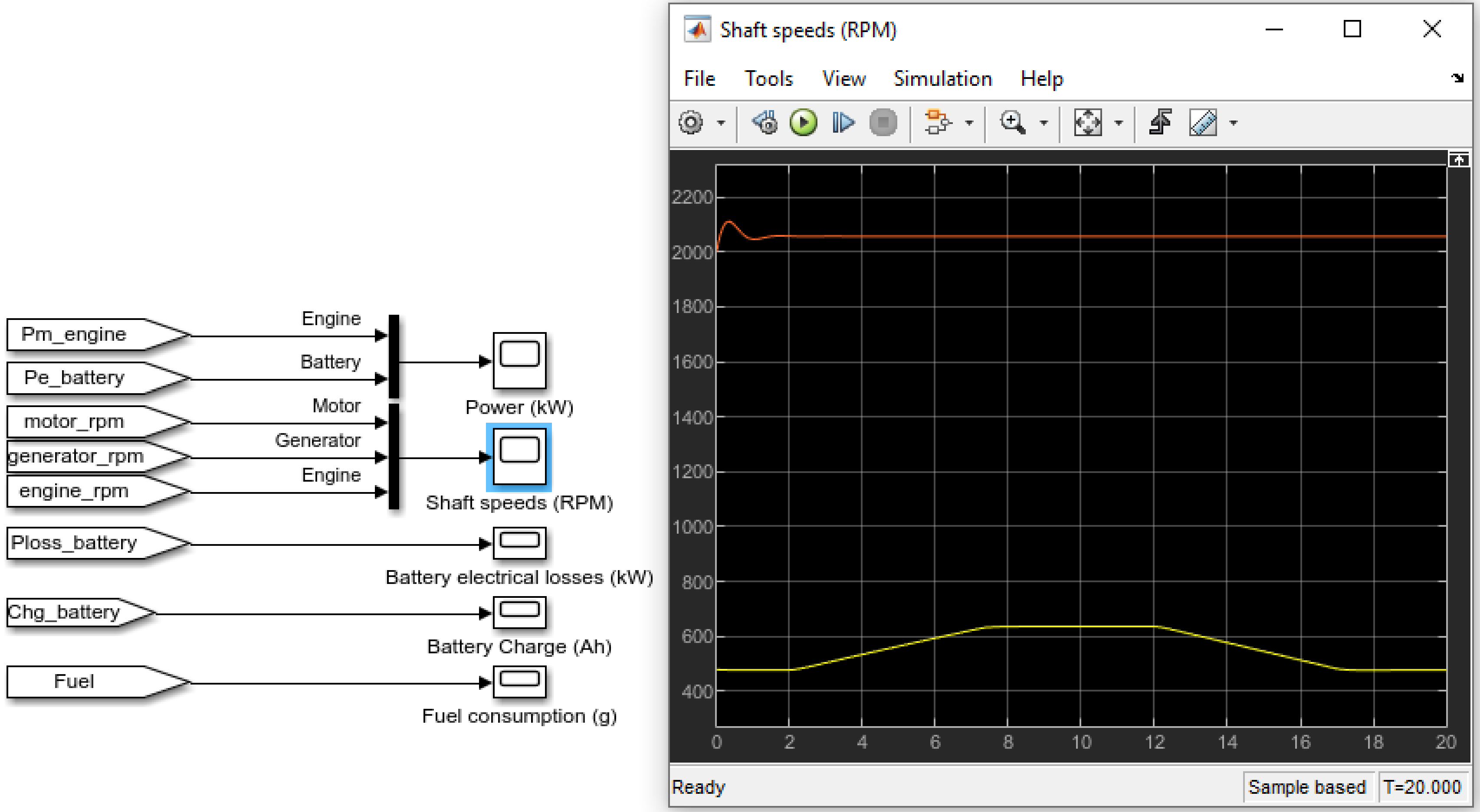
Series Hybrid Transmission – Matlab/Simulink demo (simulated vehicle speed)

Simulation of electric vehicles



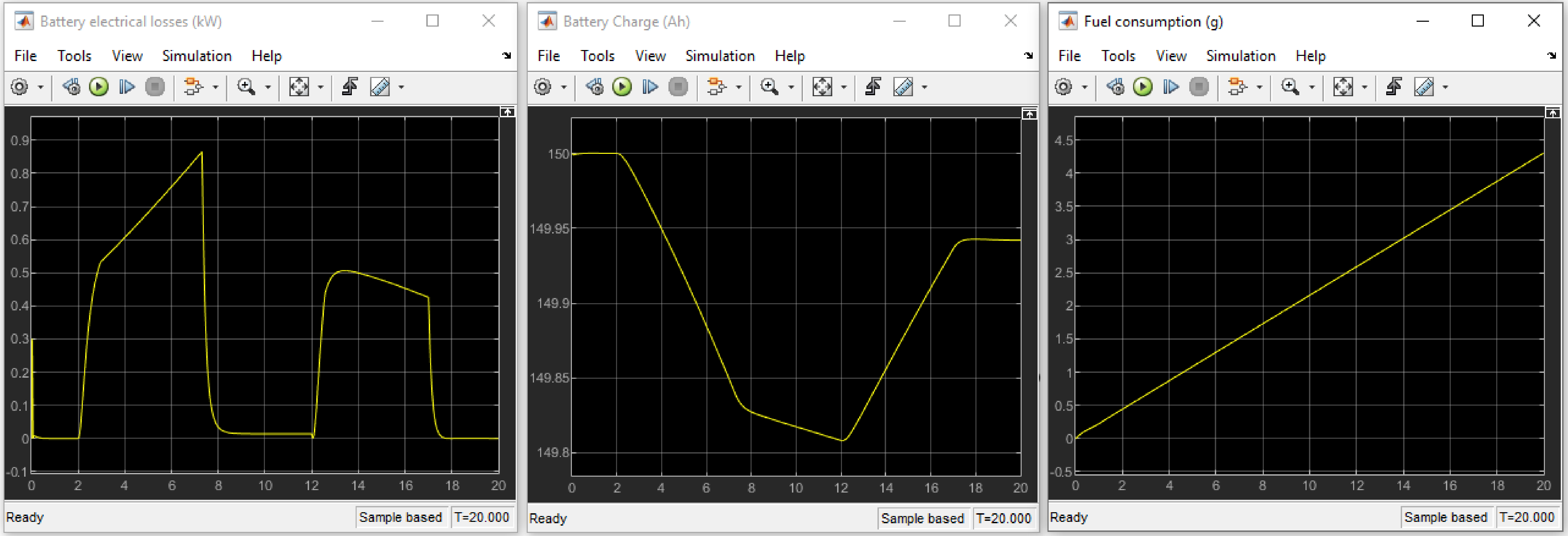
Series Hybrid Transmission – Matlab/Simulink demo (simulated powers)

Simulation of electric vehicles



Series Hybrid Transmission – Matlab/Simulink demo (simulated shaft speeds)

Simulation of electric vehicles



Series Hybrid Transmission – Matlab/Simulink demo (simulated battery losses, battery charge and fuel consumption)