Webinar: Modeling EV Powertrain with the RTDS Simulator

RTDS Technologies
AMETEK

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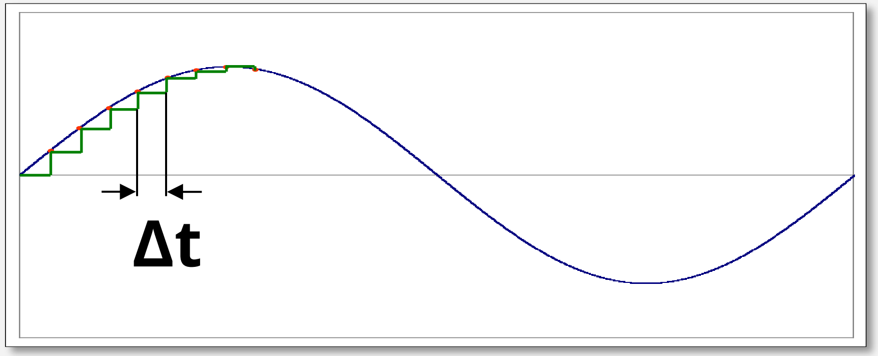
TYPES OF DIGITAL SIMULATION

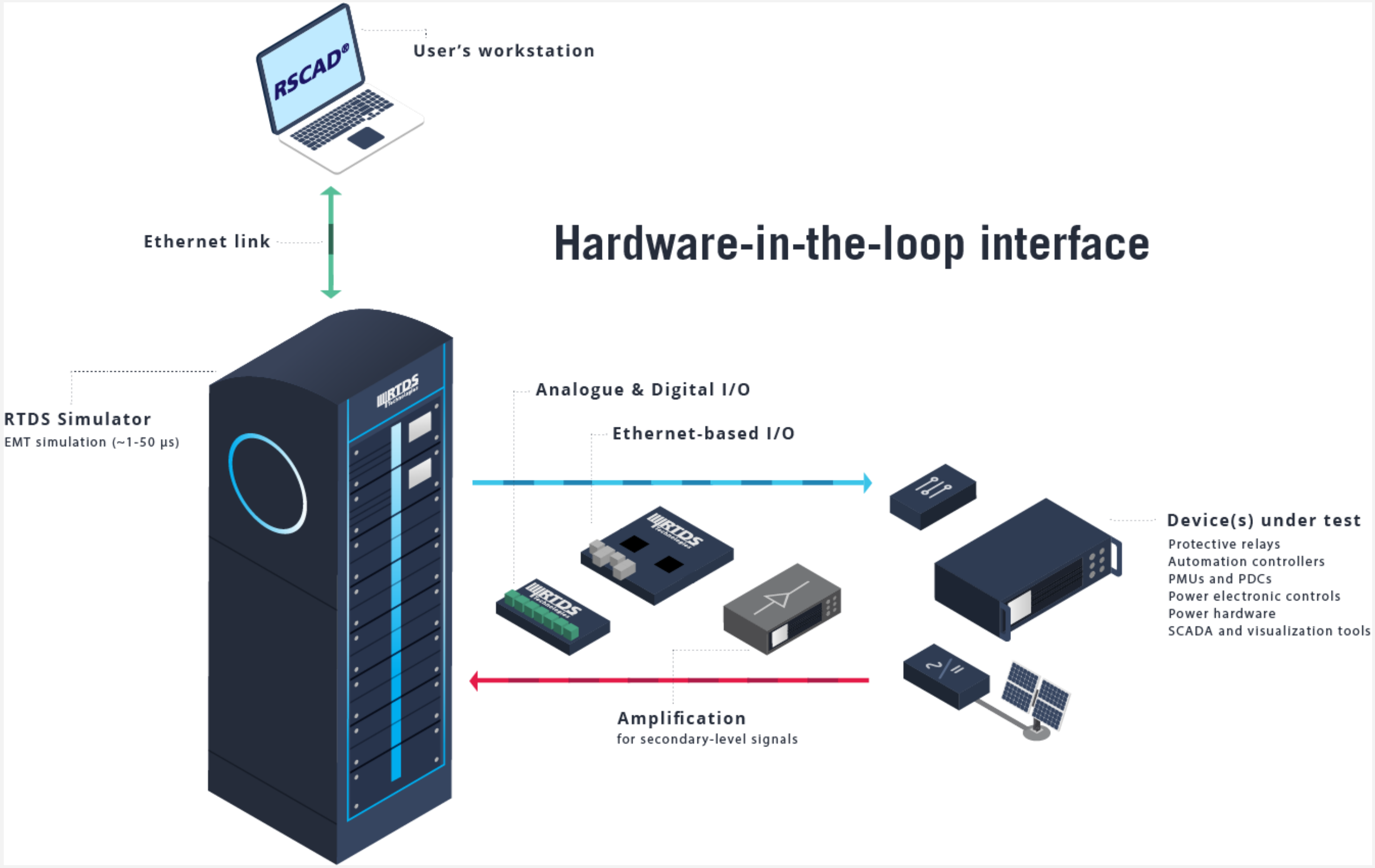
Type of Simulation	Load Flow	Transient Stability Analysis (TSA)	Electromagnetic Transient (EMT)
Typical timestep	Single solution	~ 8 ms	~ 2 - 50 μs
Output	Magnitude and angle	Magnitude and angle	Instantaneous values
Frequency range	Nominal frequency	Nominal and off-nominal frequency	0 – 3 kHz (<15 kHz)



Dommel algorithm of nodal analysis used in RTDS, PSCAD, EMTP, etc.

HIL Testing with Real Time Simulation

- **Real time operation** is what allows us to connect physical devices in a **closed loop** with the simulated environment
- **True closed-loop testing** is only possible with a real time simulator



HARDWARE IN THE LOOP FOR GRID MODERNIZATION

Distribution

- Microgrid testing
- Renewables/DERs
- Distribution automation
- Inverter testing

Power Electronics

- HVDC and FACTS
- Energy conversion
- Drives

Smart Grid

- WAMPAC testing
- PMU studies
- Cyber security

Protection

- Digital substations
- Travelling wave testing

Modeling the Electric Vehicle Powertrain with the RTDS Simulator

RTDS Technologies

AGENDA

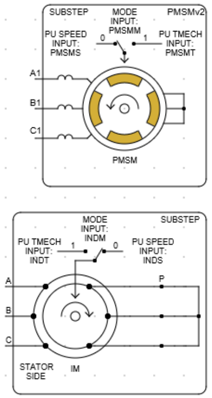
- **Introduction**
- **EV Powertrain Modeling**
  - Battery
  - Power Electronics
  - Motor
  - Mechanical
- **EV Powertrain Control**
- **Example Cases:**
  - EV Powertrain
  - Spatial Harmonics

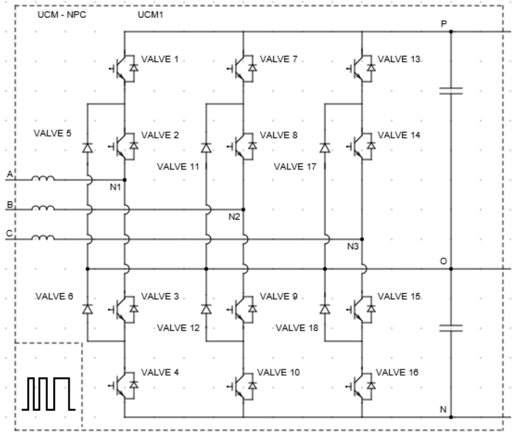
INTRODUCTION

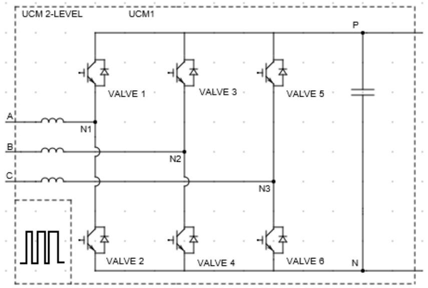
- Abundant component library for machines and power electronic converters.
- High-fidelity modeling in real time.

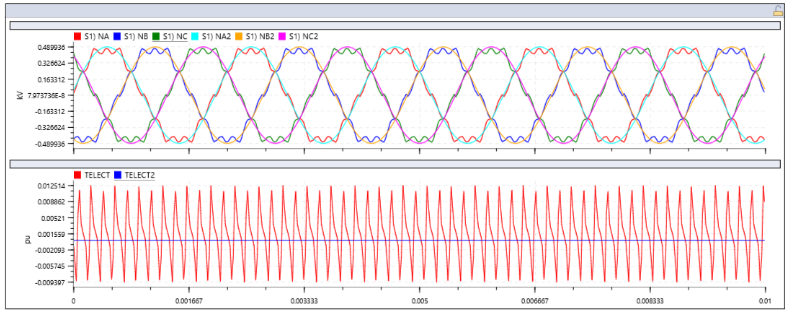
    - Improved firing pulse.

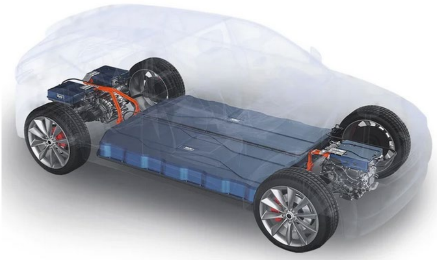
    - Flux defined PMSM derived from FEA.
- HIL test of EV powertrain
- Rapidly develop and validate EV powertrain design in a cost-effective way.



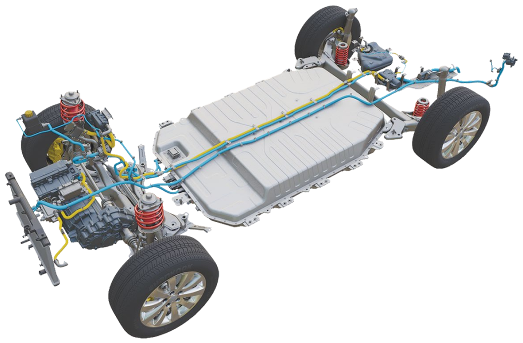






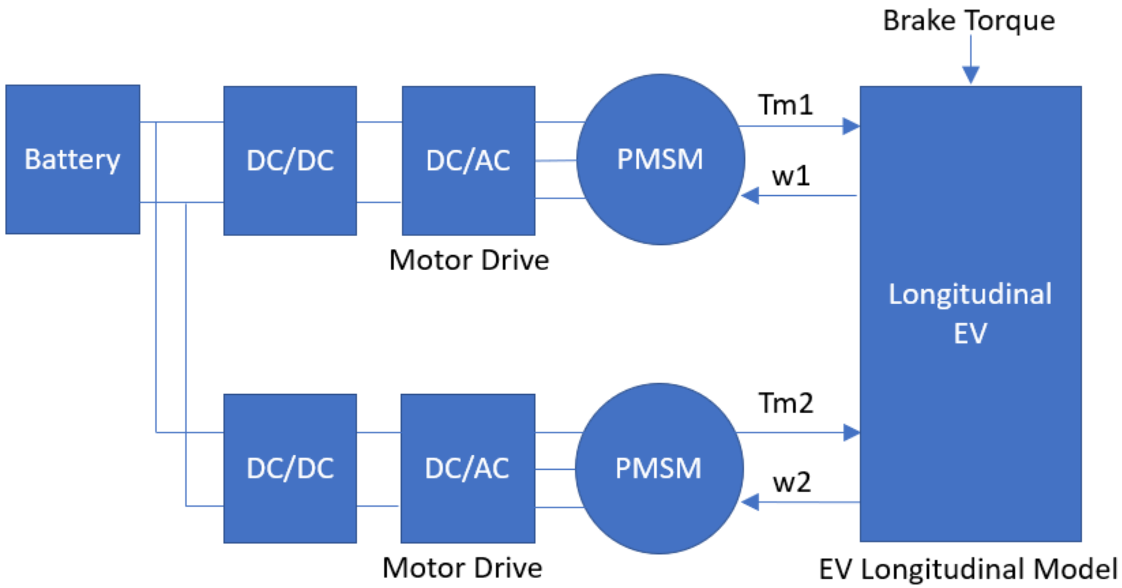


EV Powertrain

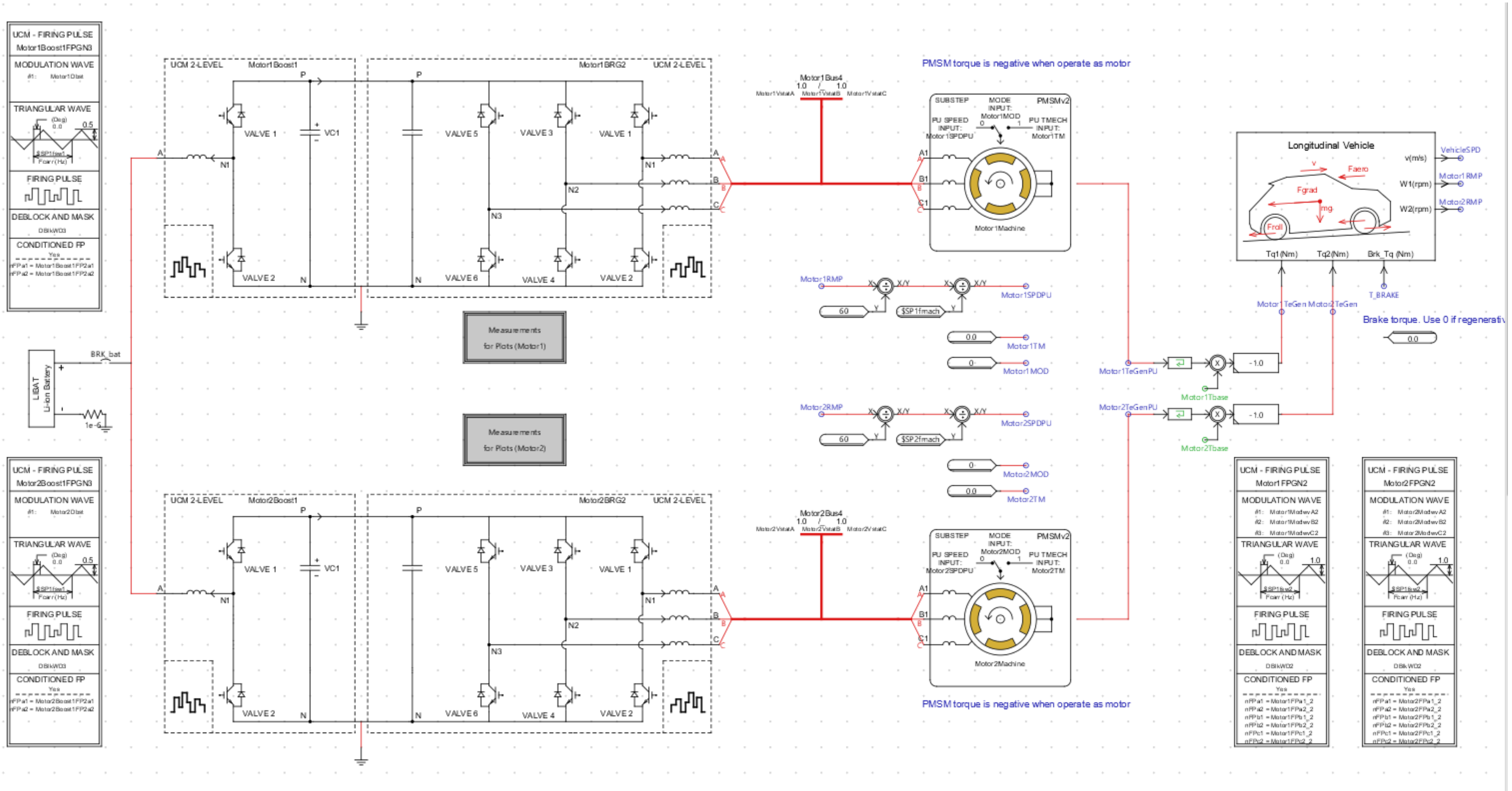


- The system that converts electrical energy into mechanical motion.
- Powertrain moves energy from battery to wheel and back.

  - Battery
  - Power electronics
  - Motor
  - Mechanical
  - Control

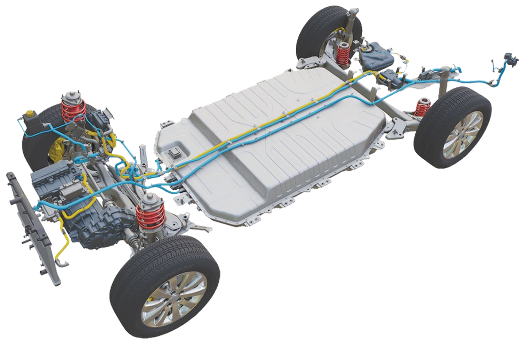


EV Powertrain

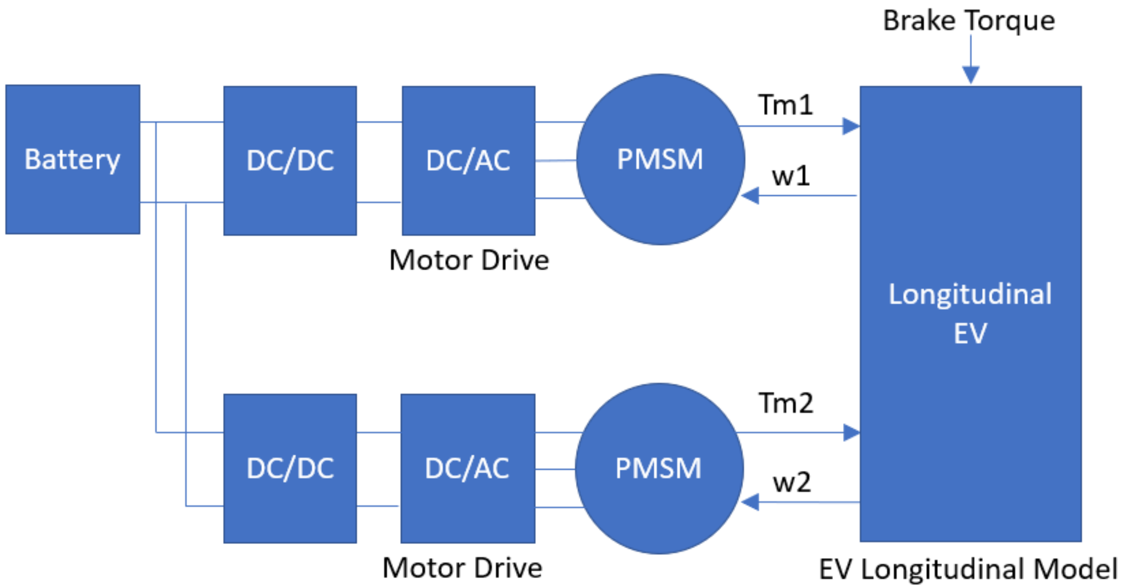


Example Cases / 12 Transportation / Electric Vehicles / EV Powertrain/ EV_Powertrain.rtfx

Li-ion Battery Model



- **Battery**
- Power electronics
- Motor
- Mechanical
- Control



Li-ion Battery Model

To model the electrical behavior of the battery, V-I characteristic

- Min/Rincon-Mora

C. Min and G. A. Rincon-Mora, "Accurate electrical battery model capable of predicting runtime and I-V performance," *Energy Conversion, IEEE Transactions on,* vol. 21, no. 2, pp.504-511, 2006.

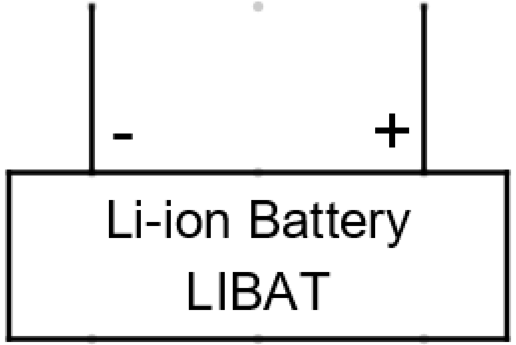
- Huria/Ceraolo/Gazzarri/Jackey

T. Huria, M. Ceraolo, J. Gazzarri, and R. Jackey, "High fidelity electrical model with thermal dependence for characterization and simulation of high power lithium battery cells," in *Electric Vehicle Conference (IEVC), 2012 IEEE International*, 2012, pp. 1-8.

- Shepherd

O. Tremblay, L. A. Dessaint, A. I. Dekkiche, "A generic battery model for the dynamic simulation of hybrid electric vehicles," Vehicle Power and Propulsion Conference, 2007,VPPC 2007, pp. 284-289, 9-12 Sept. 2007.

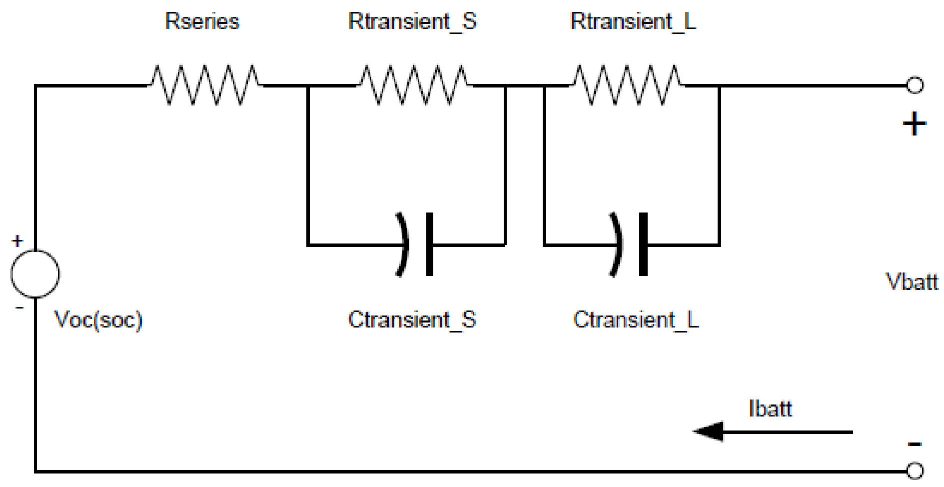
- Tabular Data



Li-ion Battery Model

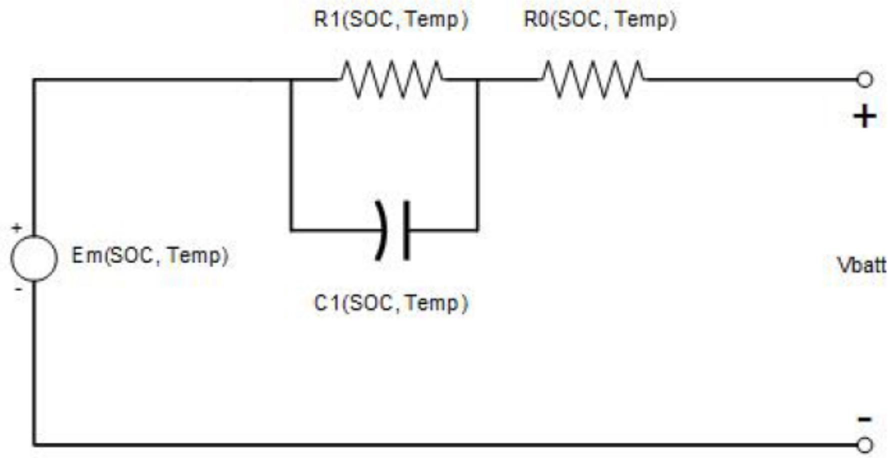
Min/Rincon-Mora

- Voc and R/C values are functions of SoC.
- Parameters are extracted from a commercial Li-ion battery product TCL-PL-383562 .



Huria/Ceraolo/Gazzarri/Jackey

- Both SoC and temperature are considered.
- Use text file to input Em and R/C values towards SoCs and temperatures.



Li-ion Battery Model

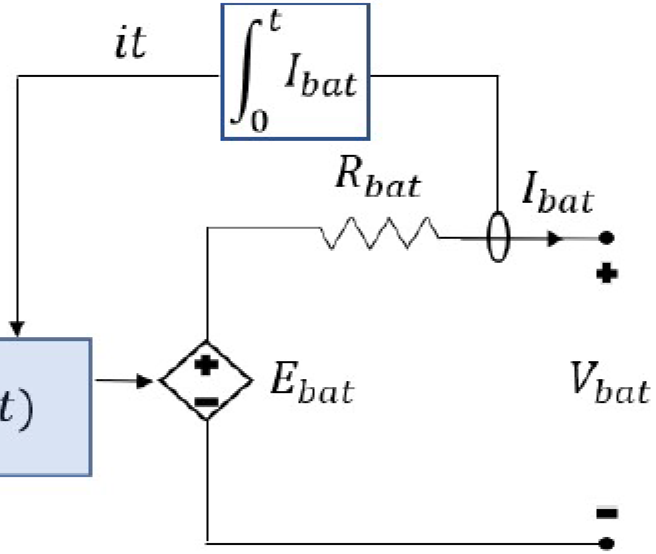
Shepherd

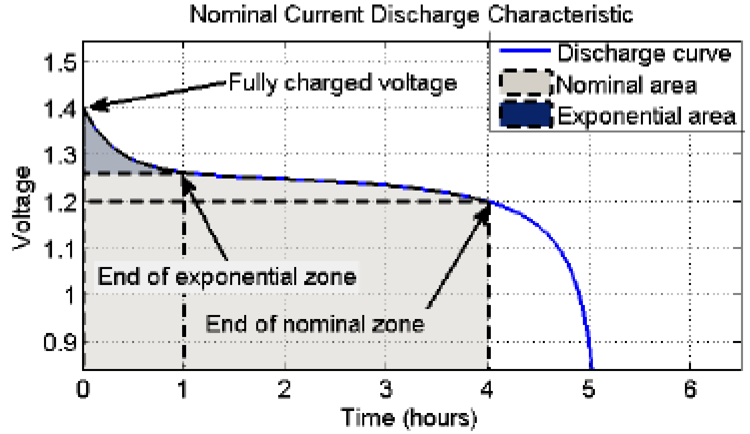
- Controlled V source behind resistor.
- Parameters can be obtained from discharge curve.

Tabular Data

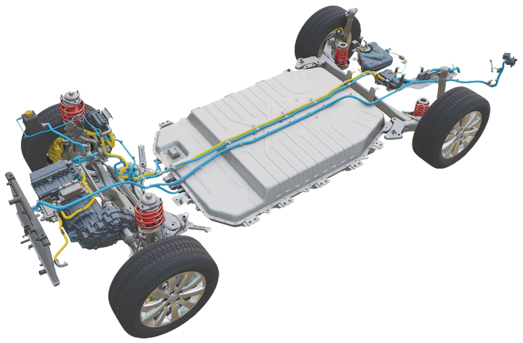
- Same equivalent circuit as Shepherd model.
- Input 10-points data tables of V(SoC) and R(SoC).

$$E_{bat} = E_0 - K\frac{Q}{Q - it} + A exp(-B.it)$$

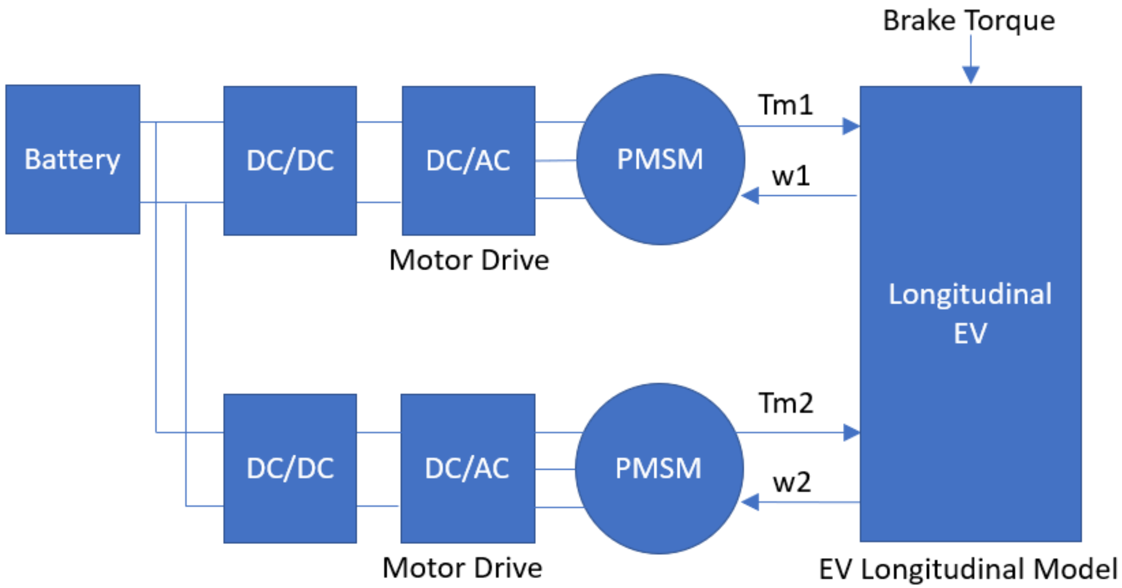




Universal Converter Model (UCM)

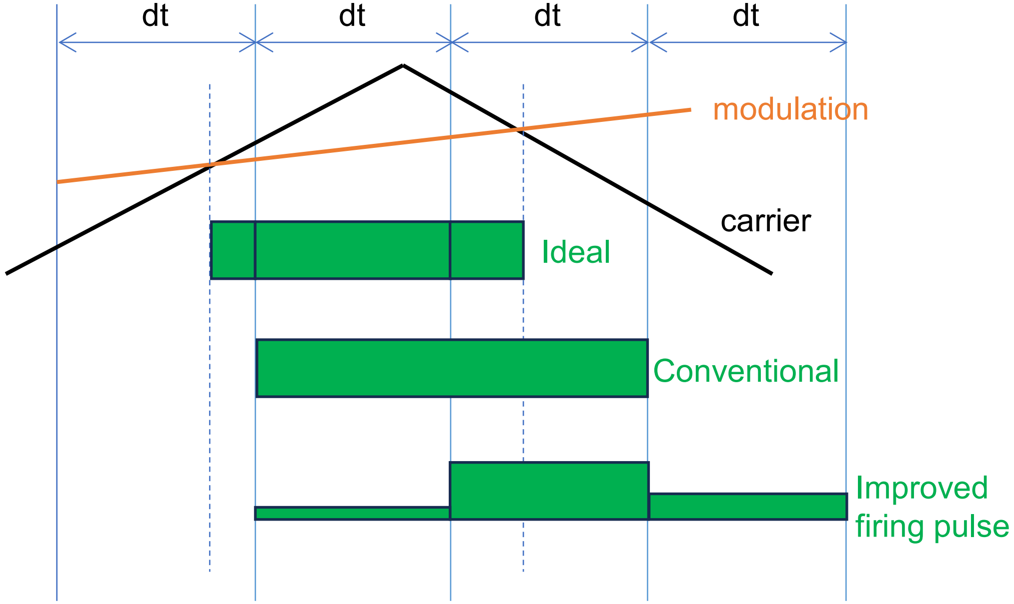


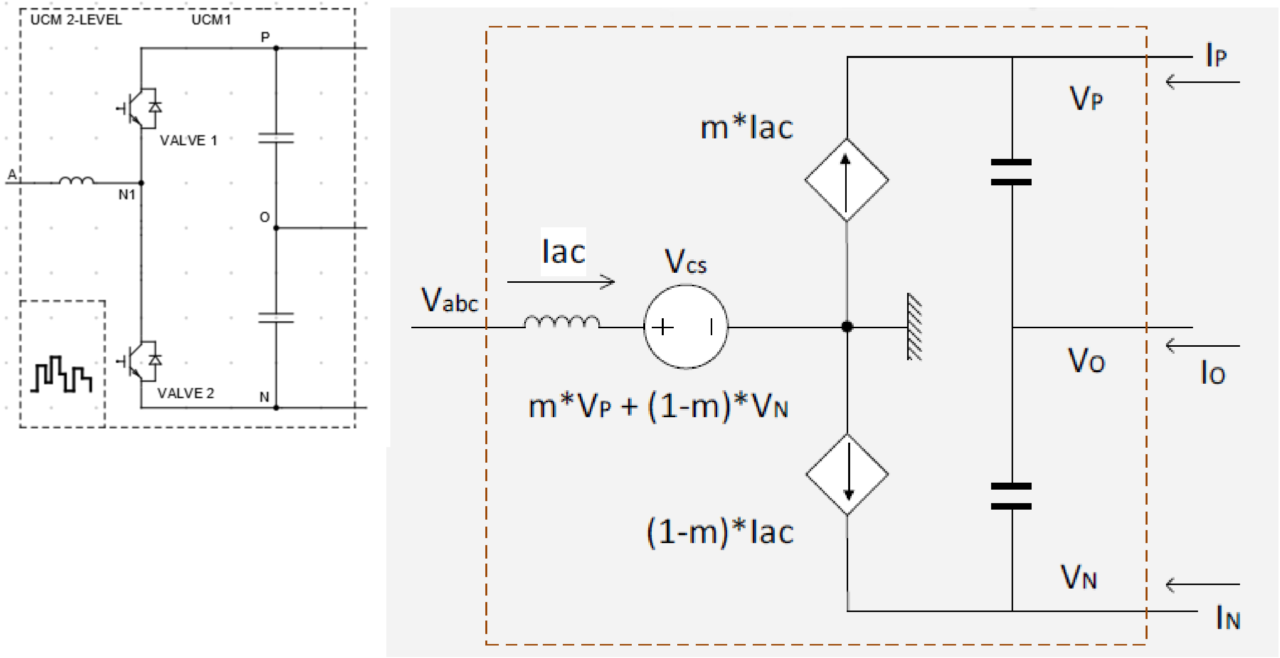
- Battery
- **Power electronics**
- Motor
- Mechanical
- Control



Universal Converter Model (UCM)

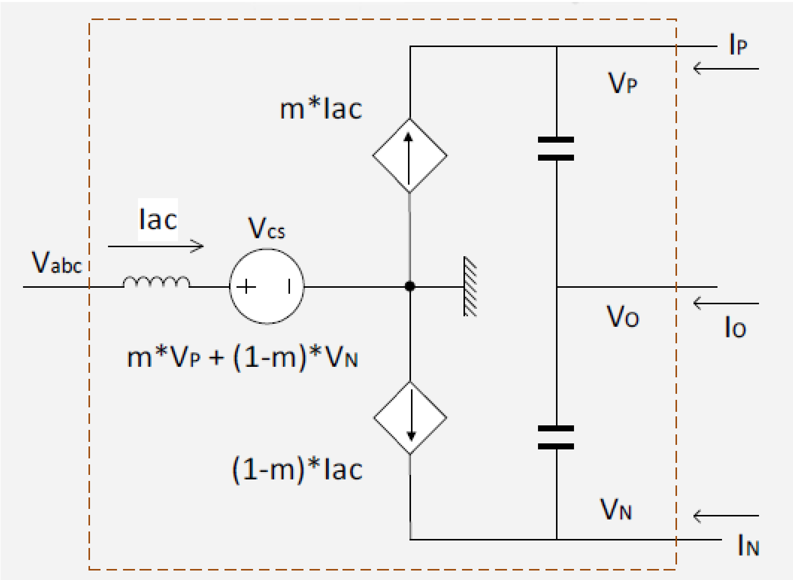
- A challenge of simulating power electronics is maintaining the high accuracy of PWM.
- Improved firing pulse - use duty cycle within one time step to model power electronics.





Universal Converter Model (UCM)

- Use Descriptor State Space to eliminate controlled source delay.
- Embedded approach provides higher stability and accuracy – Numerical stability guaranteed.



Differential Equations

$$\begin{cases} L\dfrac{\mathbf{di_{ac}}}{\mathbf{dt}} + \mathbf{Ri_{ac}} + \mathbf{v_{CS}} = \mathbf{v_{abc}} \\ i_{C\_P} = C\dfrac{d(v_P - v_O)}{dt} \\ i_{C\_N} = C\dfrac{d(v_N - v_O)}{dt} \end{cases}$$

Algebraic Equations

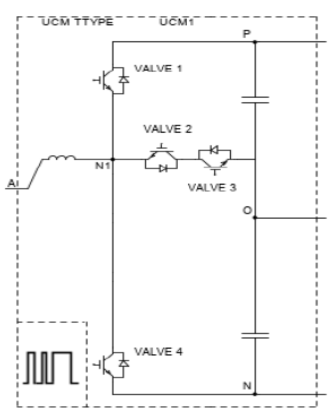
$$\begin{cases} \mathbf{v_{CS}} = \mathbf{m} \cdot v_P + (\mathbf{1} - \mathbf{m}) \cdot v_N \\ i_{CS\_P} = \mathbf{m}^{\mathbf{T}} \cdot \mathbf{i_{ac}} \\ i_{CS\_N} = (\mathbf{1} - \mathbf{m})^{\mathbf{T}} \cdot \mathbf{i_{ac}} \\ i_{ac\_a} + i_{ac\_b} + i_{ac\_c} + i_P + i_N + i_O = 0 \end{cases}$$

DSS

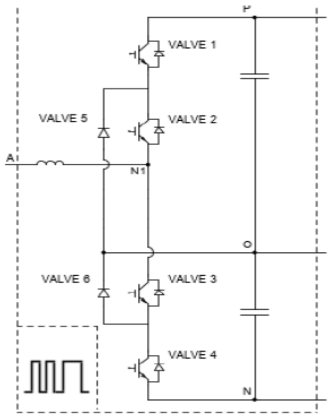
$$\mathbf{i} = \mathbf{Gv} + \mathbf{i_{his}}$$

Universal Converter Model (UCM)

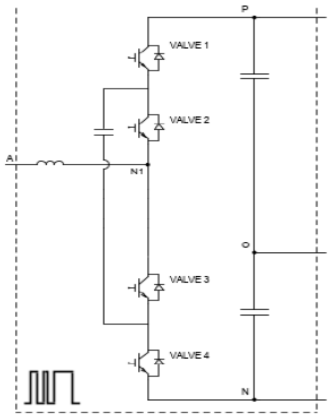
- Models supported in the Library



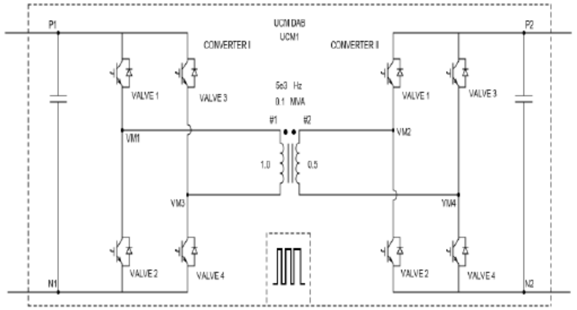
DESCRIPTOR STATE-SPACE
THREE LEVEL T-TYPE CONVERTER

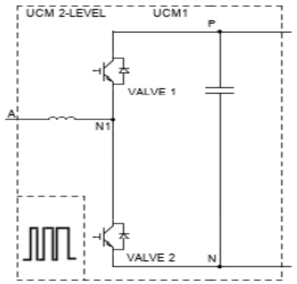


DESCRIPTOR STATE-SPACE
THREE LEVEL NPC CONVERTER

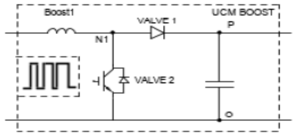


DESCRIPTOR STATE-SPACE
THREE LEVEL FLYCAP CONVERTER

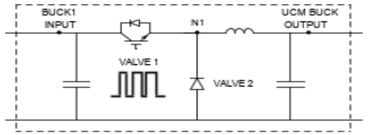




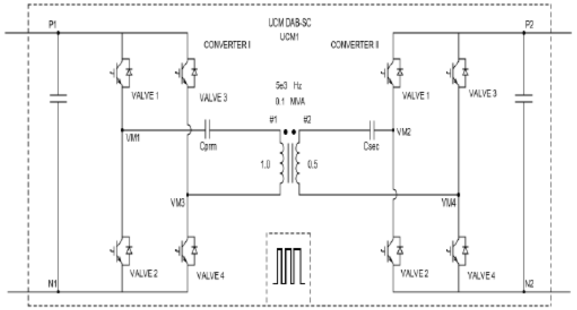
DESCRIPTOR STATE-SPACE
TWO LEVEL CONVERTER



DESCRIPTOR STATE-SPACE
BOOST CONVERTER



DESCRIPTOR STATE-SPACE
BUCK CONVERTER



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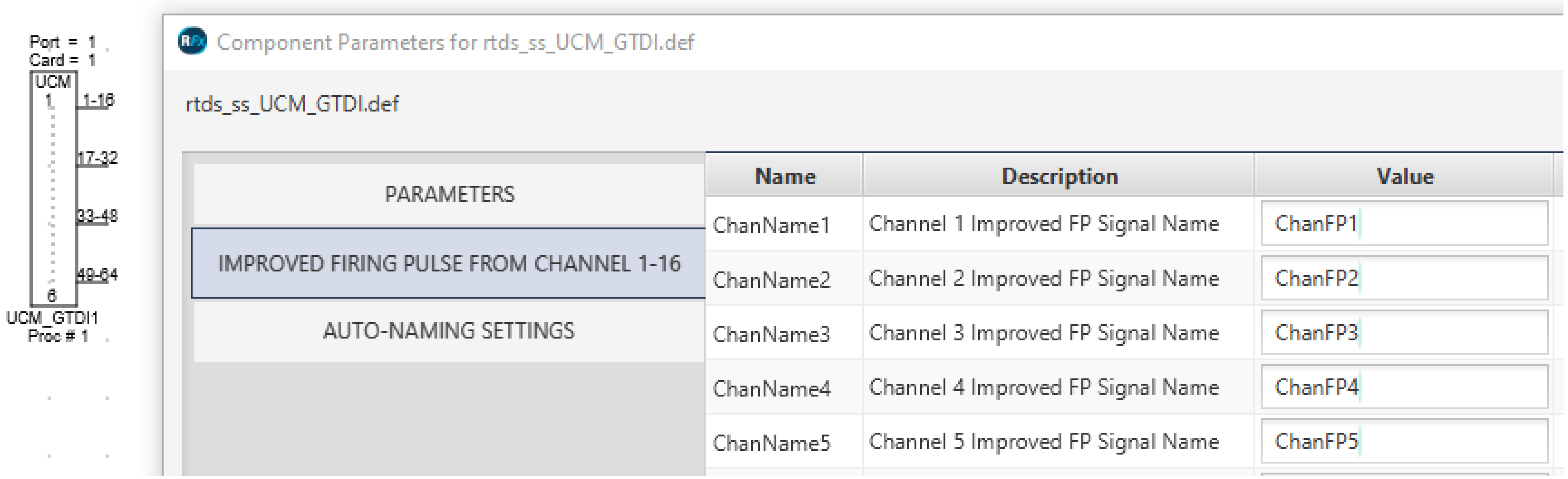
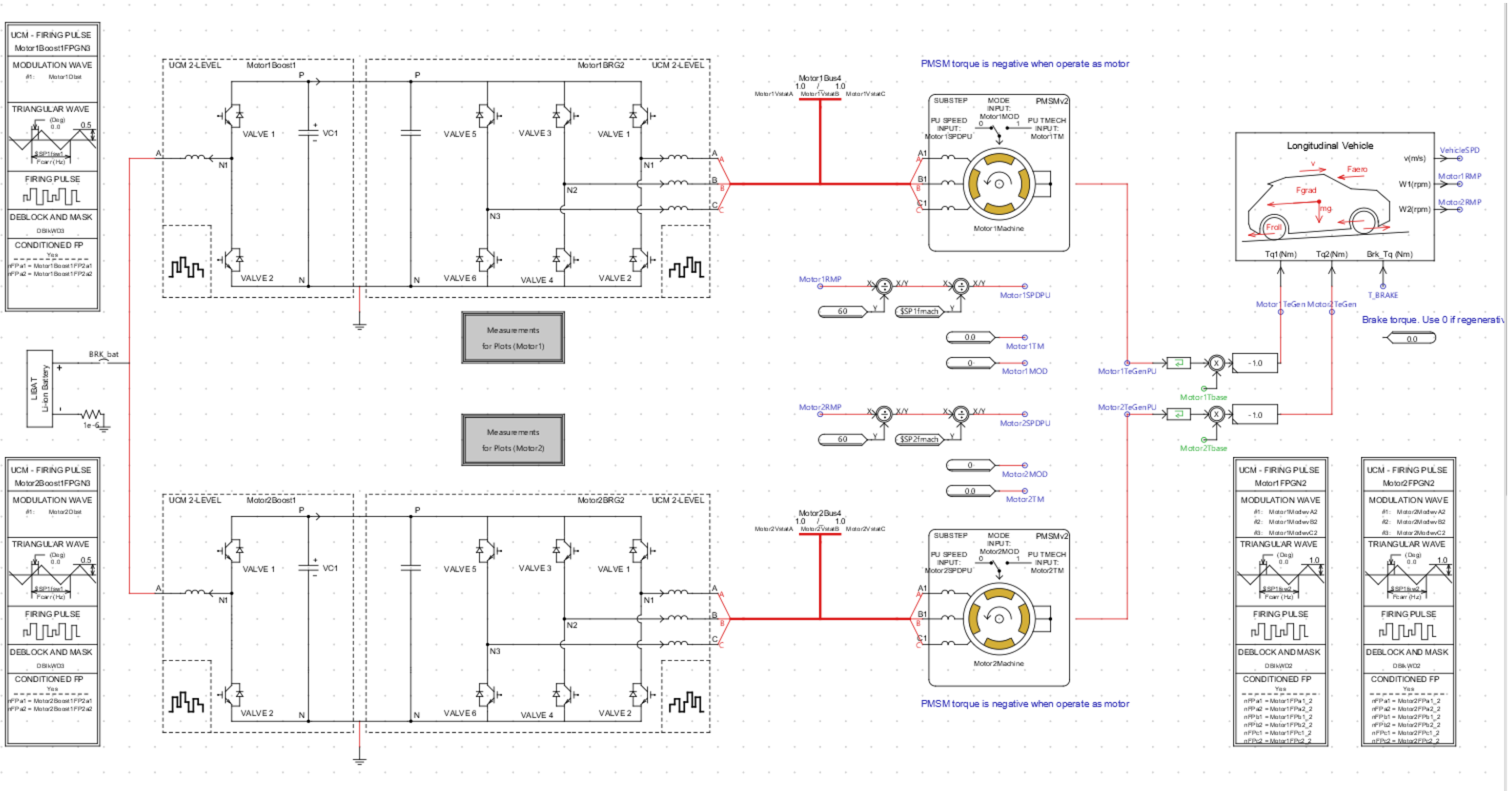
Universal Converter Model (UCM)

- GTDI supports improved firing pulse in HIL.
- 10.0ns Resolution

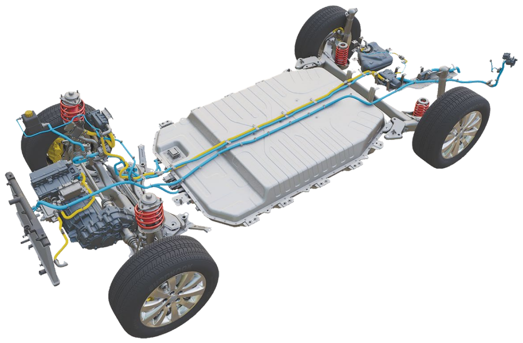


Universal Converter Model (UCM)

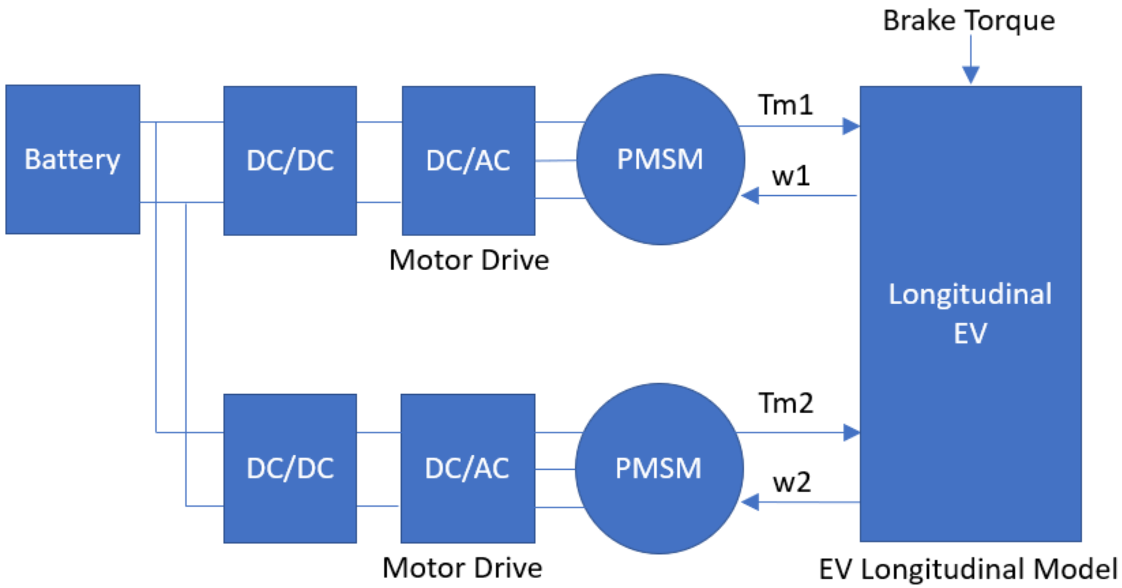
- dc-dc booster stage
- three phase 2 level converter



Motor Model

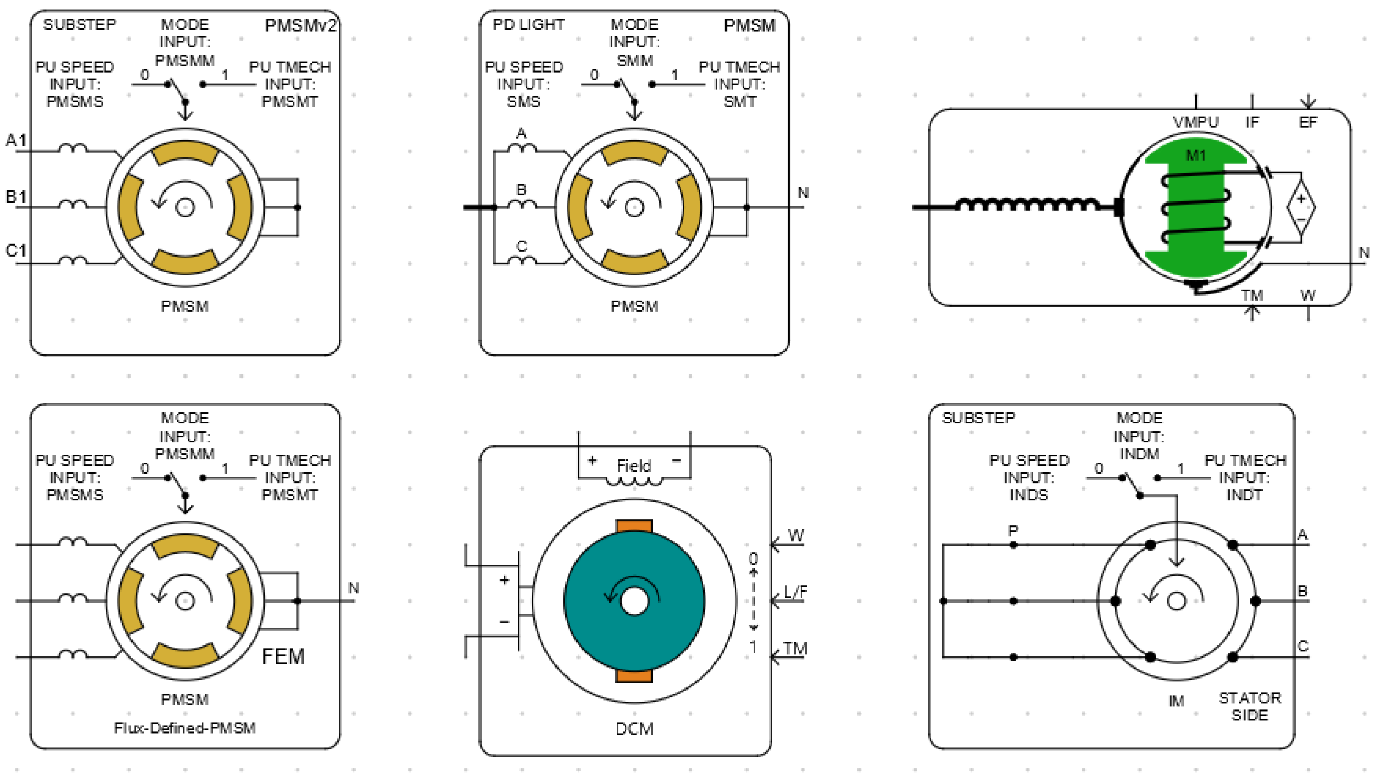


- Battery
- Power electronics
- **Motor**
- Mechanical
- Control



Motor Model

- Classic PMSM
- Flux-defined PMSM



Motor Model

- Classic PMSM
  - Flux equations

$$\begin{cases} \varphi_d = L_d i_d + \varphi_f \\ \varphi_q = L_q i_q \end{cases}$$

  - Stator voltage equations

$$\begin{cases} u_d = R_s i_d + \dfrac{d\varphi_d}{dt} - \omega_e \varphi_q \\ u_q = R_s i_q + \dfrac{d\varphi_q}{dt} + \omega_e \varphi_d \end{cases}$$

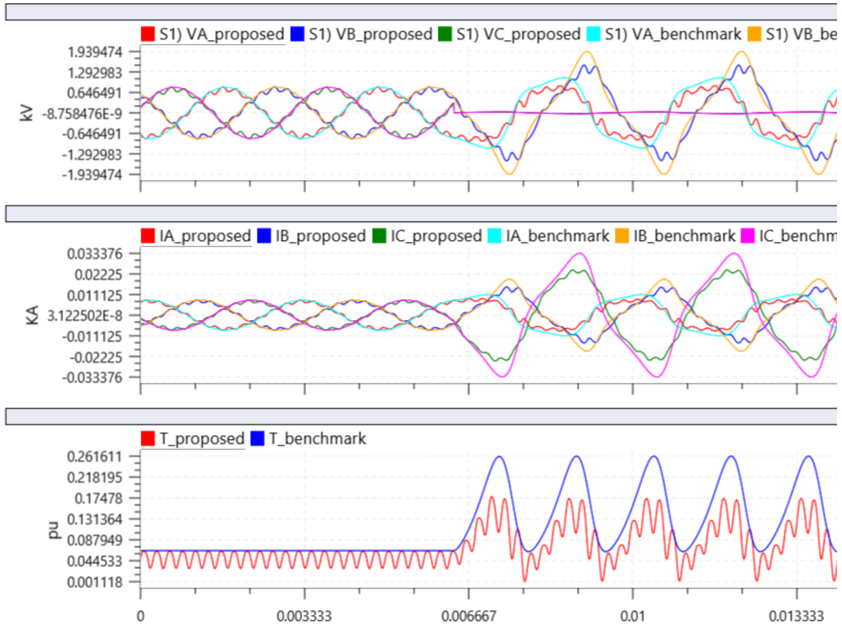
  - Torque equation

$$T_e = 1.5p\left[\varphi_f i_q + \left(L_d - L_q\right) i_d i_q\right]$$

  - Rotor motion equation

$$\frac{1}{p}\frac{d\omega_e}{dt} = \frac{1}{J}\left(T_e - \frac{D}{p}\omega_e - T_{load}\right)$$

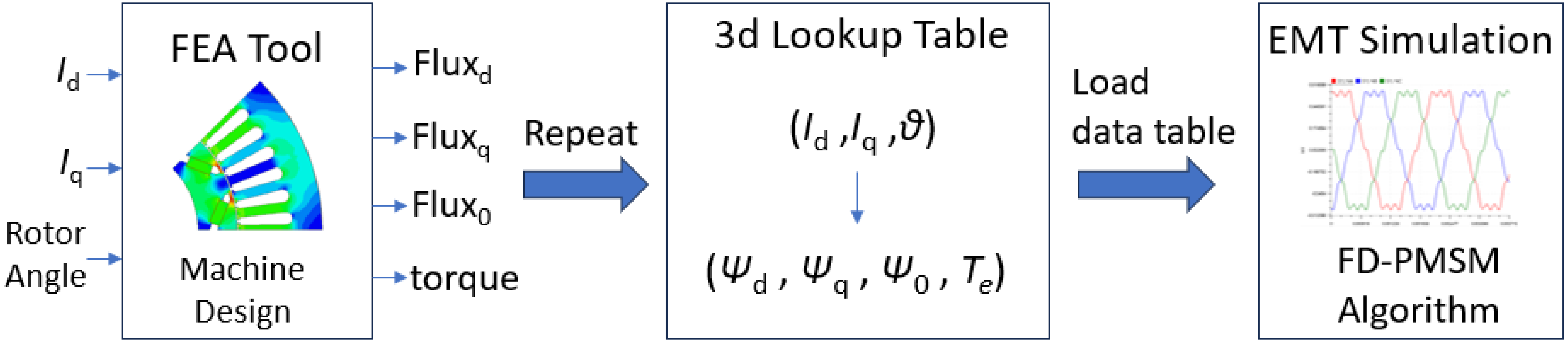
- Lumped parameter model
- Cannot model spatial harmonics and cogging torques



- Flux-defined PMSM
  - Flux equations and torque equation are replaced with data tables generated from FEA tools.

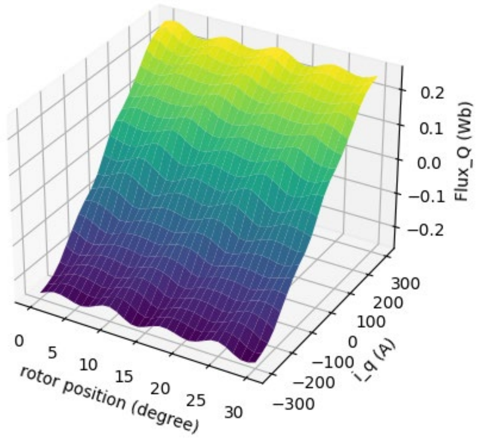
Motor Model

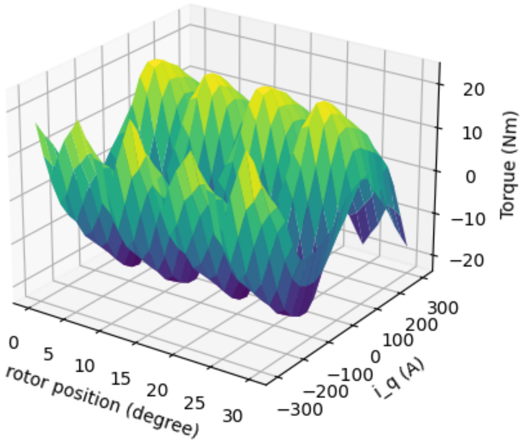
- Flux-defined PMSM
  - Finite Element Analysis tools can use highly accurate methods to solve electromagnetic fields.
  - For a given set of excitation currents and rotor position, FEA can compute the flux distribution and torque.
  - A 3-d lookup table can be generated by performing a “sweep” on all combinations of Id, Iq and rotor angle.



Motor Model

- Flux-defined PMSM
  - Data generated by Ansys/Maxwell ECE function
  - Total rows would be 21*21*31=13671

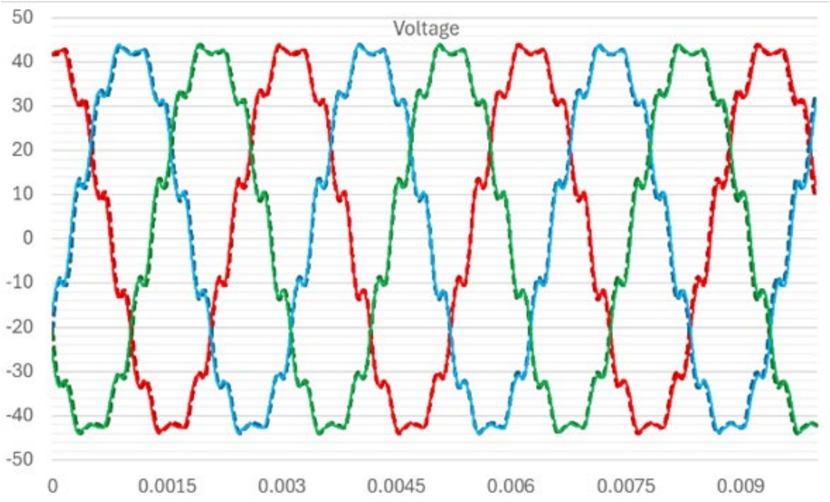


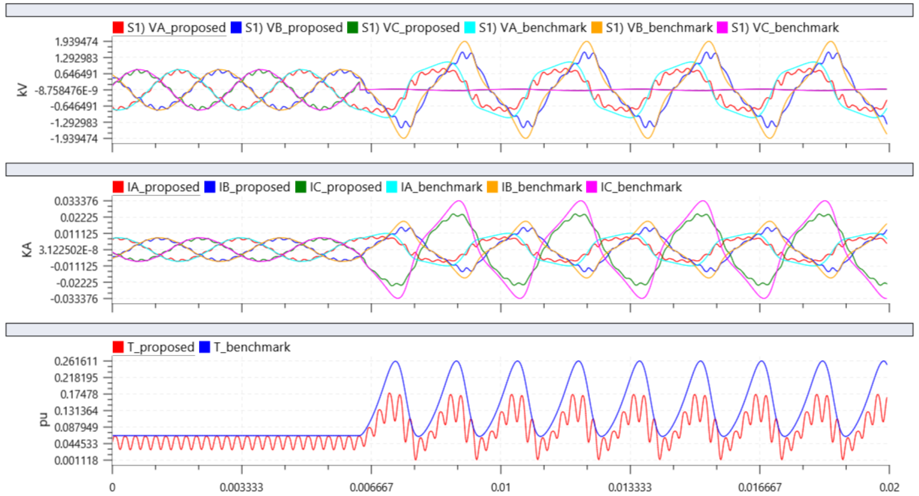



```
B_BasicData
 Version  1.0
 Poles    8
E_BasicData

B_PhaseImp 3
   PhaseA  1.0000000000e-003  1.0000000000e-006
   PhaseB  1.0000000000e-003  1.0000000000e-006
   PhaseC  1.0000000000e-003  1.0000000000e-006
E_PhaseImp

B_Sweepings
 Id_Iq    (21:  -300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 210 240 270 300)
          (21:  -300 -270 -240 -210 -180 -150 -120 -90 -60 -30 0 30 60 90 120 150 180 210 240 270 300)
 Rotate   (31:  0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30)
E_Sweepings

B_OutputMatrix DQ0
    0  -9.2992778243e-002  -3.0267057235e-001   1.8234800169e-002  4.6104655919e+002
    1  -9.0987676349e-002  -3.0591807470e-001   1.9205679741e-002  4.1951713926e+002
    2  -8.4771017229e-002  -3.0776350351e-001   1.9448601014e-002  3.8224325587e+002
    3  -8.1105538603e-002  -3.0778243236e-001   1.9480541950e-002  3.4842625386e+002
    4  -8.0991824528e-002  -3.0660917961e-001   1.9328136663e-002  3.3666929706e+002
    5  -8.3725854584e-002  -3.0516375461e-001   1.8923147654e-002  3.4482692458e+002
    6  -8.8431807922e-002  -3.0396281275e-001   1.8149772802e-002  3.6937339901e+002
    7  -9.1739531935e-002  -3.0347772145e-001   1.6688733461e-002  3.9970419846e+002
    8  -9.1400959733e-002  -3.0314844055e-001   1.4001437832e-002  4.1192991736e+002
    9  -9.0281147169e-002  -3.0255198064e-001   1.0137452648e-002  3.9595926812e+002
   10  -9.2130887481e-002  -3.0068516688e-001   4.7279733575e-003  3.6825854118e+002
   11  -9.7778924694e-002  -2.9819642524e-001  -1.7938397942e-003  3.5193638803e+002
   12  -1.0572831705e-001  -2.9638982864e-001  -8.7427508258e-003  3.5824958202e+002
```

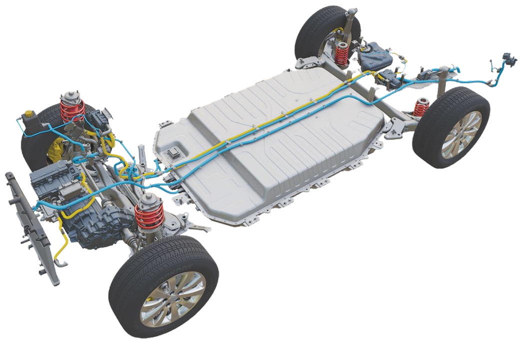
Motor Model

- Flux-defined PMSM
  - High fidelity PMSM model, same level of accuracy as FEA
  - Close gap between machine design and powertrain design without manufacturing the real machine
    - Data is available once machine being designed.
    - Old way relies on parameters obtained from test measurements of a real machine.





Model of Longitudinal Vehicle



- Battery
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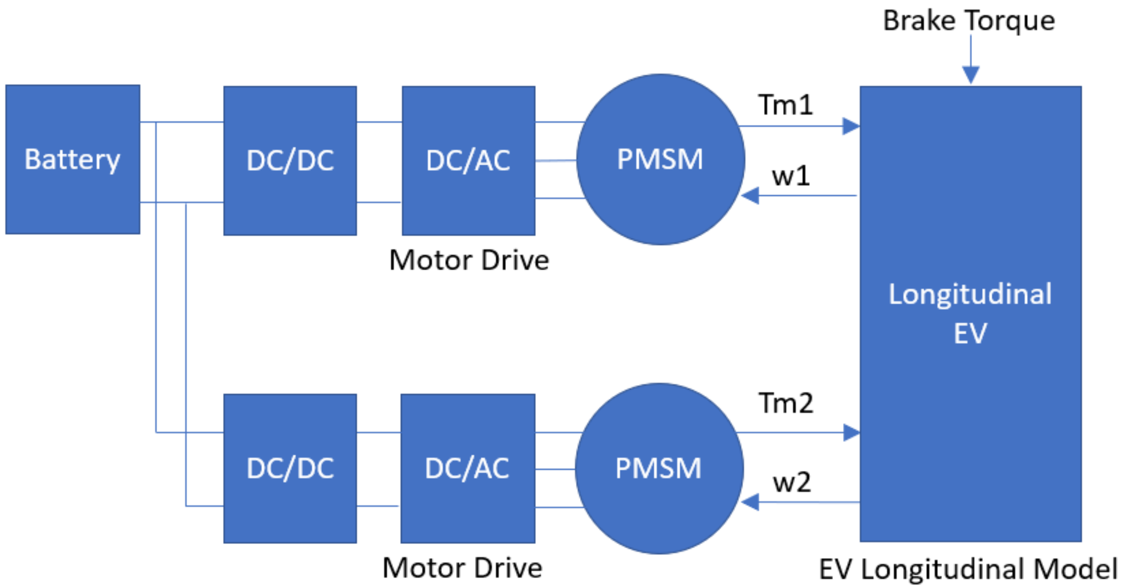
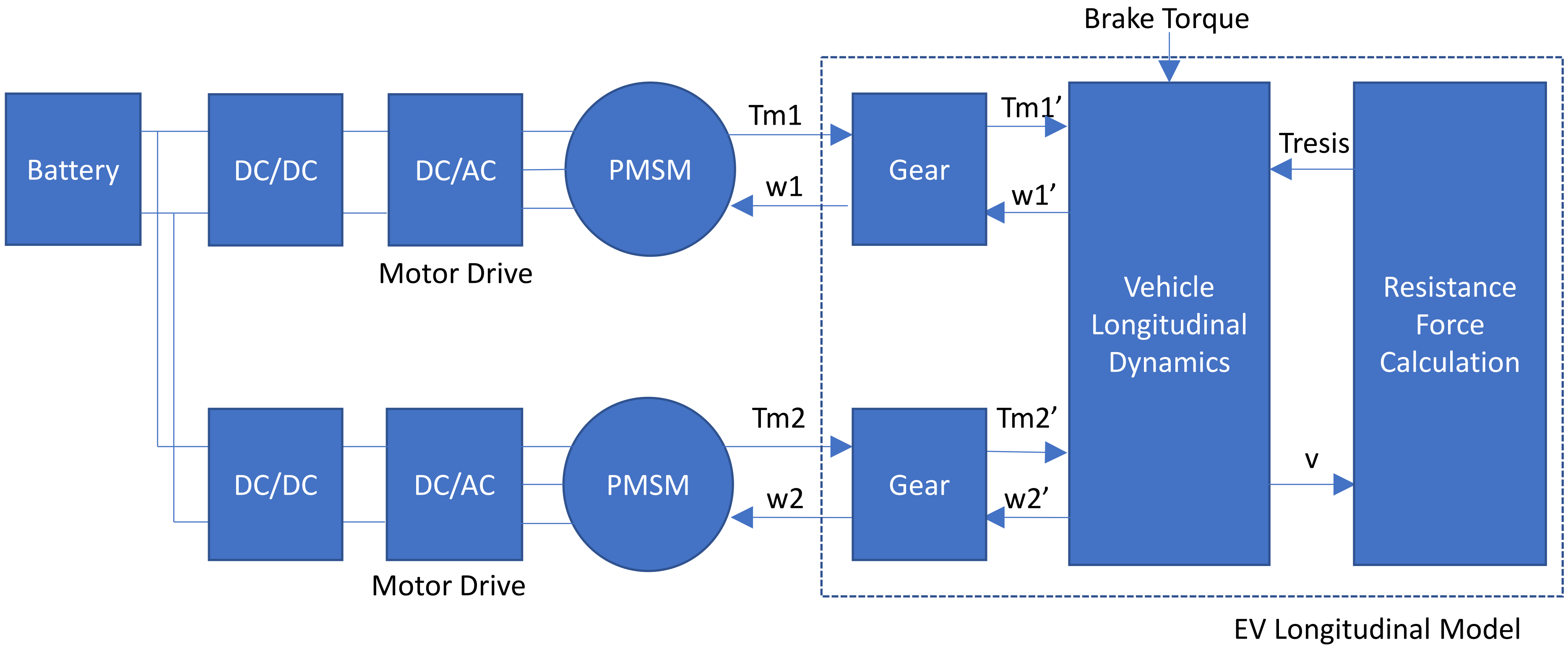
- Motor
- **Mechanical**
- Control



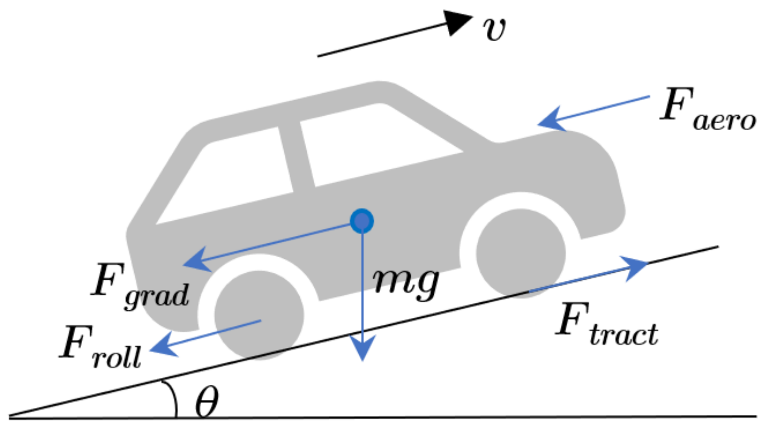
Model of Longitudinal Vehicle

- Longitudinal Model – An abstract vehicle confined to longitudinal motion.

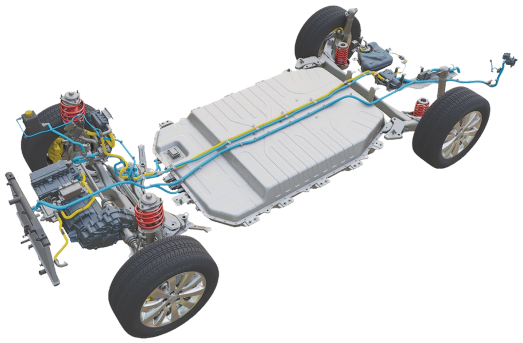


Model of Longitudinal Vehicle

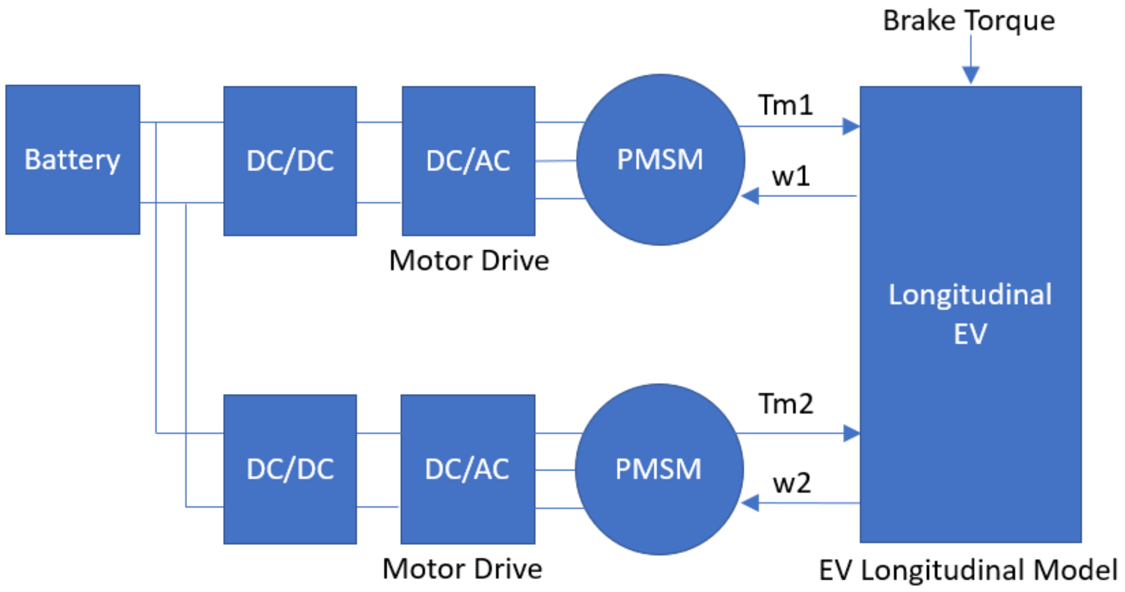
Rolling resistance	$F_{roll} = C_{rr} \cdot mg \cdot cos\theta$
Aerodynamic resistance	$F_{aero} = 0.5 \cdot \rho \cdot A \cdot v^2 \cdot C_{ar}$
Gradient resistance	$F_{grad} = mg \cdot sin\theta$
Tractive force	$F_{tract} = \frac{\sum T_{wheel}}{r} = \frac{\sum(k_{gear} T_{motor})}{r}$
Acceleration	$a = (F_{tract} - F_{roll} - F_{aero} - F_{grad} - F_{brake})/m$



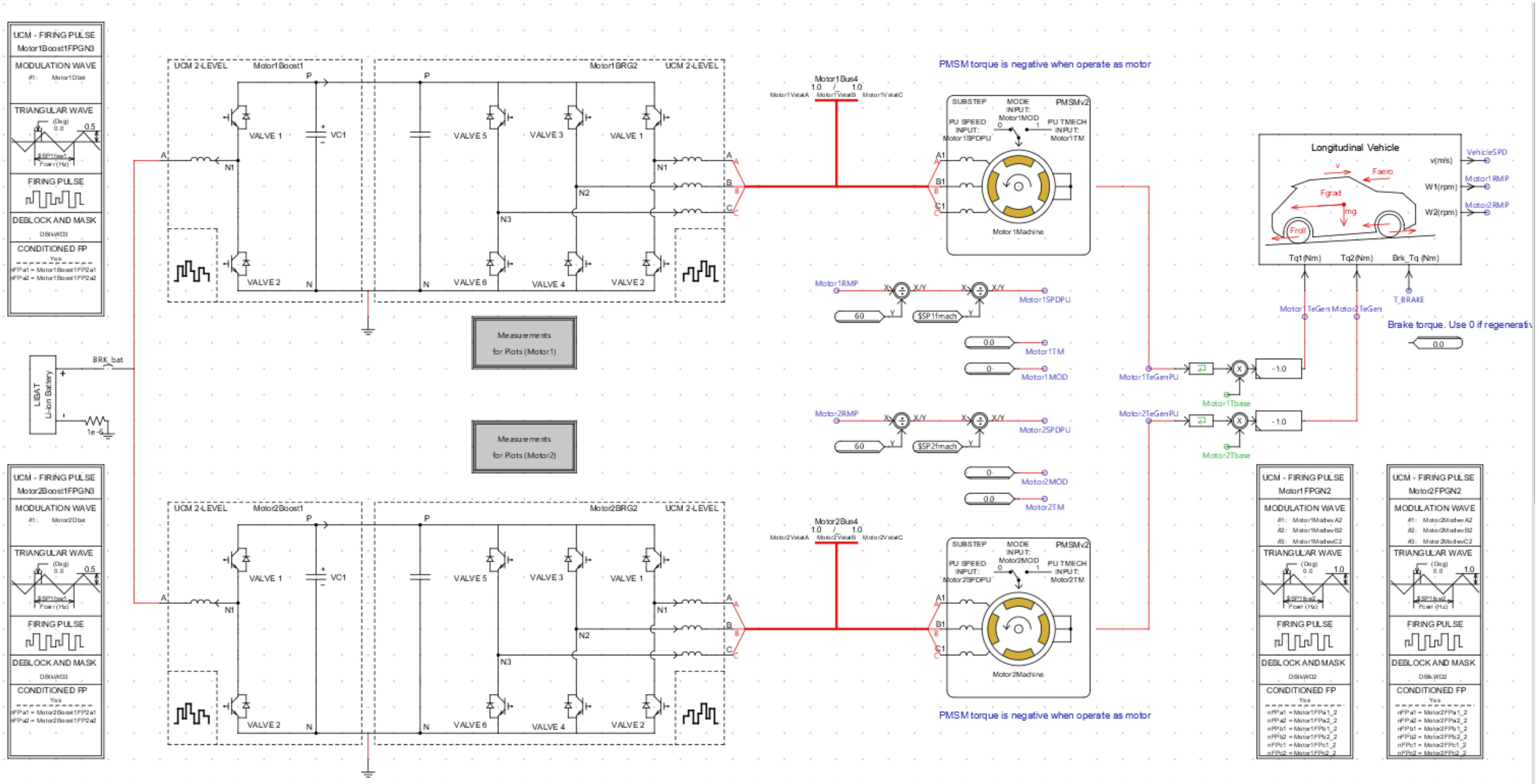
Control of EV Powertrain



- Battery
- Power electronics
- Motor
- Mechanical
- **<u>Control</u>**



EV Powertrain



Control of PMSM

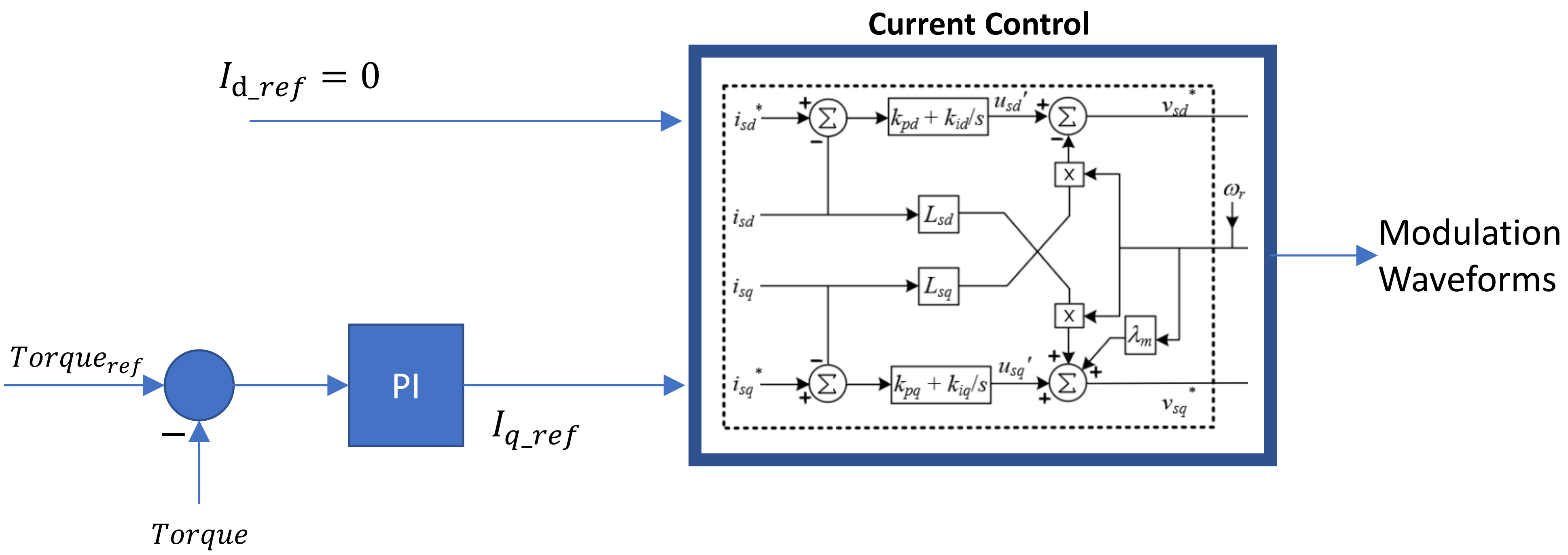
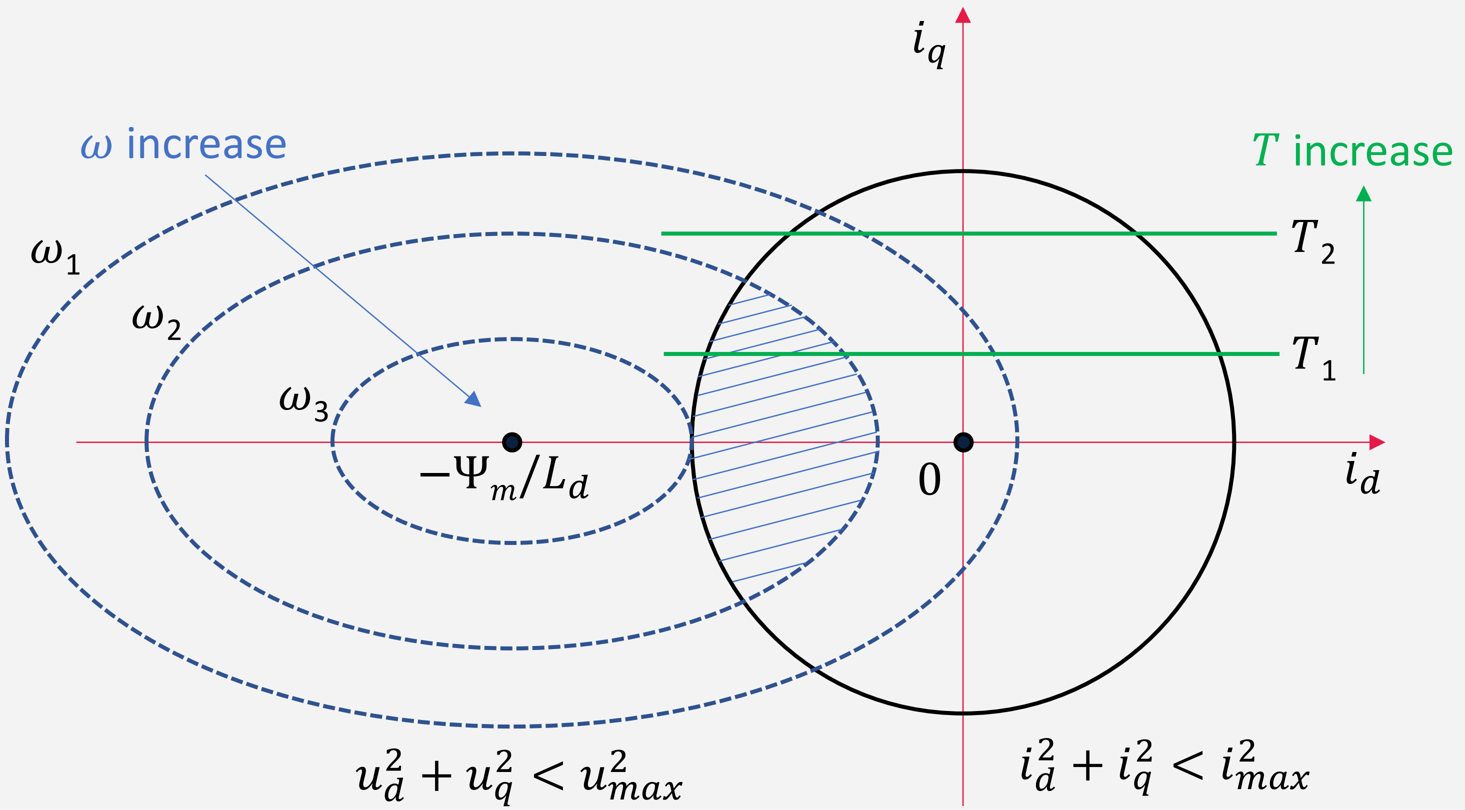


Figure 3-2 Basic Control of PMSM

$$T_{em} = 1.5p\left[\Psi_f i_q + \left(L_d - L_q\right) i_d i_q\right]$$

- For hidden pole (SPMSM), Ld=Lq, $T_{em} = 1.5p\Psi_f i_q$. Set Id=0.

Field Weakening Control



$$v_d = r_s \cdot i_d + \frac{d}{dt}\Psi_d + \omega_r \cdot \Psi_q$$
$$v_q = r_s \cdot i_q + \frac{d}{dt}\Psi_q + \omega_r \cdot \Psi_d$$

$$\Psi_d = L_d \cdot i_d + L_{md} \cdot i_D + \Psi_m$$
$$\Psi_q = L_q \cdot i_q + L_{mq} \cdot i_Q$$

$$T_{em} = 1.5p\Psi_f i_q$$

Figure 3-3 PMSM Current Trajectory

Field Weakening Control

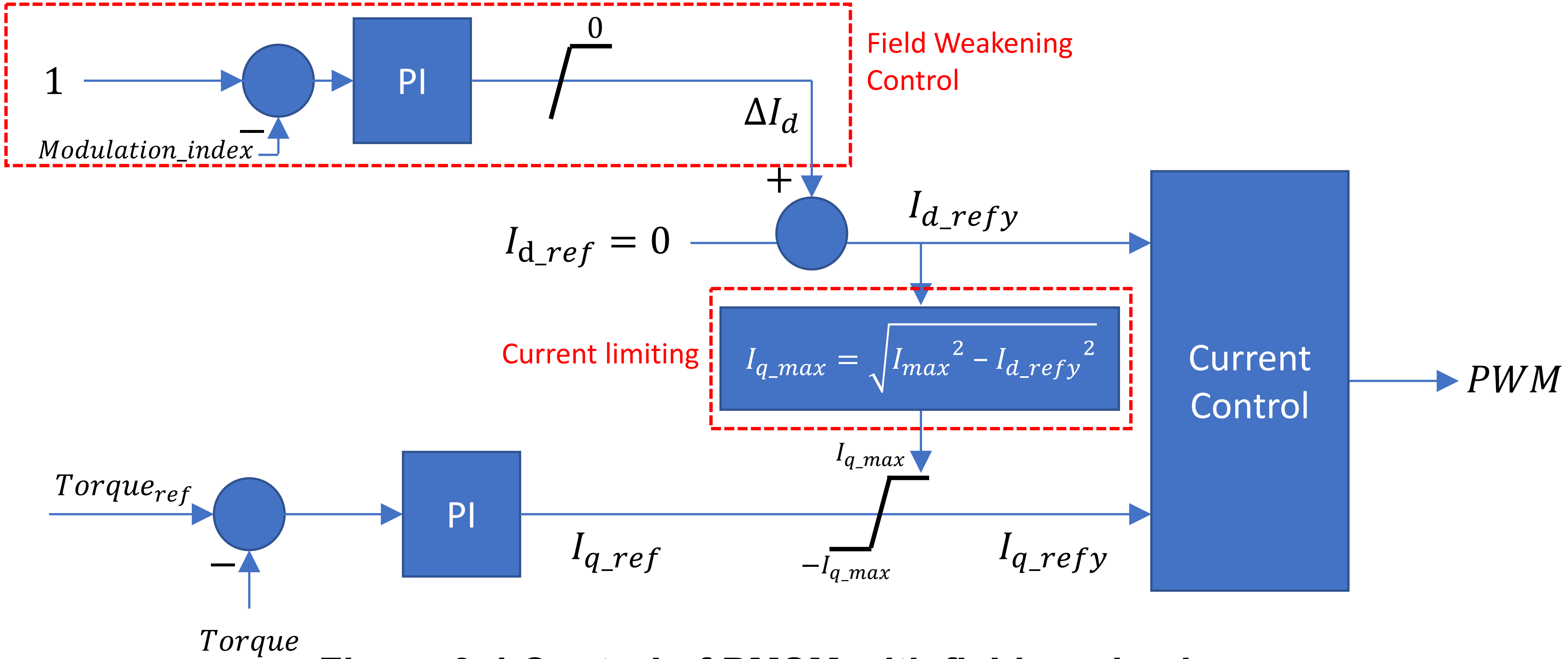
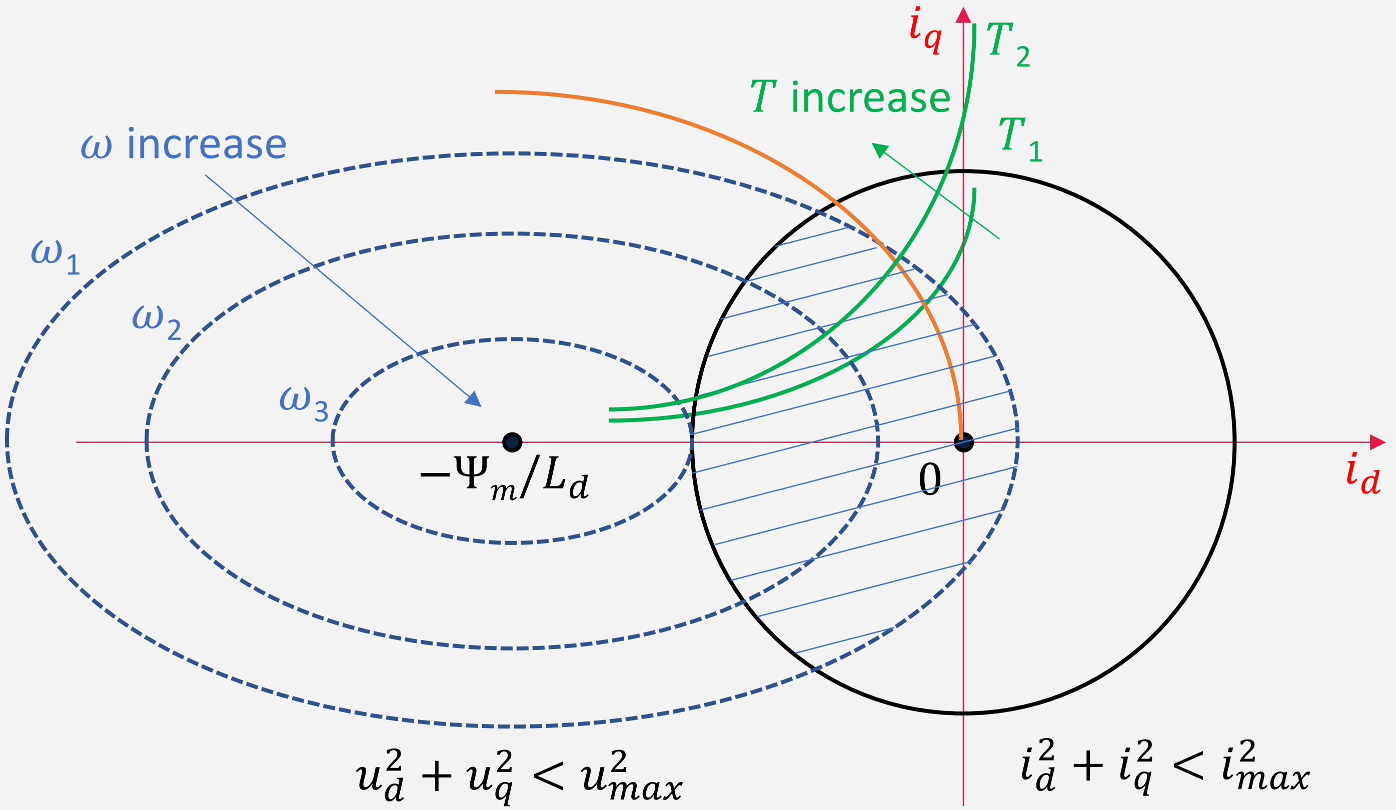


Figure 3-4 Control of PMSM with field weakening

- A PI control loop is added to keep modulation index at a certain value when speed is high.
- Use lookup table to directly follow the trajectory – accuracy depends on estimated parameters

Maximum Torque Per Amp



$$T_{em} = 1.5p\left[\Psi_f i_q + \left(L_d - L_q\right) i_d i_q\right]$$

- For salient pole (IPMSM), Ld≠Lq

$$i_d = \frac{-\Psi_f + \sqrt{{\Psi_f}^2 + 4\left(L_d - L_q\right)^2 {i_q}^2}}{2\left(L_d - L_q\right)}$$

Figure 3-5 PMSM Current Trajectory

Maximum Torque Per Amp

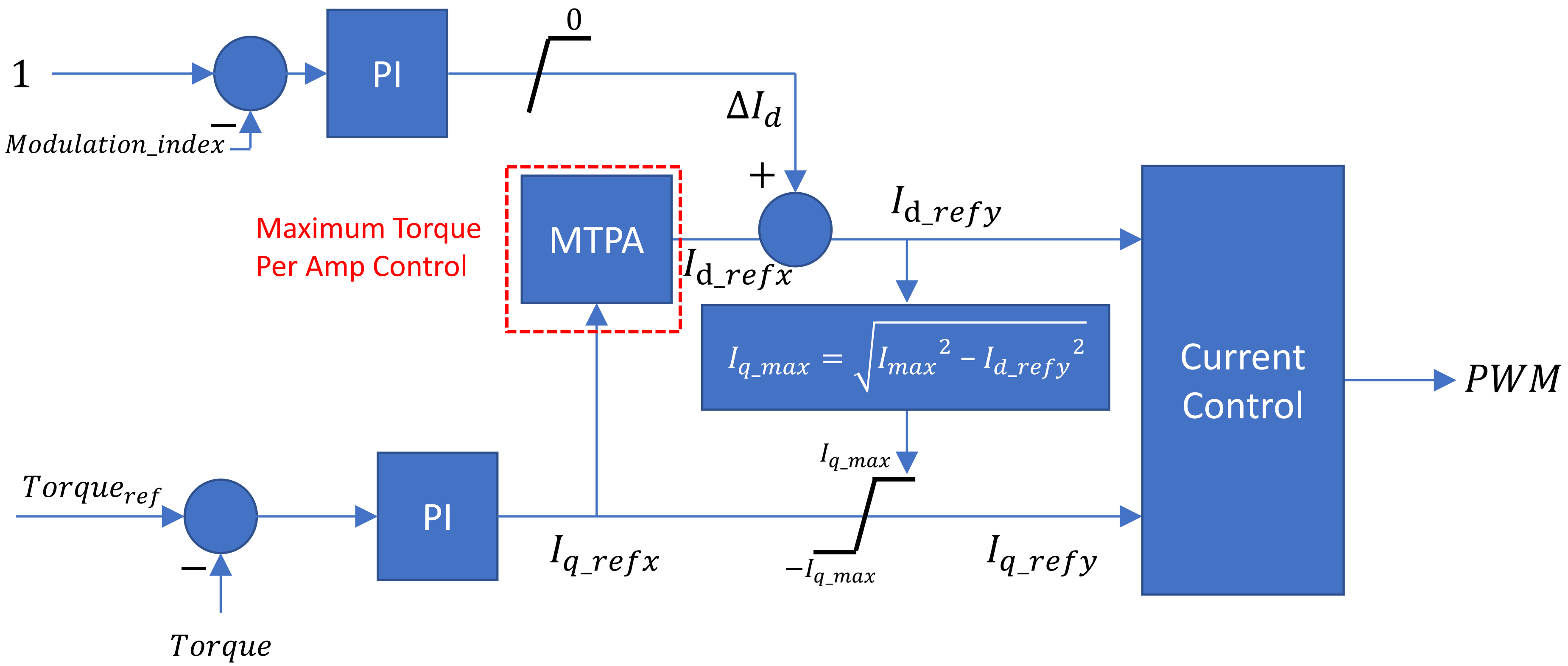


Figure 3-6 Control of PMSM with MTPA and field weakening

- MPTA can be based on the equation or lookup table.

RTDS EV Powertrain Example Demo

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EXAMPLE CASE 1 – EV Powertrain

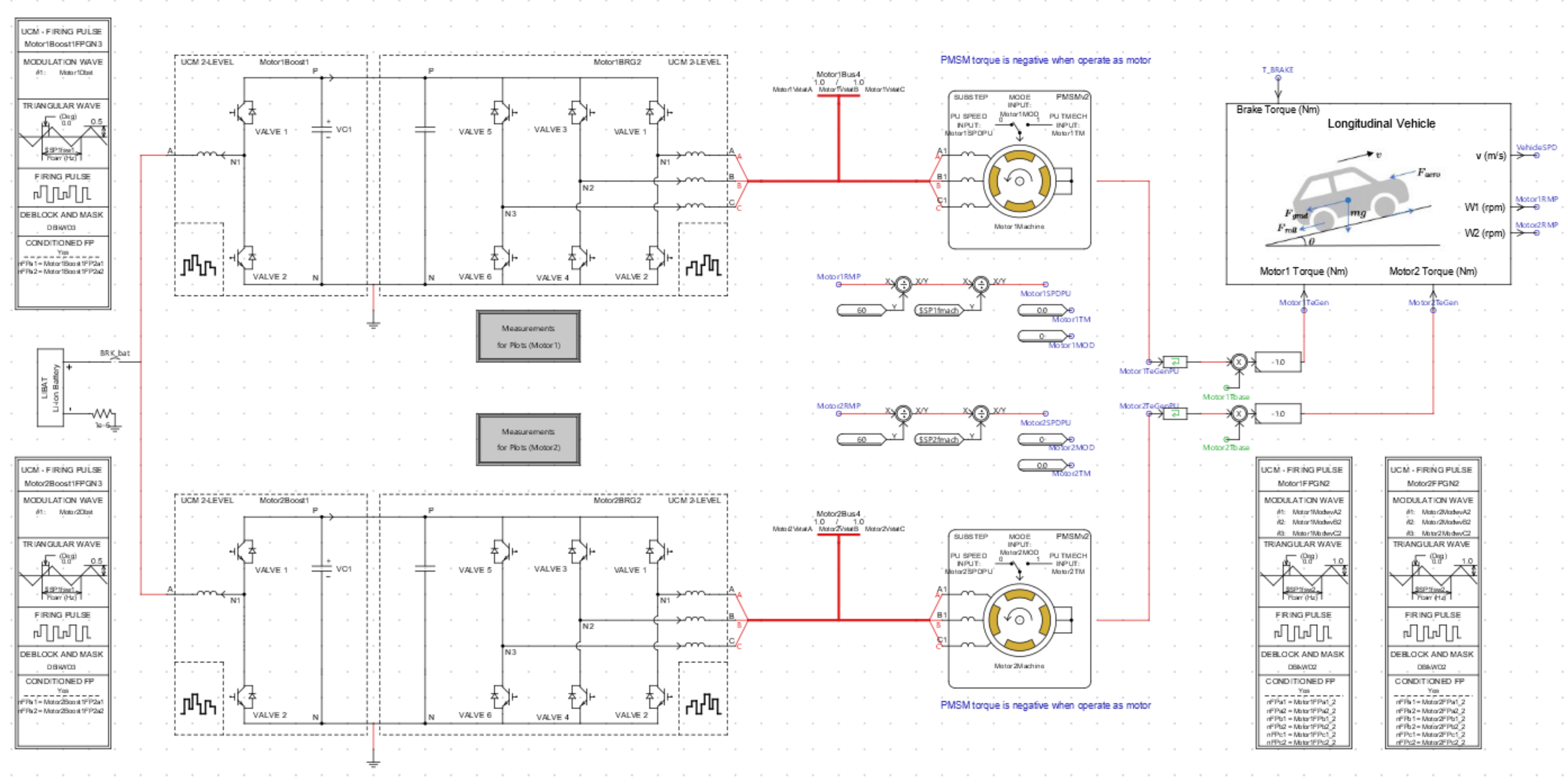
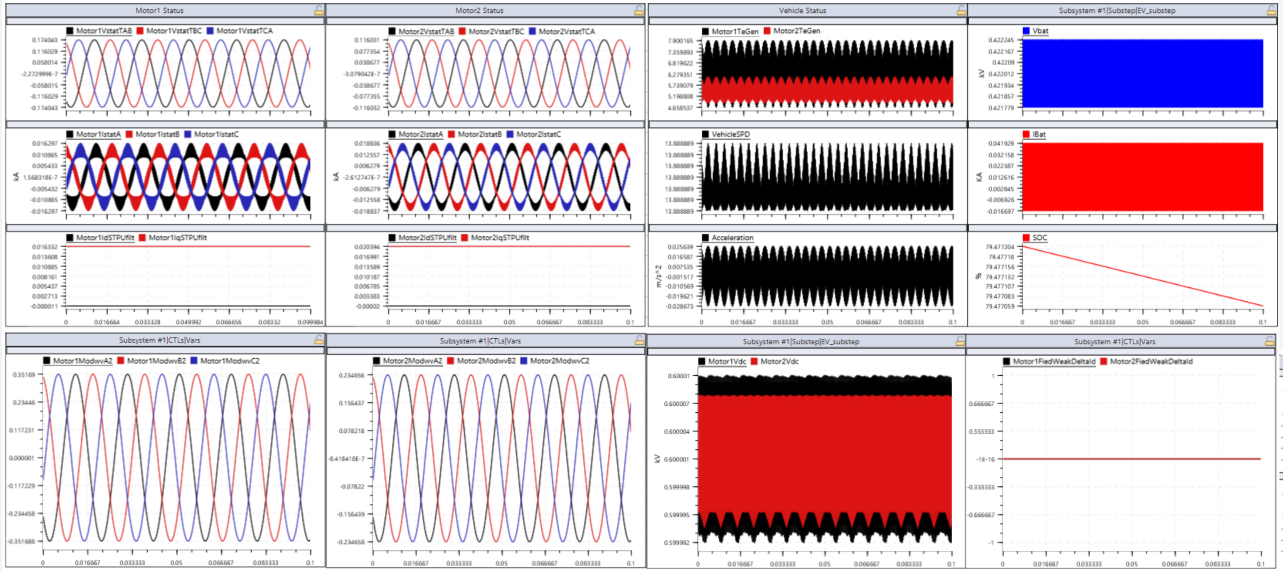


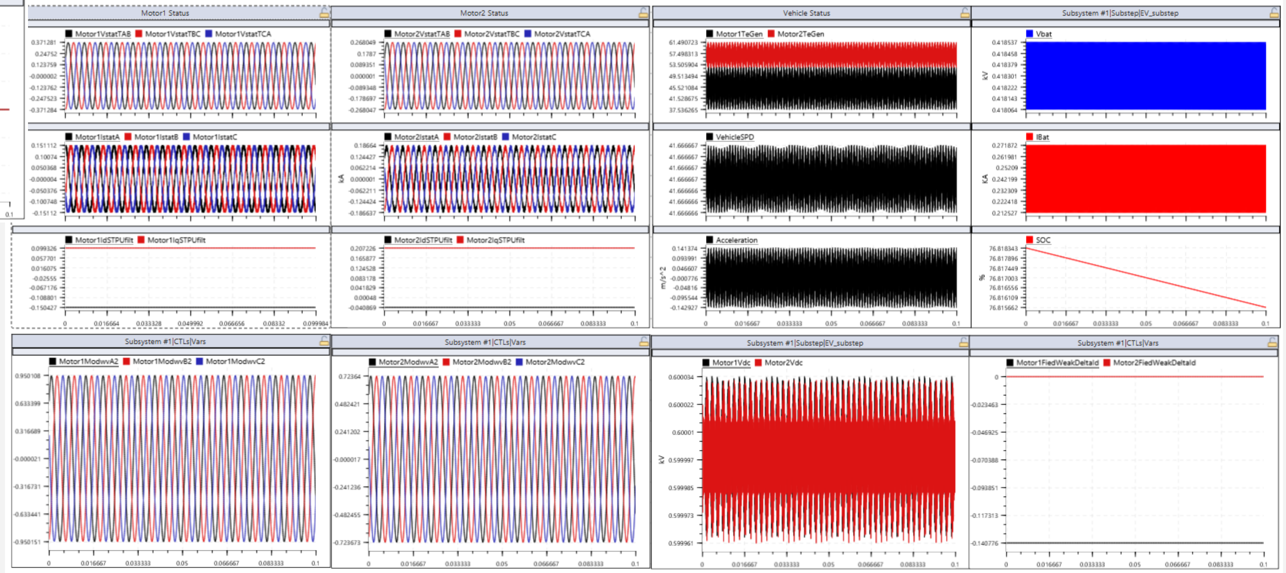
Figure 5-1 Single Line Diagram of Grid Connected VSG

EXAMPLE CASE 1 – EV Powertrain

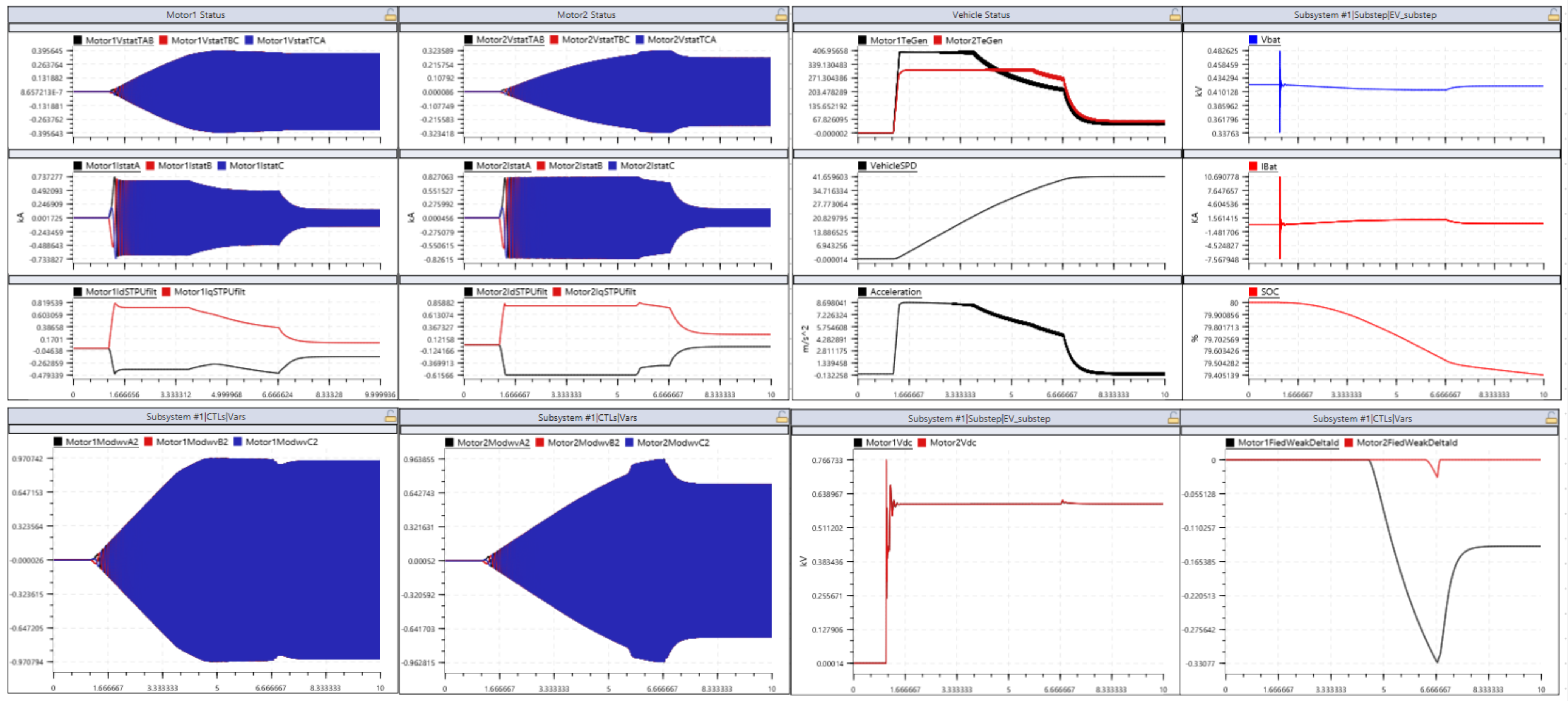


50km/h

150km/h



EXAMPLE CASE 1 – EV Powertrain



Waveforms for start-up process accelerating to 150 km/h with MTPA.

RTDS Example Demo 2

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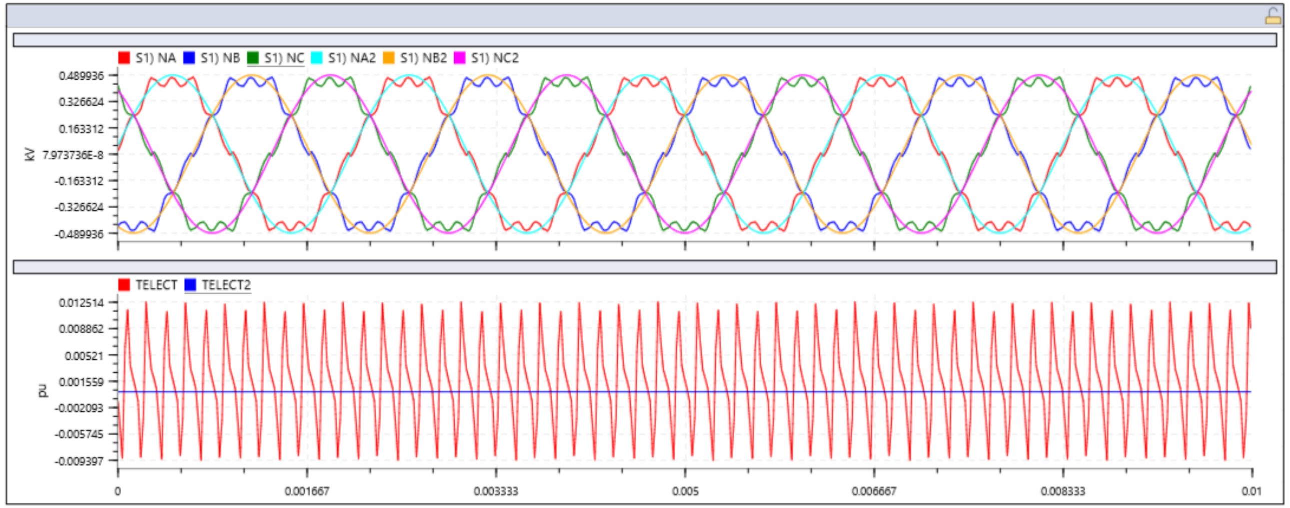
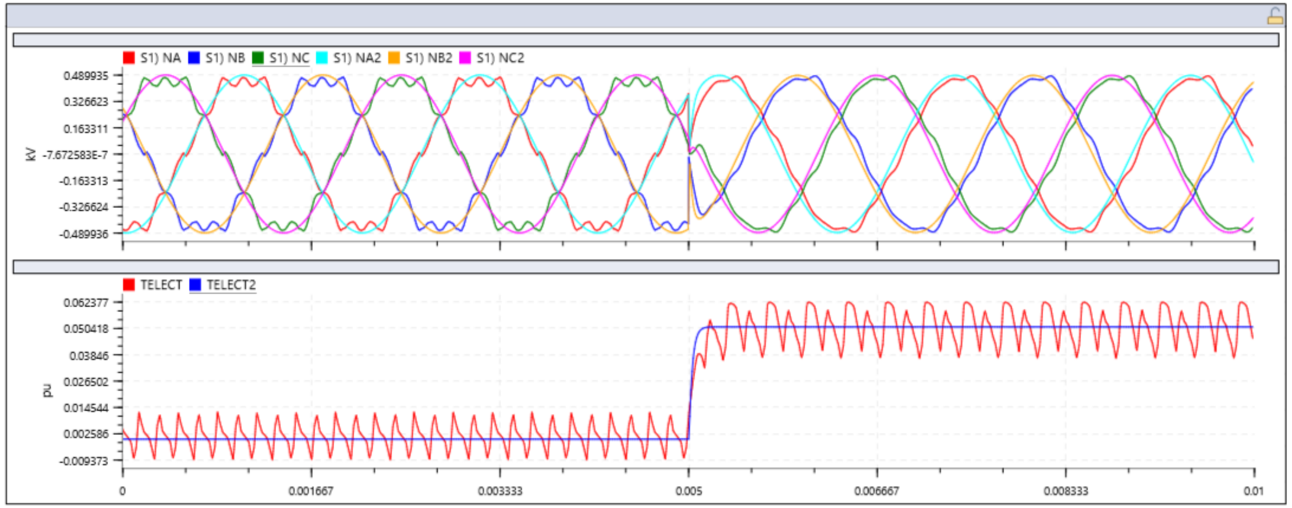
Spatial Harmonics Model in RSCAD



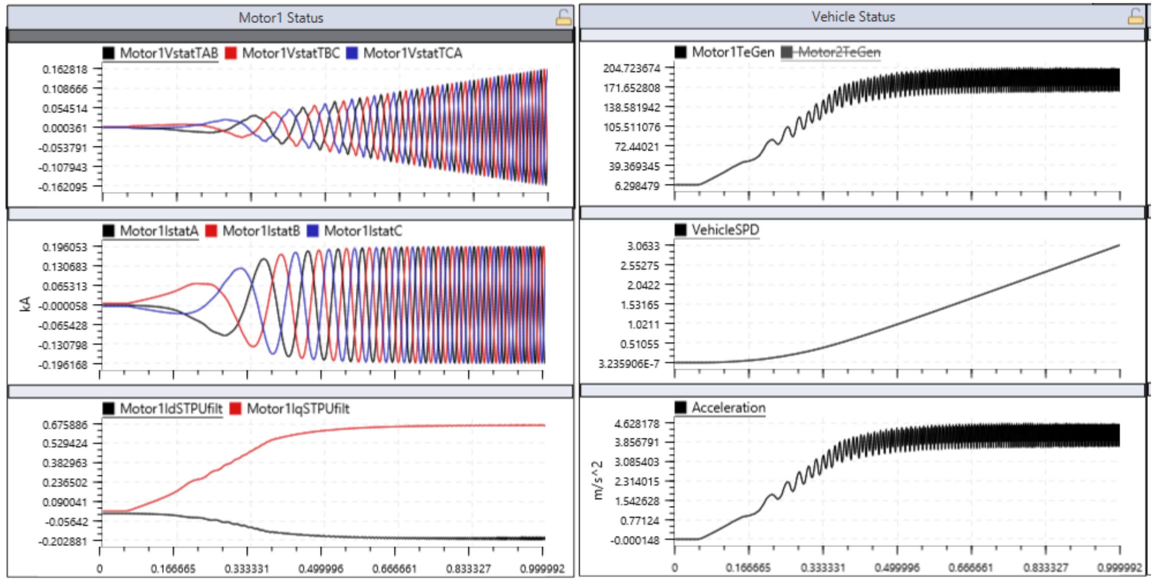
Lock speed, open circuit



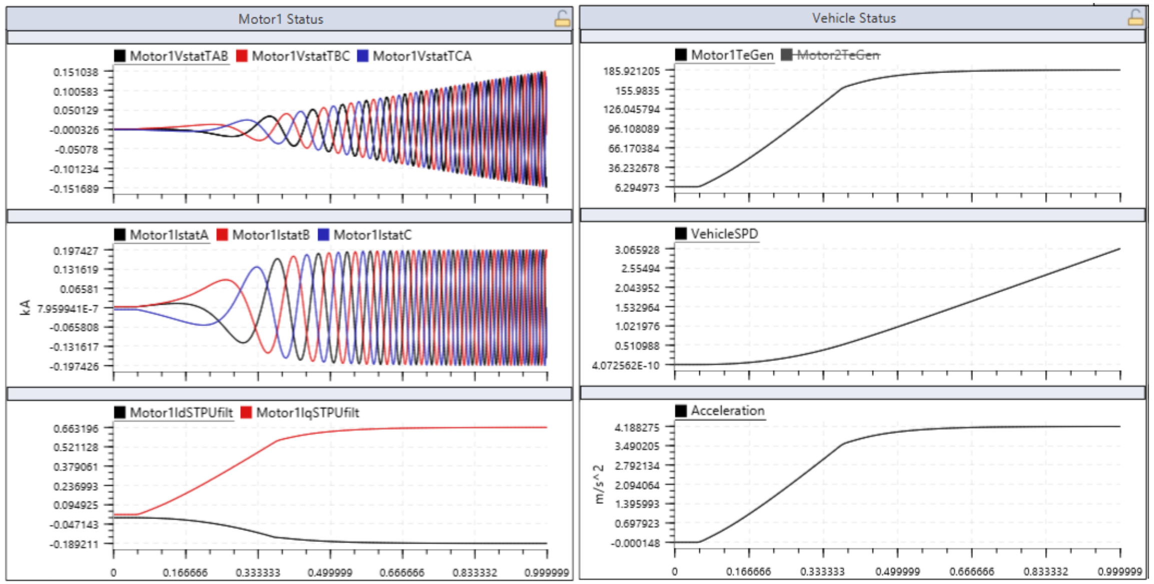
Lock speed, open circuit -> 50 ohm shunt

Spatial Harmonics Model in RSCAD

EV accelerates from stop.



With FEM-Based PMSM



With lumped-parameter PMSM

Thank You! Questions?

RTDS Technologies