ANALYZING E-DRIVE SYSTEM PERORMANCE IN ELECTRIC VEHICLE USING MATLAB AND SIMULINK

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Analyzing eDrive system performance using MATLAB/Simulink

Agenda

AGENDA

01 E-Drive System

02 E-Drive Simulation Model

03 E-Drive System analysis

04 Use Cases

05 Summary

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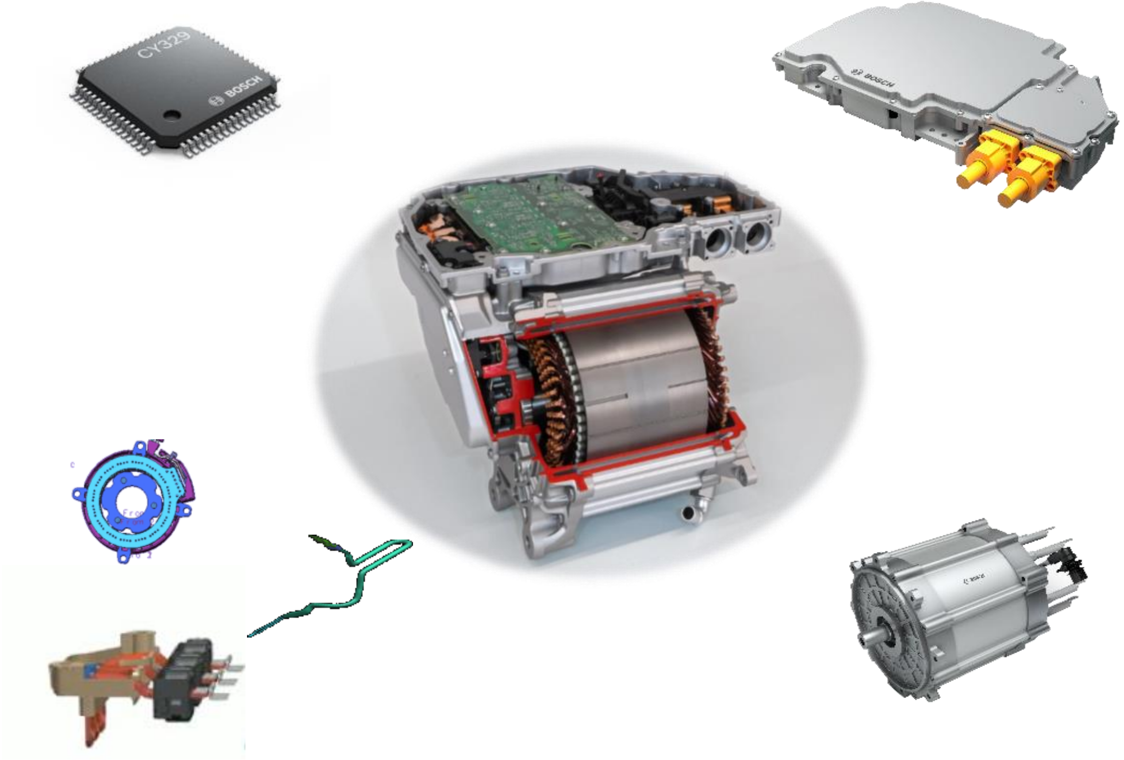
eDrive System

What is the mean by e-Drive system?

- *Electric Drive (e-Drive) is a system which converts electrical energy into mechanical energy in the form of rotational motion*
- *It is also equipped with controlling the rotational motion by providing adequate power with minimal system losses and also with safety functions*
- *Generally, an e-Drive system comprises of following major components*
    - *Electric machine*
    - *Inverter*
    - *Sensors*
    - *Software & Algorithm*
    - *Low voltage components*
    - *Cooling devices*



Different major components of e-Drive System

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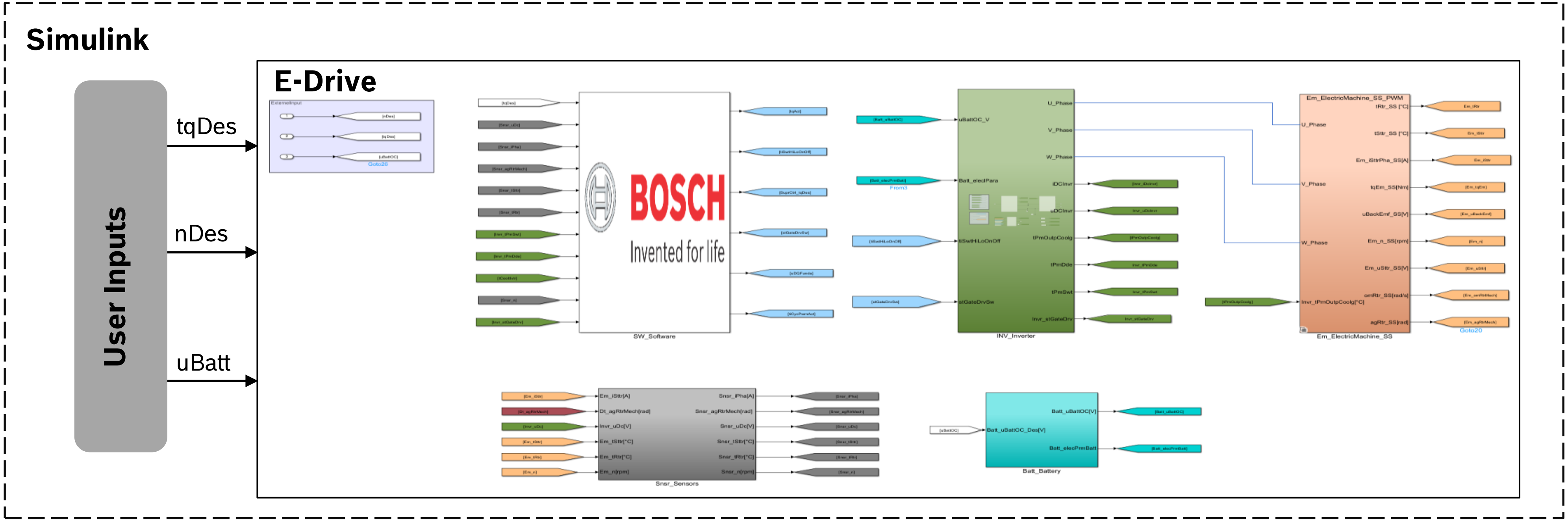
E-Drive Simulation Model in Matlab/Simulink

- *The complete Electric Drive (e-Drive) system has been virtualized and been modelled in MATLAB/Simulink Environment*
- *With help of MathWorks tools, the physical system, hardware and software components of eDrive System are modelled using both Simulink & Simscape blocks*
    - *Hardware components of Inverter is modelled using Simscape blocks*
    - *eMachine is a custom modelled physical system developed using Simscape Language*
- *The modelled software block is a complete in-house development with BOSCH algorithm and functions*
- *The entire model simulation can run natively in Simulink and be compiled as executable file to run in other simulation environment*



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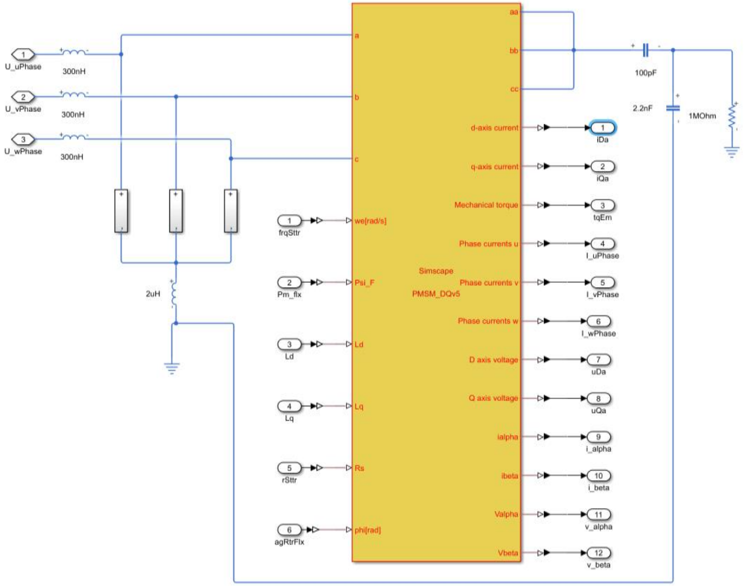
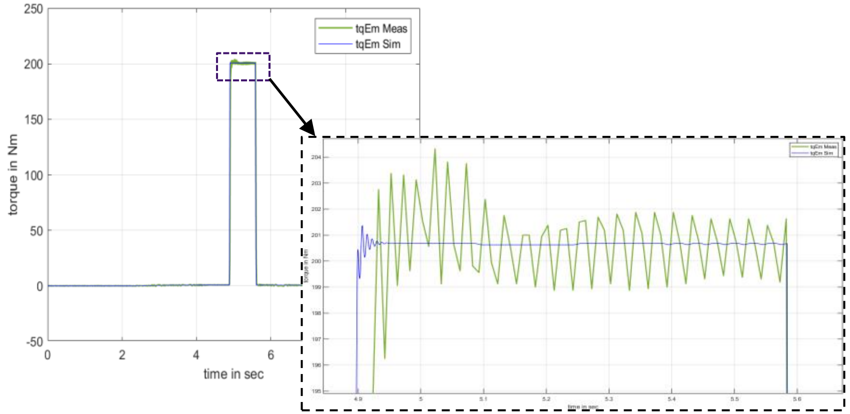
Electric Machine Plant Model

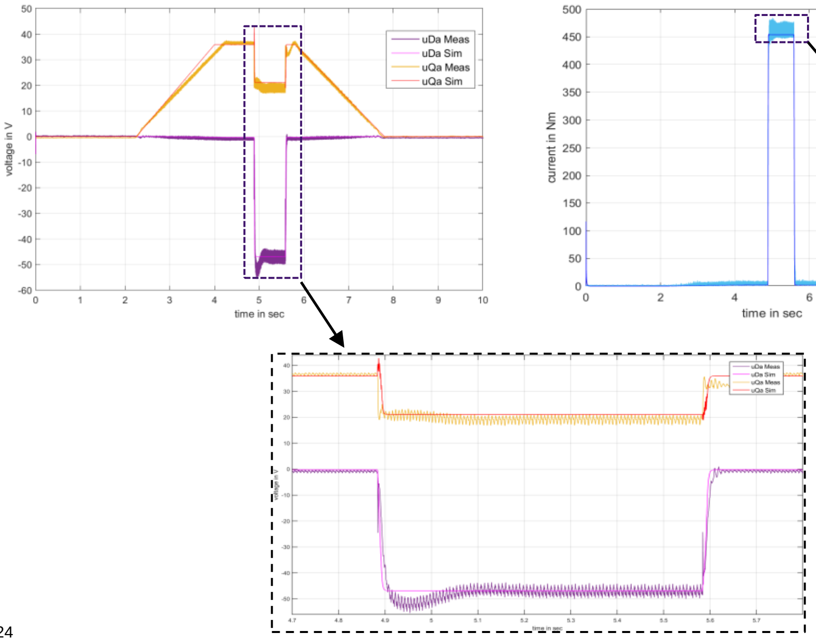
Features of eMachine Model

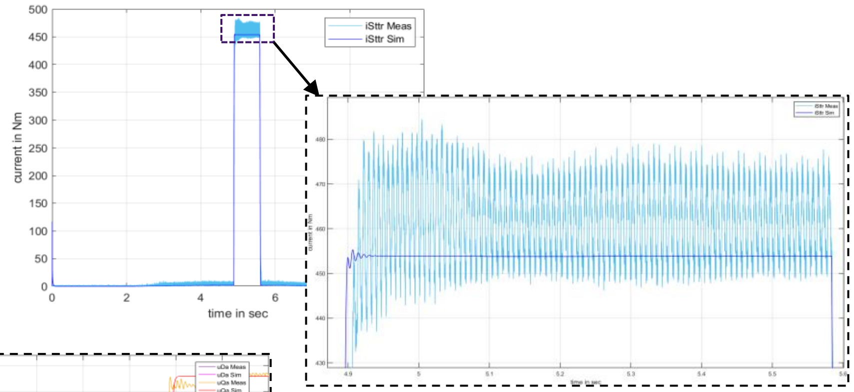
- *Simple and Customized machine model developed using Simscape Language*
- *Modelled both ASM(Asynchronous Machine) and PMSM (Permanent Magnet Synchronous Machine) in DQ Model under one physical system*
- *Capable of variant selection based on simulation need and project requirements*
- *Compatible for OEM specific machine parameters as well*



Simscape Model of PMSM







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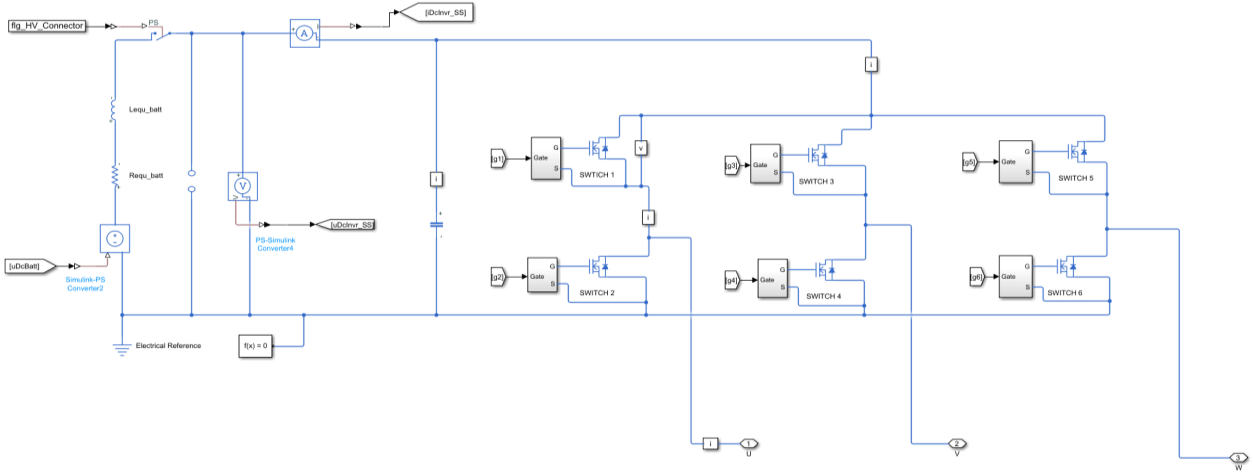
Inverter Plant Model

Features of Inverter Model

- *Converts DC input power into AC output power*
- *Inverter hardware components such power electronic switches, capacitor, etc are modelled using Simscape blocks*
- *Compatible for both Si/SiC based IGBT and MOSFET power electronic switches*
- *In-house developed Inverter thermal model and Powerloss model are implemented*
- *Capable of updating the switch properties and characteristics w.r.t supplier components*



Simscape Model of SiC MOSFET B6 Inverter

Example:

FF600R12ME4 Infineon IGBT

Parameter	Symbol	Note or test condition		Values Min.	Values Typ.	Values Max.	Unit
Collector-emitter saturation voltage	$V_{CE\,sat}$	$I_C = 600$ A, $V_{GE} = 15$ V	$T_{vj} = 25$ °C		1.75	2.10	V
			$T_{vj} = 125$ °C		2.00		
			$T_{vj} = 150$ °C		2.05		
Gate threshold voltage	V_{GEth}	$I_C = 23$ mA, $V_{CE} = V_{GE}$, $T_{vj} = 25$ °C		5.20	5.80	6.40	V
Gate charge	Q_G	$V_{GE} = \pm 15$ V, $V_{CC} = 600$ V			4.4		µC
Internal gate resistor	R_{Gint}	$T_{vj} = 25$ °C			1.2		Ω
Input capacitance	C_{ies}	$f = 1000$ kHz, $T_{vj} = 25$ °C, $V_{CE} = 25$ V, $V_{GE} = 0$ V			37		nF
Reverse transfer capacitance	C_{res}	$f = 1000$ kHz, $T_{vj} = 25$ °C, $V_{CE} = 25$ V, $V_{GE} = 0$ V			2.05		nF
Collector-emitter cut-off current	I_{CES}	$V_{CE} = 1200$ V, $V_{GE} = 0$ V	$T_{vj} = 25$ °C			3	mA

Simscape IGBT Model parameters mapped w.r.t datasheet

Main		
I-V characteristics defined by	Fundamental nonlinear equations	
Zero gate voltage collector current, Ices	3	mA
Voltage at which Ices is defined	1200	V
Gate-emitter threshold voltage, Vge(th)	5.80	V
Collector-emitter saturation voltage, Vce(s...	1.75	V
Collector current at which Vce(sat) is defin...	600	A
Gate-emitter voltage at which Vce(sat) is d...	15	V
Measurement temperature	25	degC

Parameter	Symbol	Note or test condition		Typ.	Max.	Unit
Input capacitance	C_{ies}	$f = 1000$ kHz, $T_{vj} = 25$ °C, $V_{CE} = 25$ V, $V_{GE} = 0$ V		37		nF
Reverse transfer capacitance	C_{res}	$f = 1000$ kHz, $T_{vj} = 25$ °C, $V_{CE} = 25$ V, $V_{GE} = 0$ V		2.05		nF
Collector-emitter cut-off current	I_{CES}	$V_{CE} = 1200$ V, $V_{GE} = 0$ V	$T_{vj} = 25$ °C		3	mA
Gate-emitter leakage current	I_{GES}	$V_{CE} = 0$ V, $V_{GE} = 20$ V, $T_{vj} = 25$ °C			400	nA
Turn-on delay time (inductive load)	t_{don}	$I_C = 600$ A, $V_{CC} = 600$ V, $V_{GE} = \pm 15$ V, $R_{Gon} = 1.5$ Ω	$T_{vj} = 25$ °C	0.160		µs
			$T_{vj} = 125$ °C	0.210		
			$T_{vj} = 150$ °C	0.210		
Rise time (inductive load)	t_r	$I_C = 600$ A, $V_{CC} = 600$ V, $V_{GE} = \pm 15$ V, $R_{Gon} = 1.5$ Ω	$T_{vj} = 25$ °C	0.090		µs
			$T_{vj} = 125$ °C	0.090		
			$T_{vj} = 150$ °C	0.100		

Junction Capacitance		
Parameterization	Specify fixed input, reverse transfer, and output capacitance	
Input capacitance, Cies	37	nF
Reverse transfer capacitance, Cres	2.05	nF
Output capacitance, Coes	0	nF
Charge-voltage linearity	Gate-collector capacitance is constant	
Total forward transit time	0.25	us

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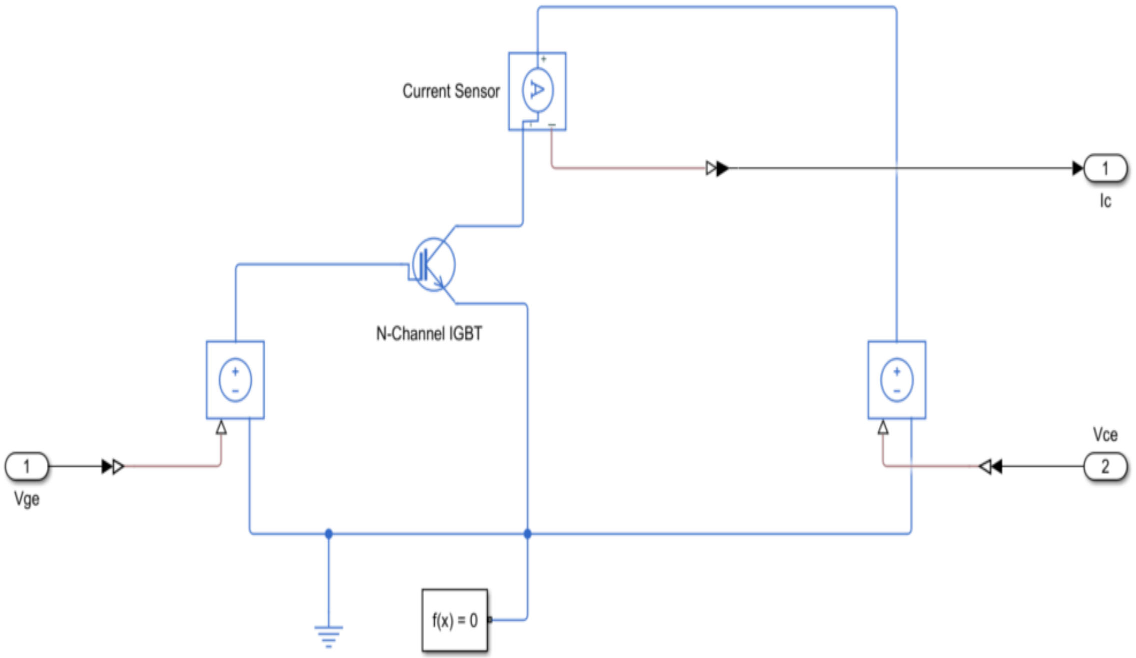
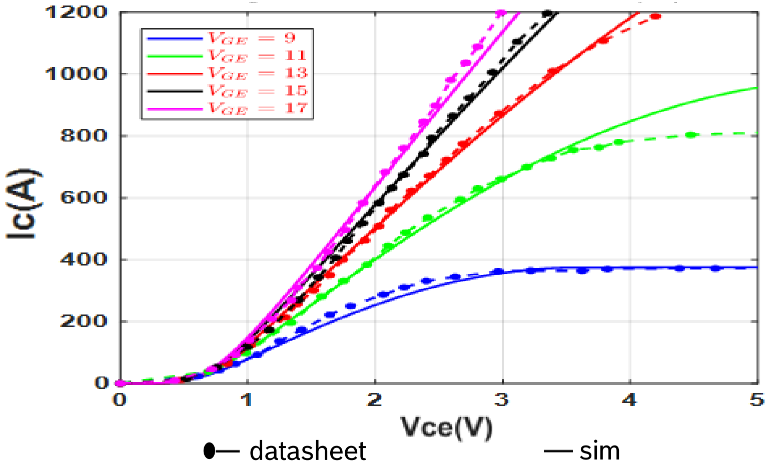
IGBT Parameterization and Validation

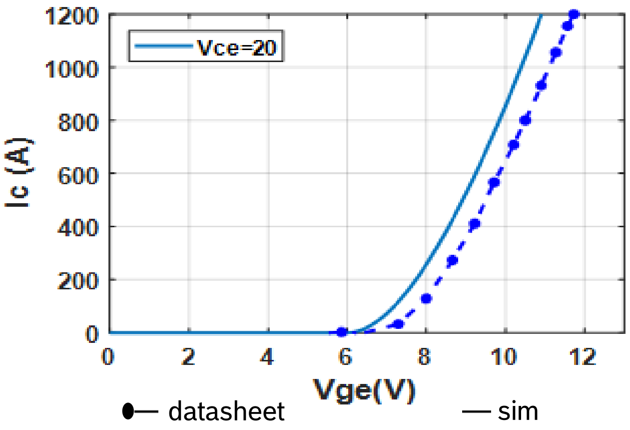


Simscape IGBT Modelling considered for parameterization and validation

Output Characteristics at Tvj= 150 degC



Transfer Characteristics at Tvj= 25 degC



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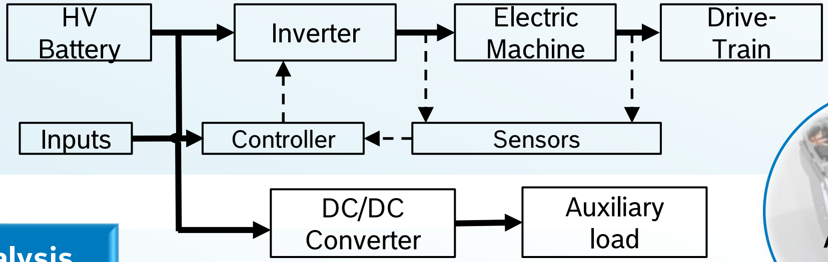
E-Drive System simulation

System Analysis

- ❑ *Cause effect relationship analysis of overall eDrive System*
- ❑ *Optimization of current control parameters of specified controller design*
- ❑ *Time domain and frequency domain analysis*
- ❑ *Sensitivity and tolerance analysis of eDrive*

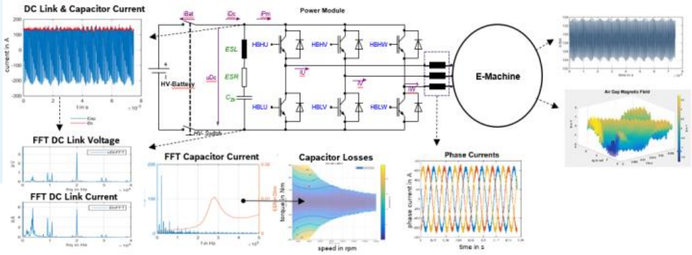


Thermal Analysis

- ❑ *In-House developed thermal model for complete eDrive System*
- ❑ *Component level & System level thermal rise and behavior analysis*
- ❑ *Steady state and transient state thermal analysis*
- ❑ *De-rating strategy of eDrive system*

Performance Analysis

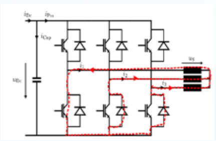
- ❑ *Inverter component sizing w.r.t thermal and phase current constraints*
- ❑ *Component level & System level Power loss estimation*
- ❑ *eDrive efficiency calculation with respect to Drive Cycle input*
- ❑ *Impact analysis of Modulation method and switching frequency on eDrive*



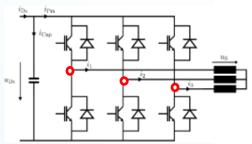
Fault Analysis

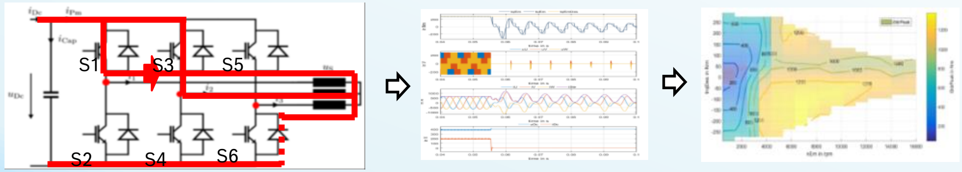
- ❑ *Open Circuit & Short Circuit analysis*
- ❑ *High Voltage network failure analysis*
- ❑ *Overcurrent/Overvoltage fault analysis*
- ❑ *Component or Inverter Gate Driver/Switch failure analysis*

Short Circuit



Open Circuit





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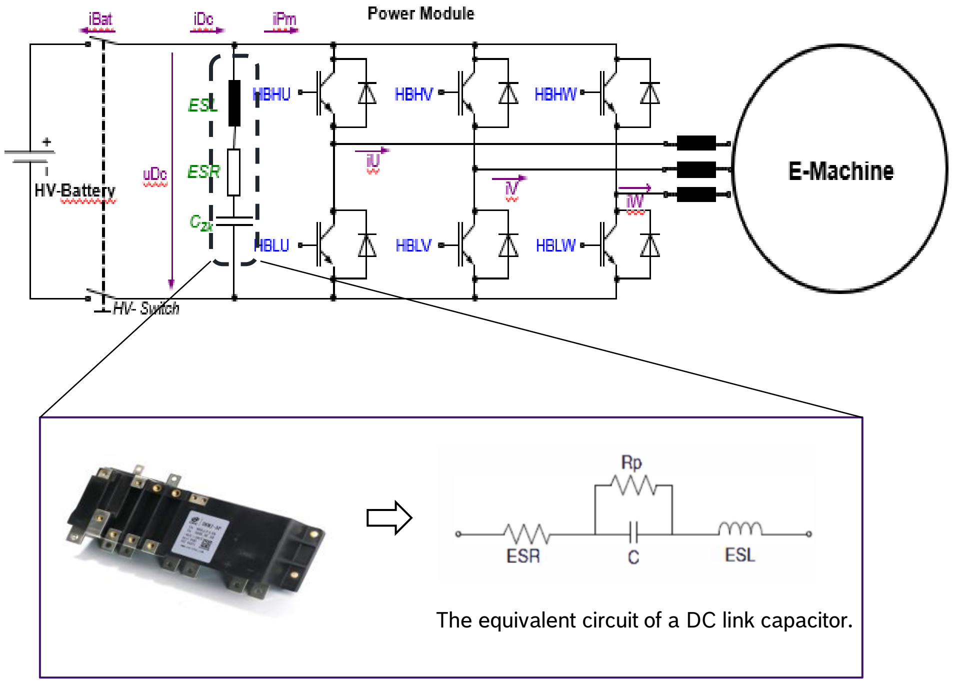
Use Case – Capacitance sizing of DC-link capacitor

DC link Capacitor & its need in eDrive System

- *The inverter convert DC into AC by turning on and off the power electronic switches (IGBT/MOSFT)*
- *Due to presence of parasitic components in the HV network and switching action of inverter switches , results in higher voltage/current ripple across the capacitor*
- *Such high frequency ripples leads to*
  - *Temperature rise in capacitor (Overheating)*
  - *Affect the stability of the system control*
  - *Induces momentary high sudden voltage surge*
  - *Increases the emission of electromagnetic interface*
- *Therefore, DC link capacitor is required to*
  - *Attenuate and filter the voltage/current ripple across HV network*
  - *Suppress the voltage spike caused by leakage inductance and switching action*
  - *Reduce EMI and improve voltage stabilization*



The equivalent circuit of a DC link capacitor.

ESR => *Equivalent series resistance*

C => *Capacitance*

ESL => *Equivalent series inductance*

Rp => *High resistance DC path*

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Factors that influence DC-link voltage ripple

DC-link voltage ripple

Capacitance

- *For the same operating point and supply voltage, increasing the capacitance value of DC-link capacitor decreases voltage ripple*
- *Based on the capacitor current equation*

  Icap = C * (dV/dt)

  dV_{ripple} = Icap * dt / C

  ⇧C ⇩dV_{ripple}
- *Increase in capacitance, increase size & cost*

Switching Frequency

- *For the same load, increasing the PWM switching frequency (fPWM) decreases voltage ripple*
- *Based on the voltage ripple equation*

  dV_{ripple} = Icap / (2*fPWM) *C

  ⇧fPWM ⇩dV_{ripple}
- *Increase in PWM switching frequency, increase the switching losses as well*

Modulation Index

- *Modulation index (M) is defined as the ratio between fundamental peak phase voltage to the input DC voltage*
- *Modulation index can be varied w.r.t change in input DC voltage & w.r.t varying load demand for specific input voltage and Modulation strategy*
- *Based on capacitor current equation*

$$\text{icap} = \text{iSttr}\sqrt{[2M\{2[\frac{\sqrt{3}}{4\pi} + cos^2\phi\left(\frac{\sqrt{3}}{\pi} - \frac{9}{16}M\right)\}]}$$

⇧M ⇧iCap ⇧dV_{ripple}

Stator Current

- *Increase in load demand for specific speed and capacitor , increases iSttr*
- *As the stator current(iSttr) increases, the capacitor current also increases which in turn increases the voltage ripple*
- *Based on the capacitor current equation*

$$\text{icap} = \text{iSttr}\sqrt{[2M\{2[\frac{\sqrt{3}}{4\pi} + cos^2\phi\left(\frac{\sqrt{3}}{\pi} - \frac{9}{16}M\right)\}]}$$

⇧iSttr ⇧iCap ⇧dV_{ripple}

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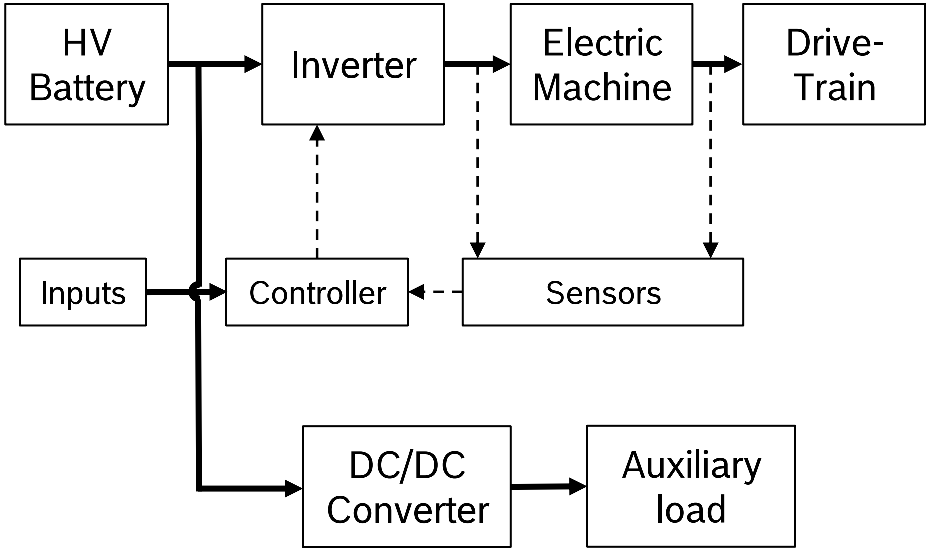
Use Case – Sensitivity analysis eDrive system

Background

- *In eDrive system apart from software components it also consist of a several hardware components of different physical domain (electrical, mechanical, thermal, etc)*
- *For real time monitoring of those physical domain information, proper functioning and optimization of system, detect and protect system from any failure events, etc., with good precision and accuracy sensors are used*
- *The different sensor that are present in the eDrive system are*
    - *Current Sensor => To sense and measure the phase currents at the eMachine input*
    - *Resolver/Encoder => To sense and measure the rotational angle and speed of the eMachine rotor*
    - *Temperature Sensor => To sense and measure the temperature of different HW component of eDrive System at several hotspot*
    - *Voltage Sensor => To measure the battery voltage and voltage across the DC-link capacitor, etc.,*
- *All sensor has its own measuring tolerances due to manufacturing, aging , environmental conditions, etc*
- *Any impact in the eDrive system will be translated to eMachine output in the form of torque and speed. Such impact may give rise to unintended oscillation and accuracy error*
- *It is important to make sure that the overall eDrive system is capable to deliver the output with certain accuracy*



Simplified block diagram of EV Powertrain system

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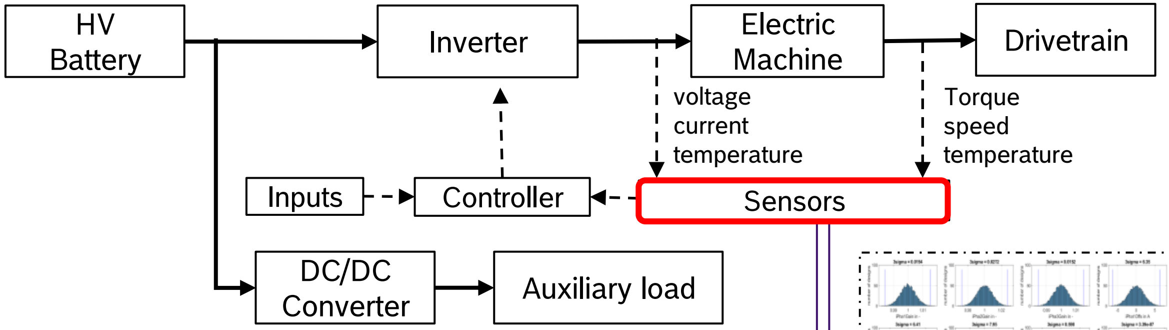
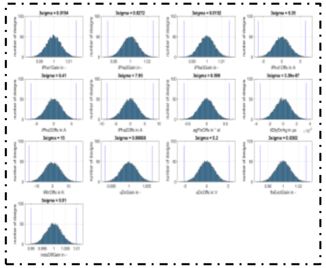
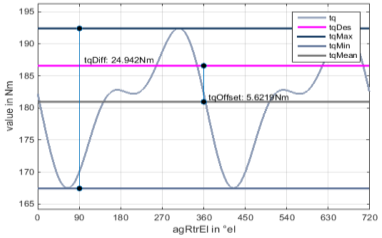
Monte Carlo tolerance and sensitivity analysis of eDrive torque

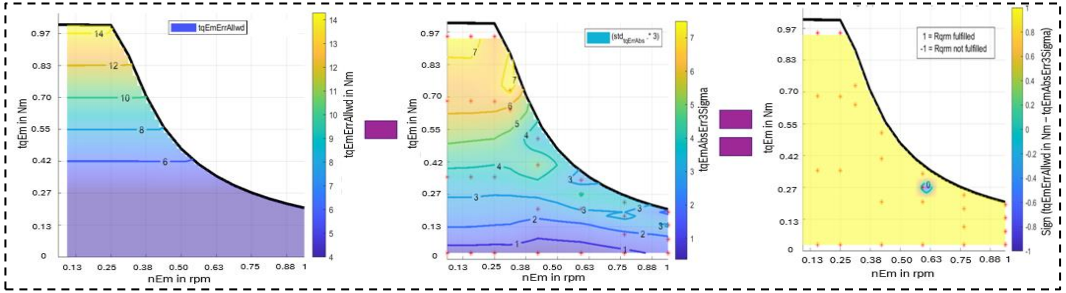
- *Based on each sensor characteristics, determine its own measuring tolerances in 1σ, 3σ values*
- *Create and distribute the tolerances of each sensor in gaussian distribution*
- *Perform Monte Carlo simulation of eDrive System with the influence of distributed sensor tolerances*
- *Error in sensor measurement of current/voltage/temperature/rotor position signals lead to iDa and iQa current error from machine controller point of view*
- *Error in iDa and iQa current lead to*
  - *Static torque error (offset)*
  - *Periodic torque error (amplitude, frequency)*

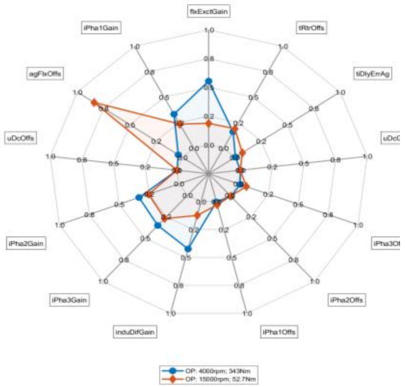




3 sigma tolerance Spread







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Summary

- *Usage of Simscape components and MathWorks solution, enable the ease of virtualization of eDrive system along with flexible development of critical hardware and software components of system*
- *Capability of MathWorks Simscape components to update the components characteristics w.r.t actual hardware characteristics, enables to analyze with great accuracy close to real environment conditions*
- *The presence of such virtualized simulation model, enable to analyze several cause effect analysis and impact analysis of overall eDrive system*
- *Enables in system simulation which supports in many system development process such as*
    - *Software Development*
    - *Algorithm Development*
    - *Cross domain simulation*
    - *Calibration*

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Reference

Kolar, J.W and Round, S.D '*Analytical calculation of RMS current stress on DC link capacitor of voltage PWM-converter systems*', 2006

Thank You

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