

Ultra-High Speed Motor and Engine Cranking System

— VHDL-AMS Applications —

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S e n i o r A p p l i c a t i o n E n g i n e e r

A n s o f t J A P A N

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Application Workshops for High-Performance Design

Outline

1. Background

- Process “V”
- Multi Domain Simulation

2. Ultra-High Speed motor

- Nagasaki University
- DSP, FPGA, Inverter, Motor

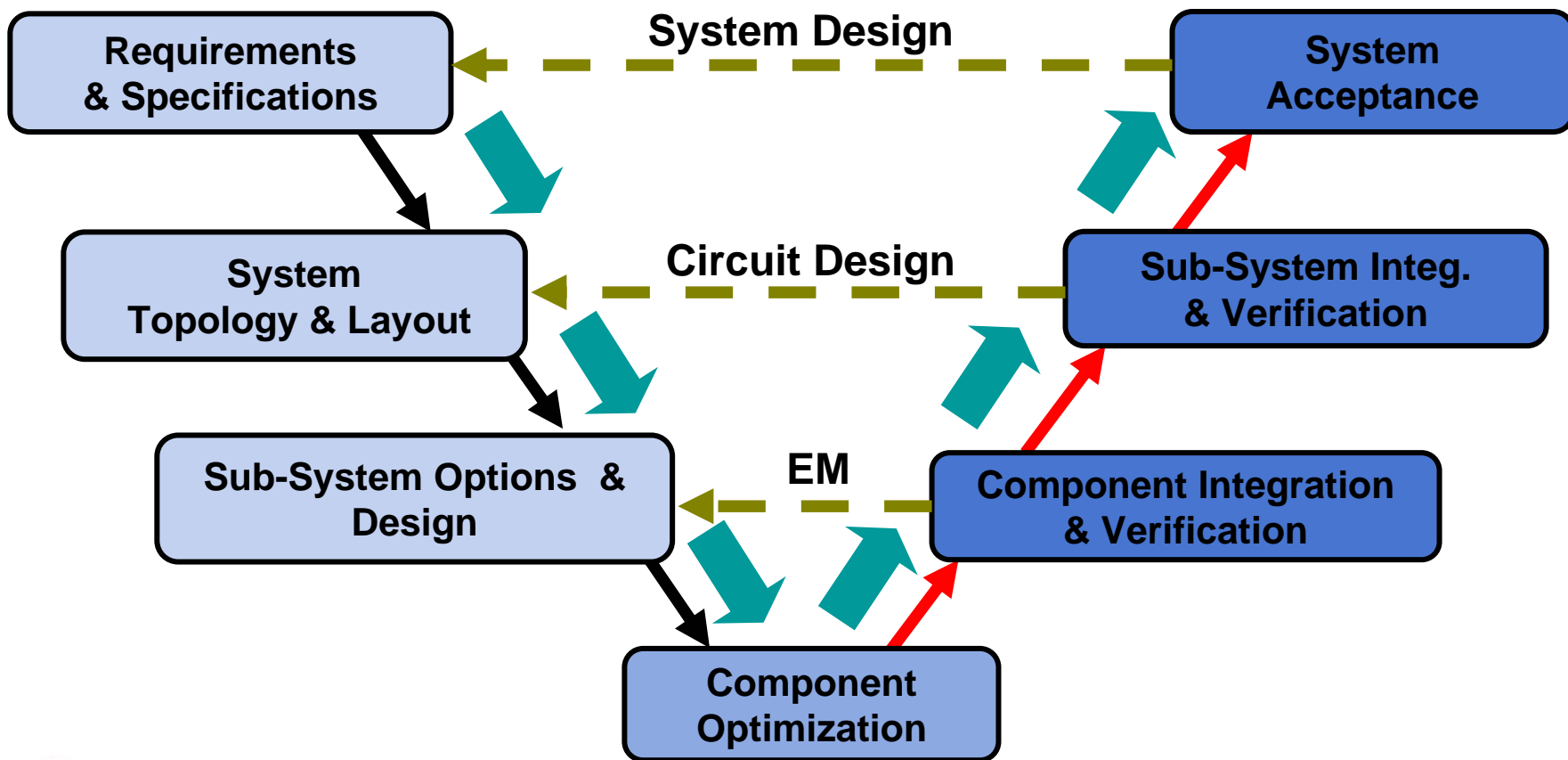
3. Engine Cranking System

- TOYOTA motor corporation
- Engine, Battery, Starter

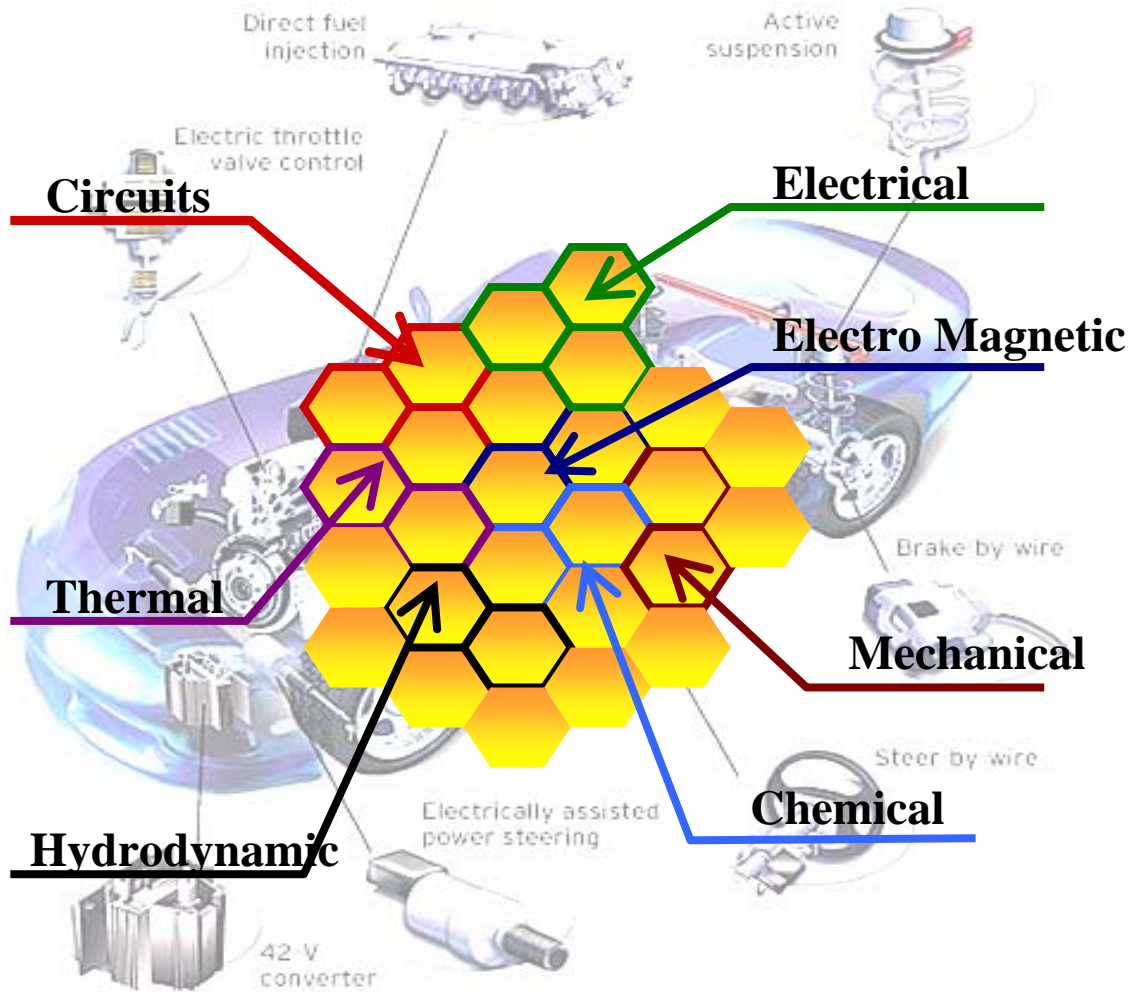
4. Conclusion



The sum of the optimal components is not equal to the optimal system.



Automotive System



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VHDL-AMS

Merits of Common Modeling Language

1. Standardization

Standardization Safety and steadiness of software language is very important for the accumulation of intellectual property in Automotive Engineering. IEEE standards will give you the steadiness

2. Affinity

Modeling should

- be easy for engineer.
- not be technical and complex for modeling.
- be employed to analog and digital mixed signal for system simulation.





Small and Ultra High Speed motor system simulation by using VHDL-AMS

Jyun Oyama, Tsuyoshi Higuchi, Takashi Abe, Ryutaro
Moriguchi (Nagasaki University)





Back Ground

Ultra High Speed Motor...

High Speed Motor : Small and High Power

Application (Size)

- Assist Motor for Turbo charger
- Co-generation system

Application (Speed)

- compressor

Prototype : Rated Speed : 240krpm
Rated Output Power : 5kW



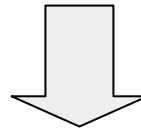


Power Electronics System

- Digital System : DSP,FPGA
- Electronics Circuits
- Mechanical System : Load, Fan
- Temperature effects : Friction, Iron Loss



Multi Domain
Complex System

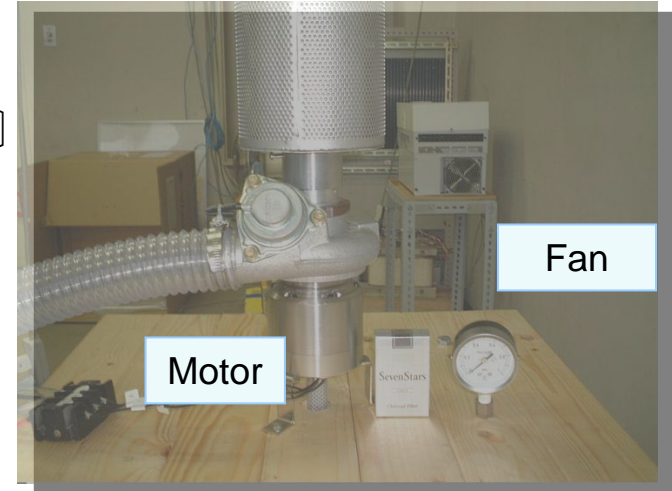
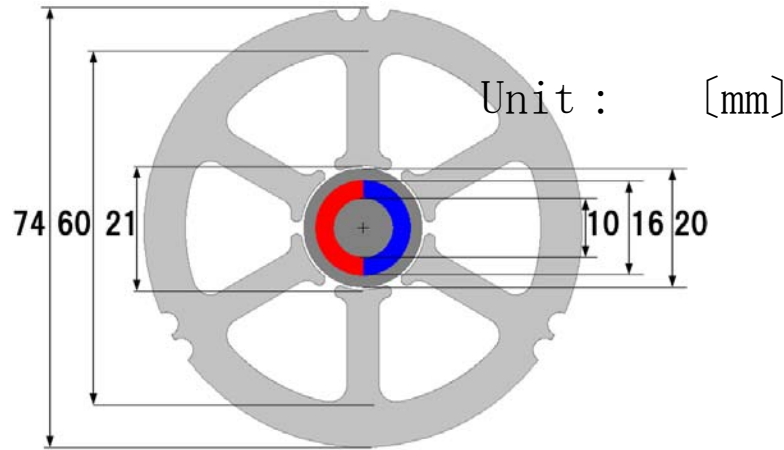


The VHDL-AMS (IEEE 1076.1) is one of the best modeling language for Multi Domain simulation.





Ultra High Speed Motor



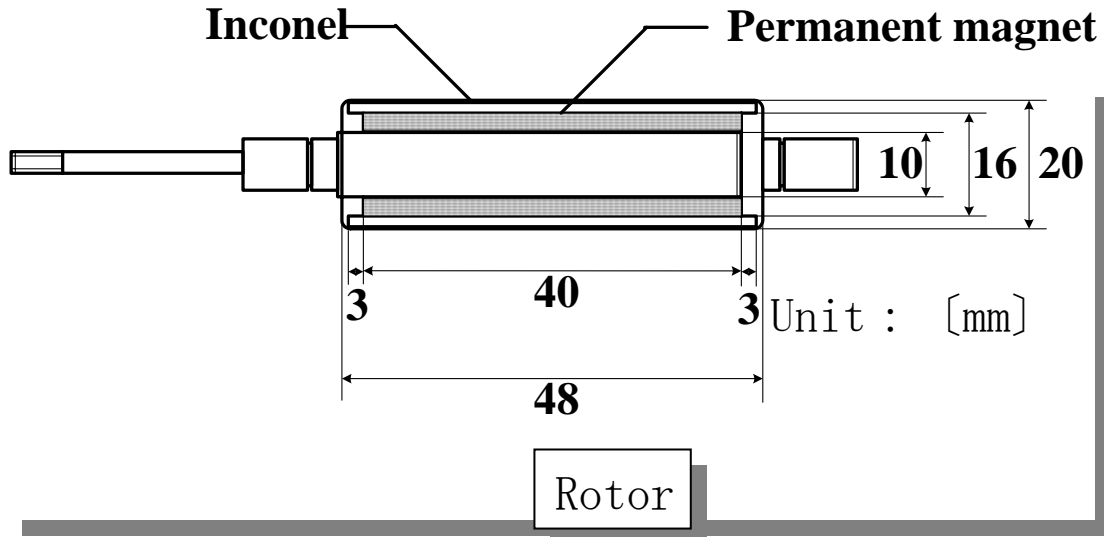
This motor is

- (1) Surface type permanent magnet synchronous motor (2 Poles)
- (2) Rotor surface is covered by the inconel material for shatterproof of the magnet
- (3) Protection from oil infiltration
- (4) In order to reduce the space for end windings, the concentrated winding is employed.





Rotor



- Magnetizing
radial magnetized
- Material
Neodymium alloy





Specification



Rated Output	5 kW
Rated Voltage	200 V
Rated Speed	240,000 rpm
Number of Poles	2
Stator Length	40 mm





Cooling System

Ultra-High Speed Operation



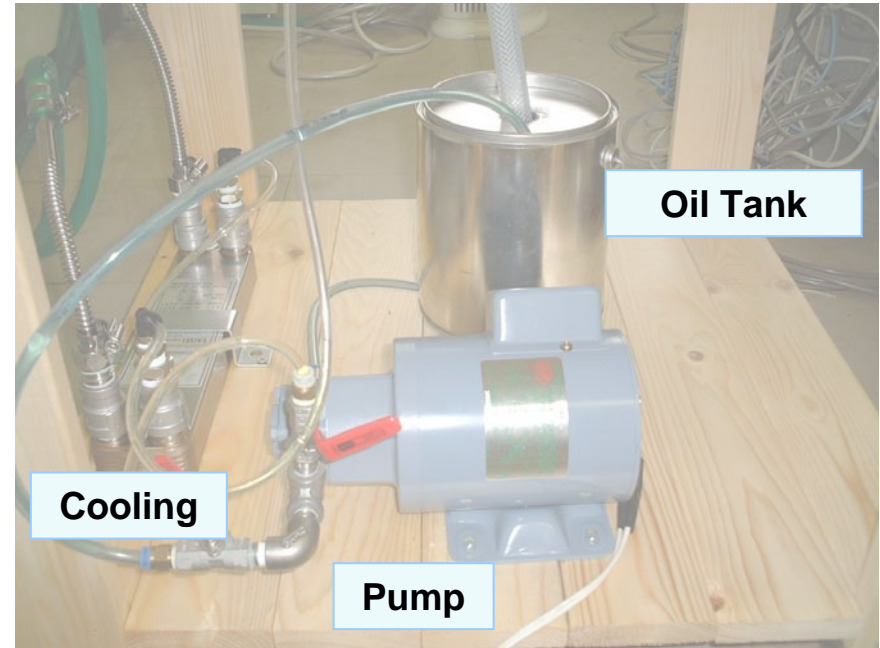
Temp. from friction and loss



deGauss
Winding melting



Oil Cooling



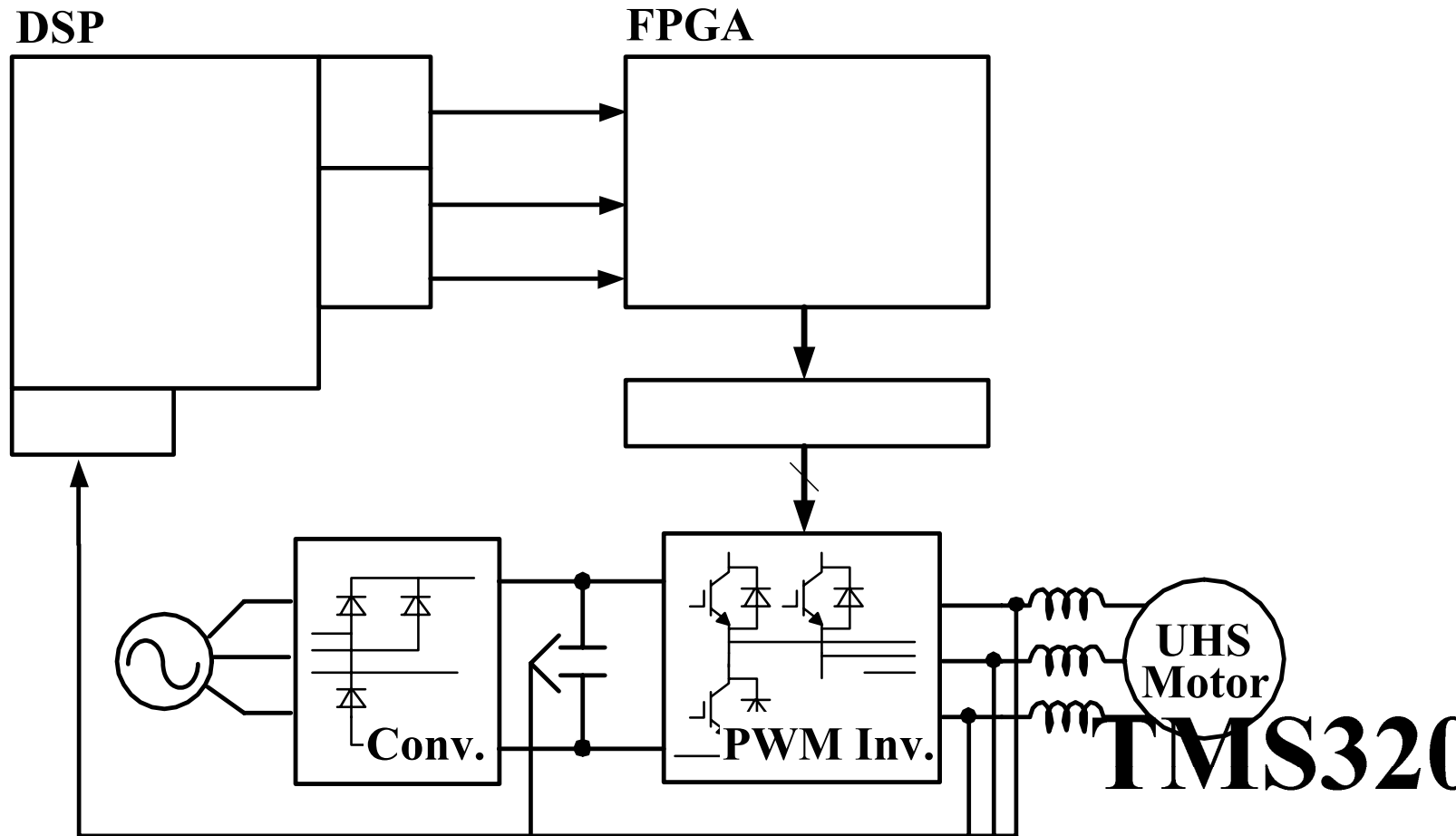
Cooling System

Oil also plays as rotor bearing





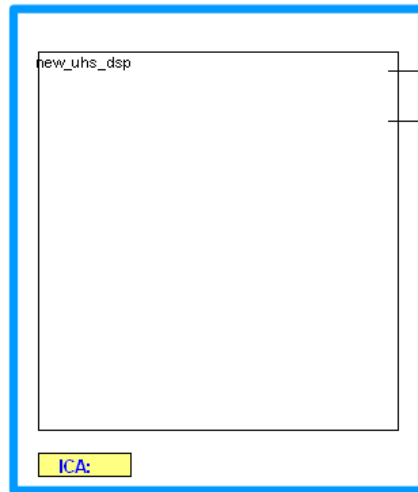
Experiment System



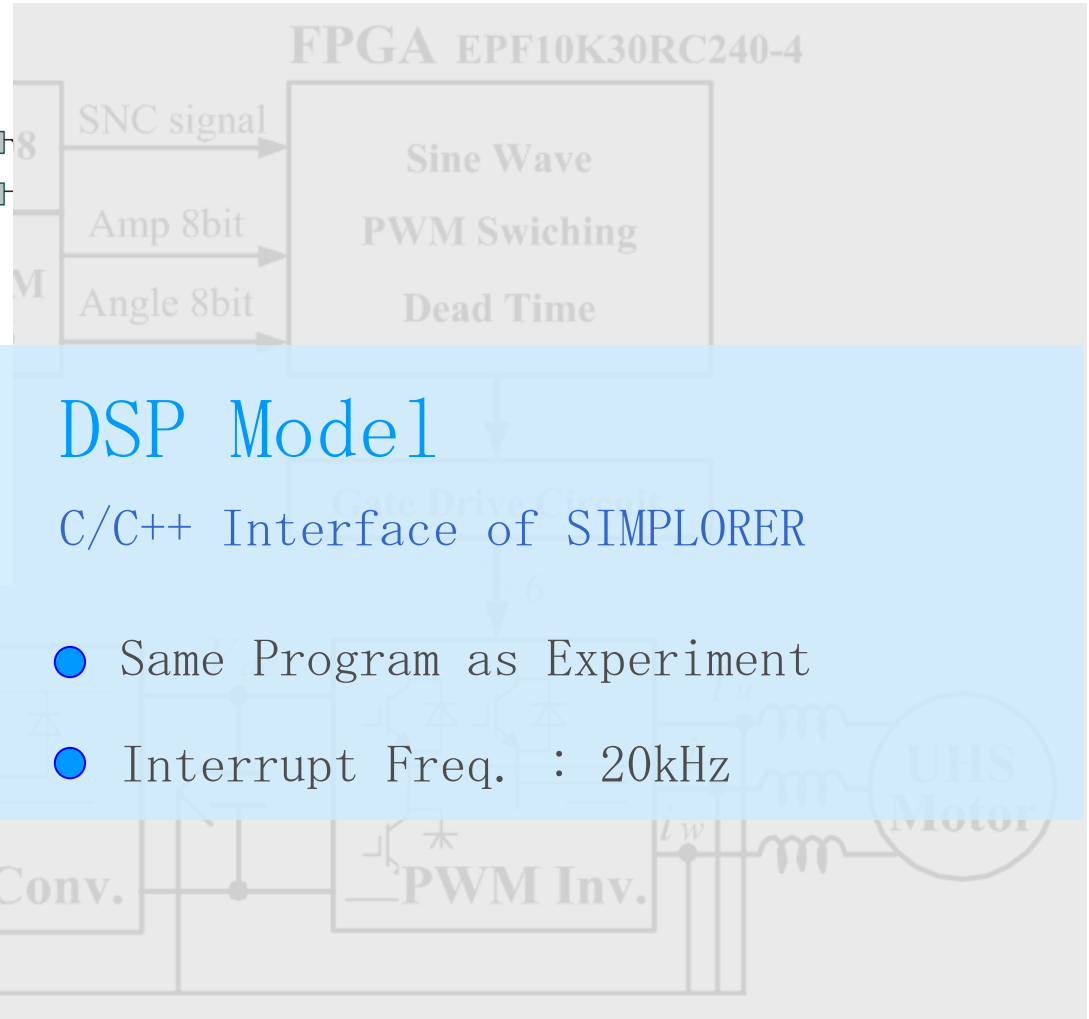


Controller : DSP Model

DSP Model

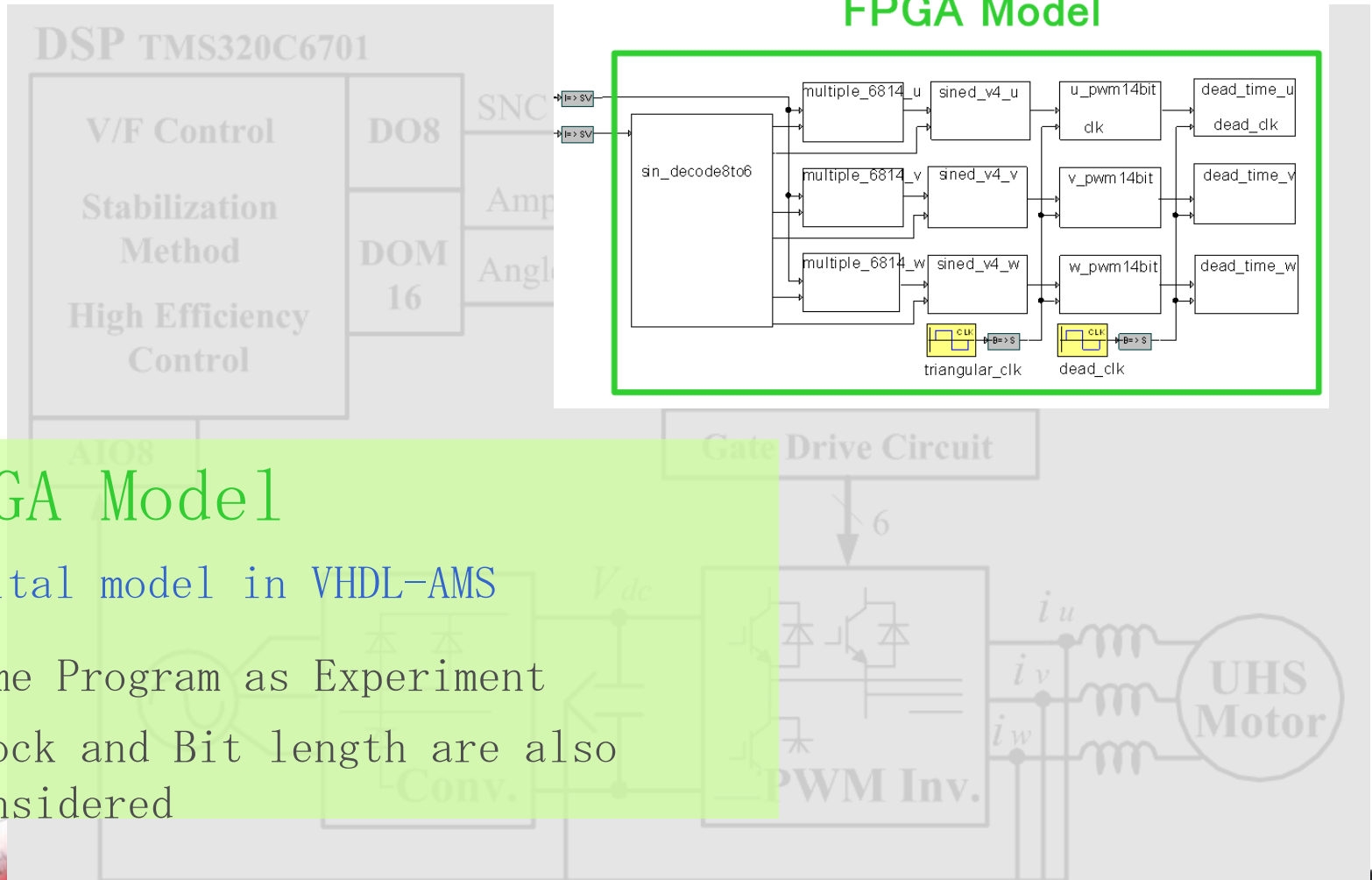


c freq:=700





Controller : FPGA Model



FPGA Model

Digital model in VHDL-AMS

- Same Program as Experiment
- Clock and Bit length are also considered



Controller : FPGA+DSP Model

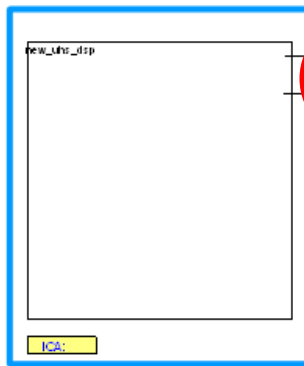
DSP output

signal:Analog

FPGA

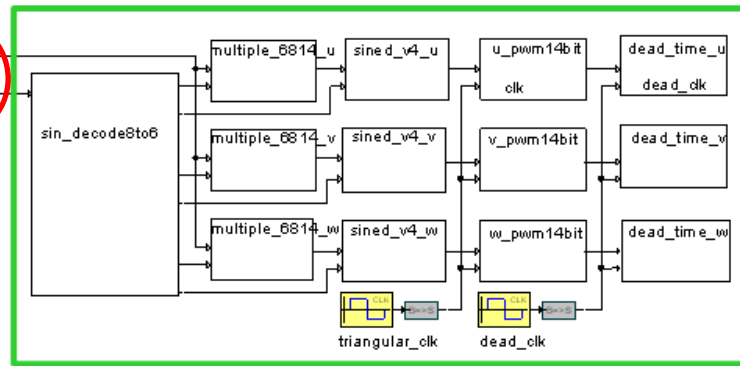
signal

DSP Model



Digital I/O Port

FPGA Model



1. The same C-Code can be used in both Experimental and Simulation.
2. No need to translate from Experimental to Simulation model and Simulation to Experimental DSP code.
3. This capability allows you to be reliability and reduce the time.



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Inverter Model

DSP TMS320C6701

FPGA EPF10K30RC240-4

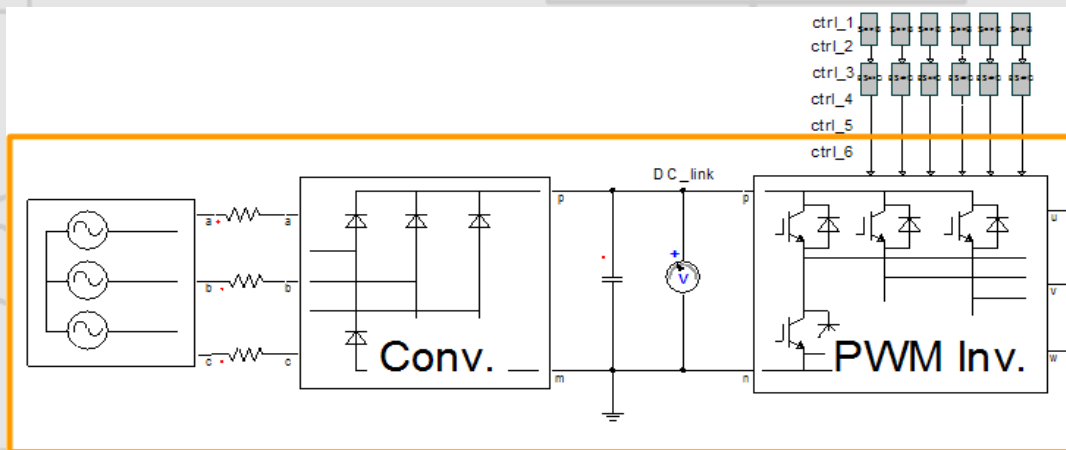
PWM inverter Model

Three Blocks : Power Supply, Converter and Inverter

- IGBT, Diode : Modeled by VHDL-AMS equations
- Switching delay dose not considered

AIO8

Gate Drive Circuit



PWM inverter Model



VHDL-AMS

Main Circuits : VHDL-AMS

VHDL-AMS

Across and Through Variable Equations is used to define the model

Electro-

Across : Voltage [V]

Through : Current [A]

Resistance • $v = Ri$

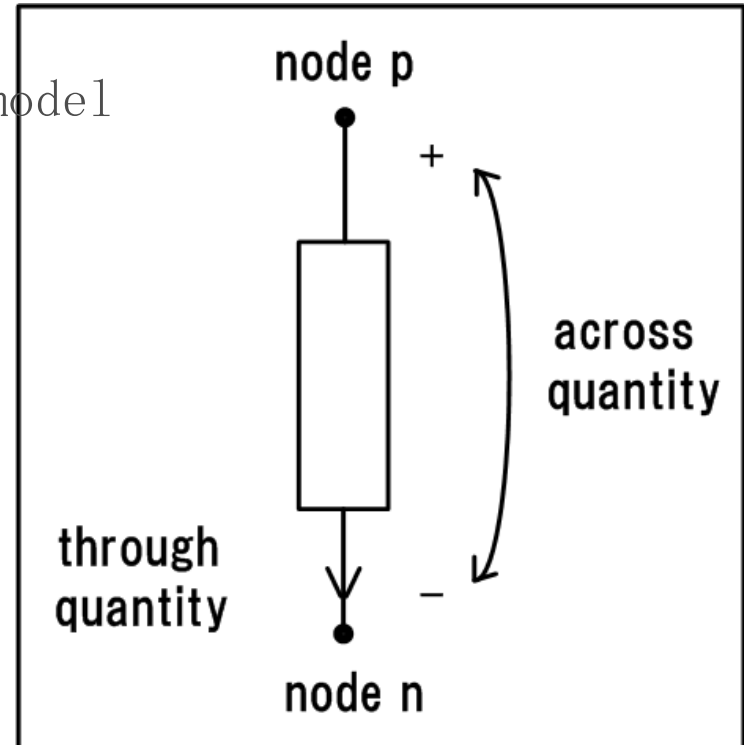
• •

Inductance • $v = L \frac{di}{dt}$

• •

R+L $v = Ri + L \frac{di}{dt}$

• • •





IGBT Elements

$$i(t) = I_s \cdot \left(e^{\frac{v(t)}{V_t}} - 1 \right) \text{ for } v(t) \geq 0$$

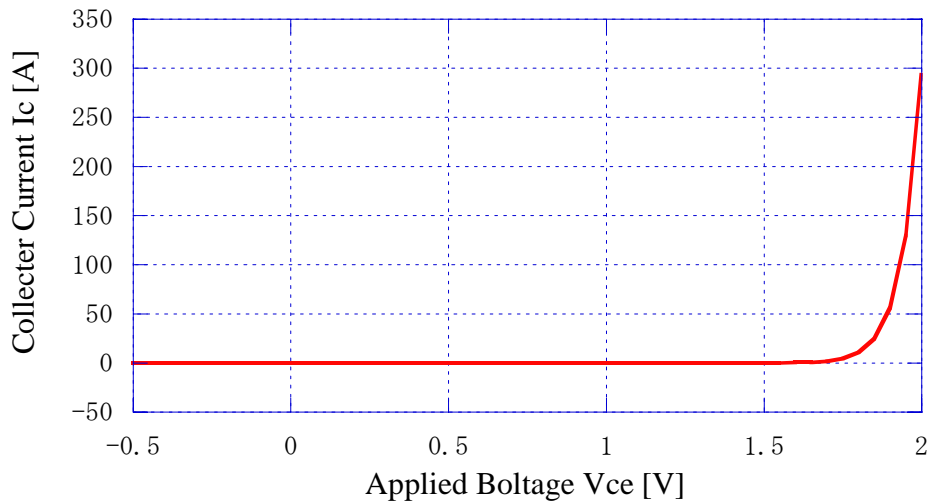
$$i(t) = \frac{v(t)}{R_r} \text{ for } v(t) < 0$$

$v(t)$: Terminal Voltage

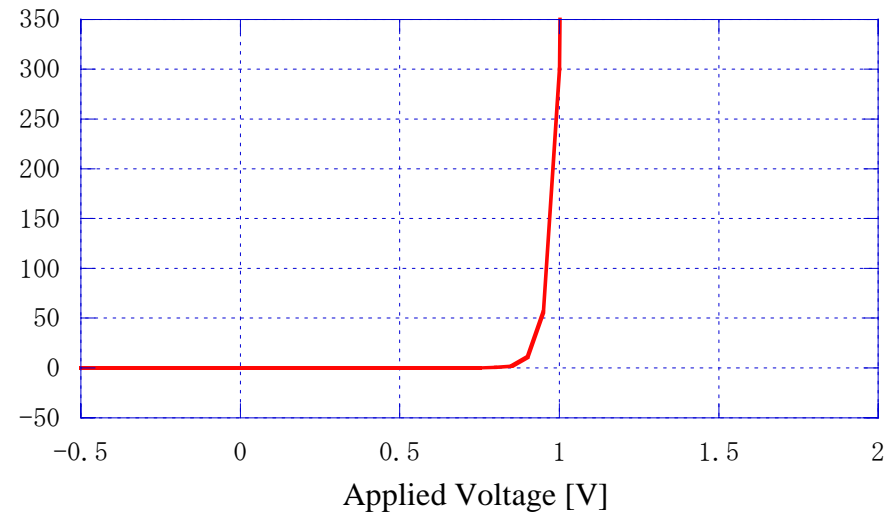
I_s : Saturation Current

V_t : Fitting Parameter

R_r : Reverse Resistance



IGBT on Voltage 1.7V



Diode on Voltage 0.8V



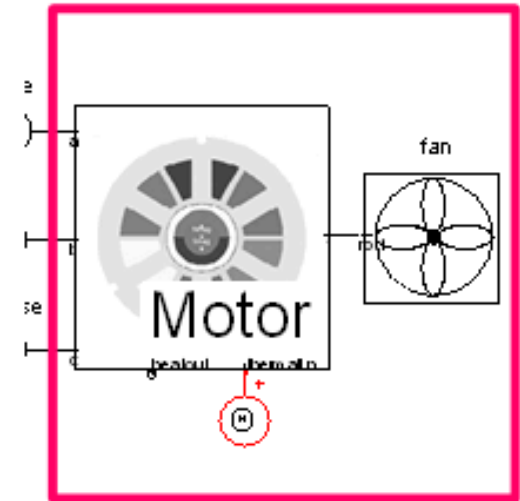


Motor Model

UHS Motor Model

Modeled by VHDL-AMS with Equivalent Circuits

- Benefit : Easy to define model for Fan as Load and take into account of Losses and Temperature effects.
- Model : Temperature dependent resistance and Load characteristics had been considered.



UHS Motor Model





Motor Model (Equivalent Circuits)

dq Axis model is considered

dq Voltage Equation

$$v_d = R_s i_{d0} + \frac{d\phi_d}{dt} - \omega \phi_q$$

$$v_q = R_s i_{q0} + \frac{d\phi_q}{dt} + \omega \phi_d$$

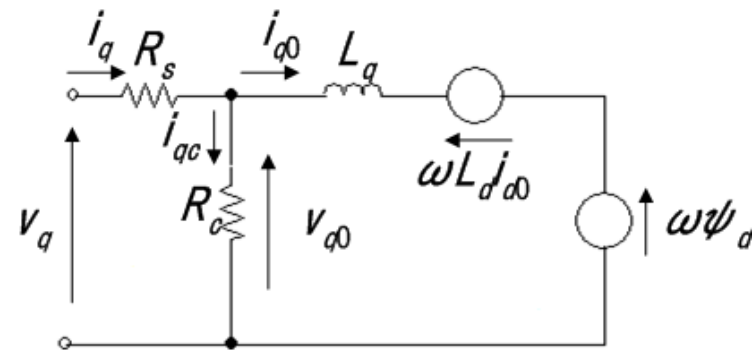
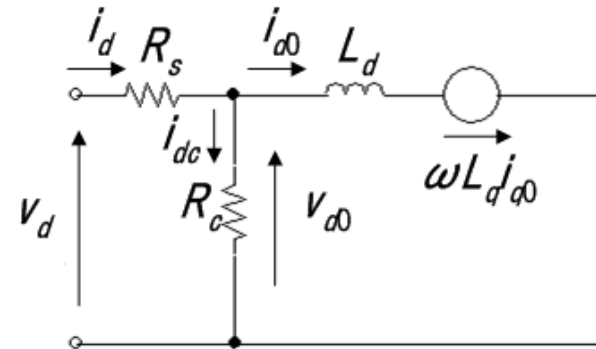
dq Flux

$$\phi_d = L_d i_{d0} + \phi_d$$

$$\phi_q = L_q i_{q0}$$

Torque

$$T = \phi_d i_q - \phi_q i_d$$



R_s : Winding R R_c : Eqv. Iron

L_d, L_q : d, q Inductance

ϕ_d : 永久磁石によるd軸鎖交磁束





Motor Model (Load)

Load : Fan model by VHDL-AMS

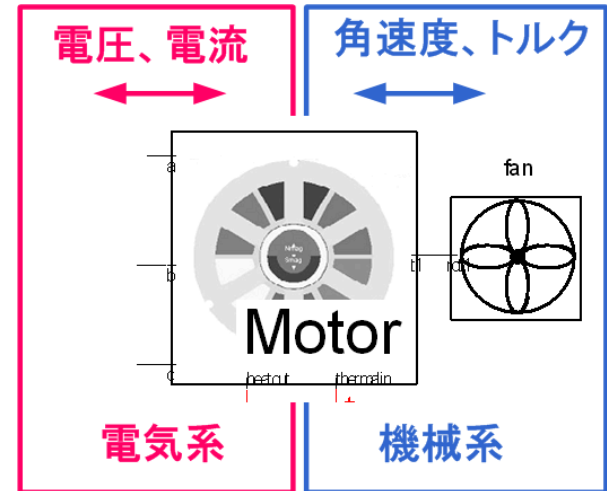
Voltage-Current . . .
Electrical
 Angular Velocity, Torque . . .
Mechanical
 Torque Equation for Fan

$$T = a\omega^2 + b\omega$$

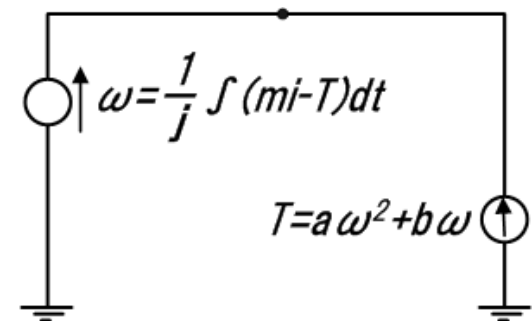
Motor Kinetic Equation

$$\omega = \frac{1}{j} \int (mi - T) dt$$

a, b : parameter
 j : Inertia



Motor ← → Load



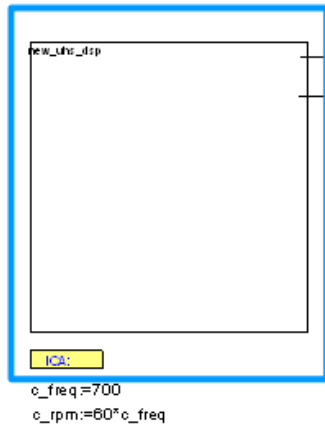
Eqv. Circuits for Mech.



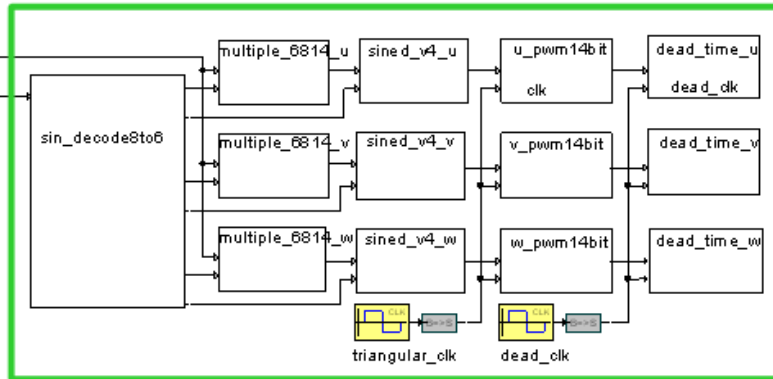


System Simulation Model

DSP Model



FPGA Model

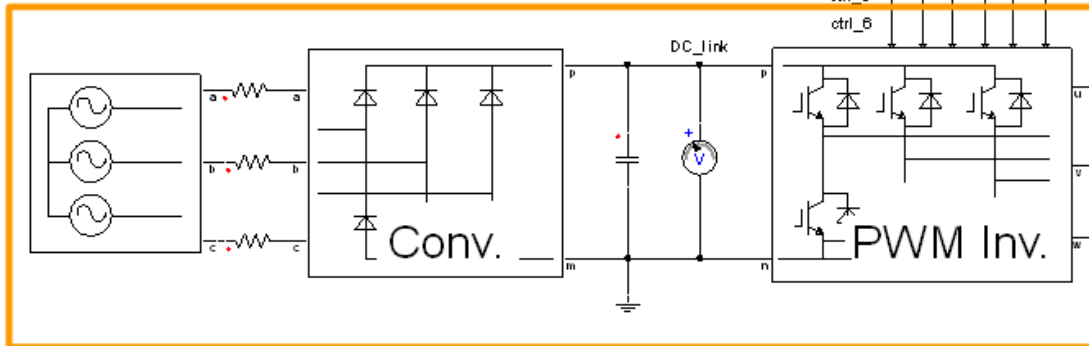


VHDL-AMS

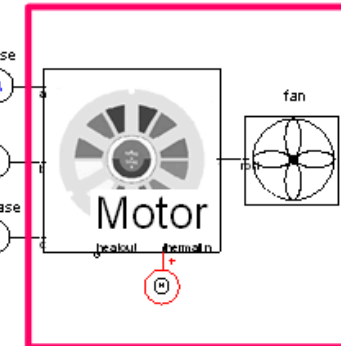
- PWM inverter Model
- UHS Motor Model

VHDL-AMS
(Digital)

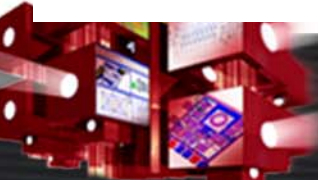
- FPGA Model



PWM inverter Model



UHS Motor Model





Simulation Parameters

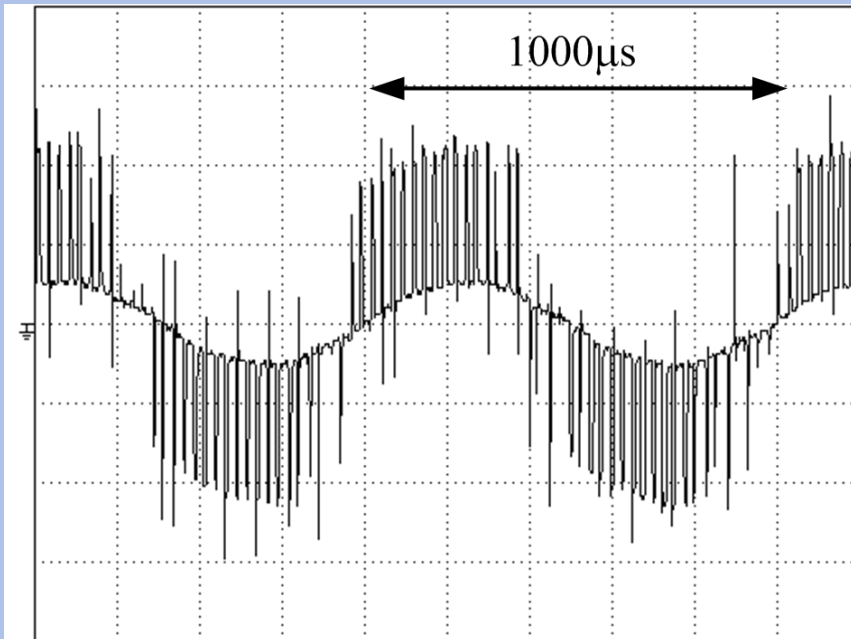
DC Link Voltage	200 V
Motor Inductance	$L_d = 0.093\text{mH}$ $L_q = 0.093\text{mH}$
Winding Resistance	$R = 0.1\ \Omega$
External Inductance	$L = 0.12\text{mH} / R = 0.16\ \Omega$
Carrier Freq.	20 kHz
Time Step	$0.5\ \mu\text{sec}$
Simulator	SIMPLORER ver7.0



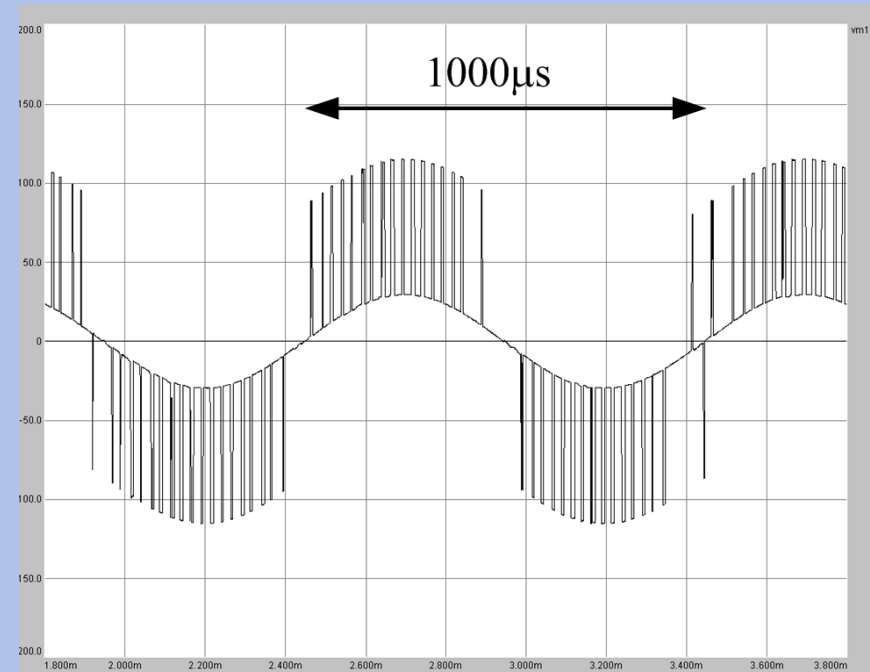


Results I

Terminal Voltage @60,000rpm



Experimental 50V/div



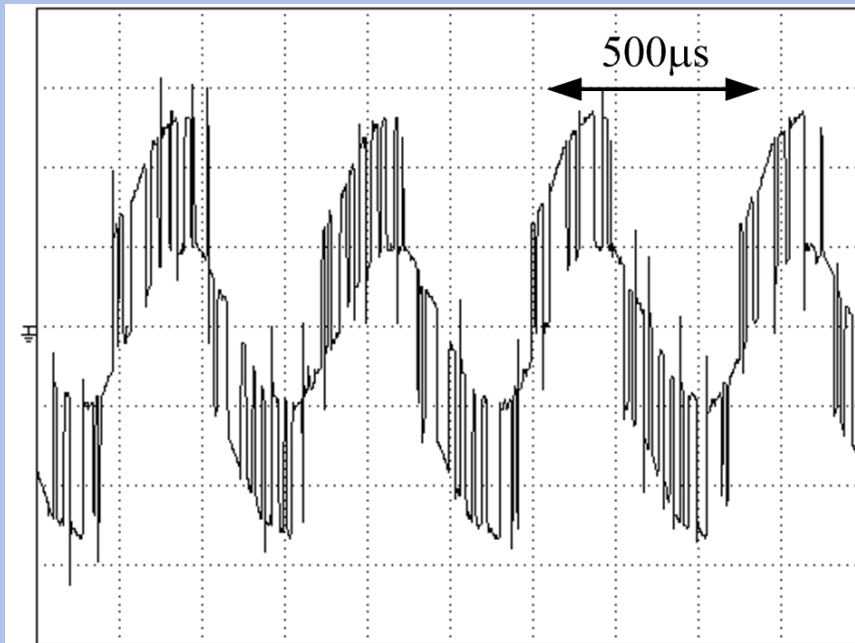
Simulation 50V/div



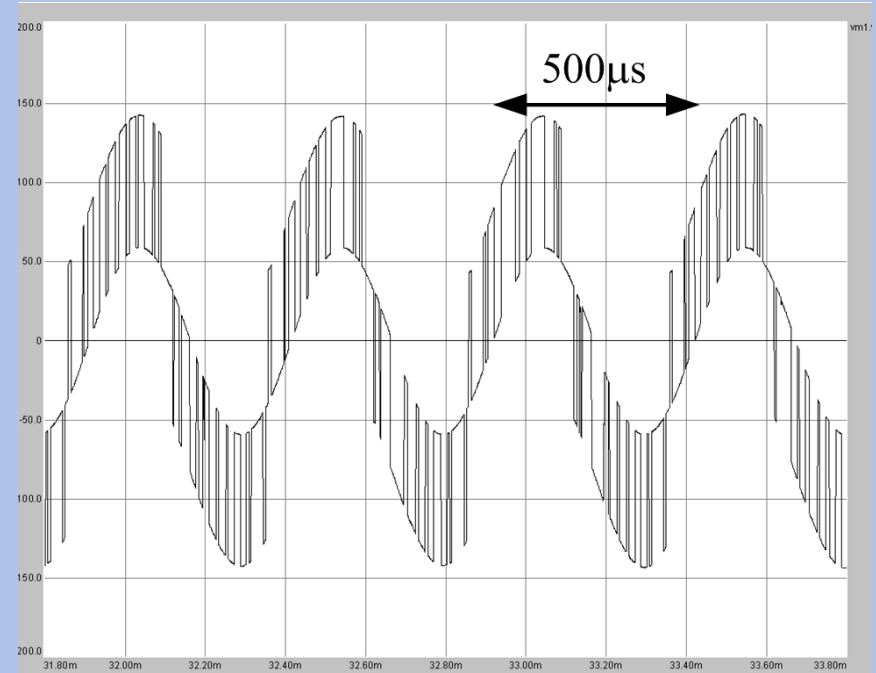


Results II

Terminal Voltage @120,000rpm



Experimental 50/div



Simulation 50V/div





Motor Model from ECE

Because the UHS Motor has special structure and materials, it is important to consider the Motor characteristics precisely.

Motor model should be modeled by using FEA and Equivalent Circuits Extraction from Maxwell.





Motor Model II

- FEA Model

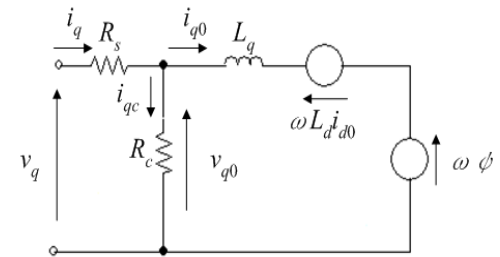
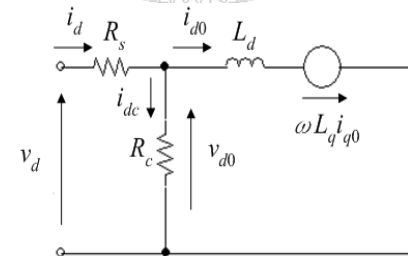
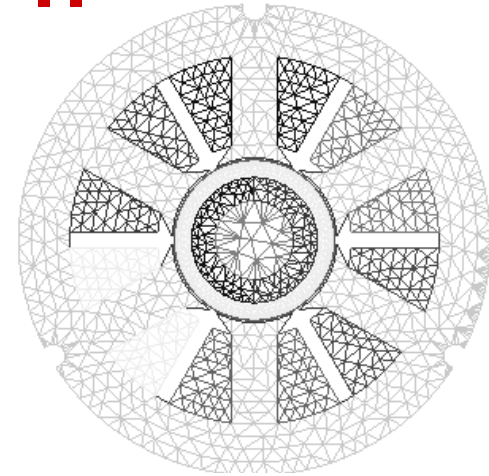
- Motor shape, dimension, Materials can be considered.
- Long Simulation time

Good for Motor on Design stage

- Equivalent Circuits Model

- Fast calculation
- Motor speed constant will help to represent an actual behavior
- Difficult to examine motor shape, dimension and materials

Good for conventional



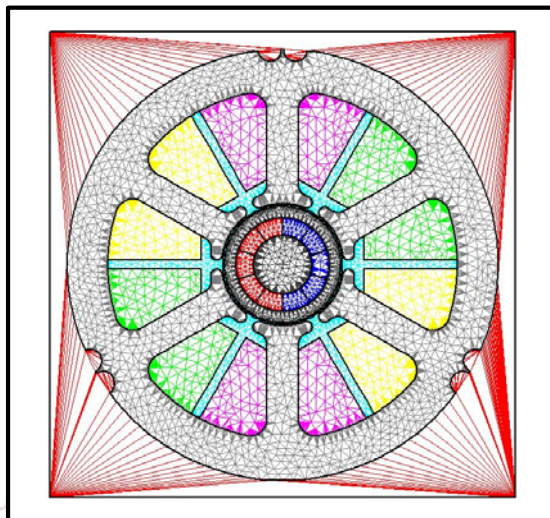


Motor Model by FEA I

1. Lookup Table from Maxwell (FEA)

- Motor Model : Linkage Flux and Torque
- Lookup Table : Parametric Analysis for Currents, Phase and Rotor

Position
Maxwell



Lookup table

Setup	Phase	angle	IA	IB	IC	Save Fields	Phase	Temperature	Energy(J)	Excess (J)	Torque (Nm)
setUp1	T	0	-800	-800	-800	H	H	1790	17.15124	0.403951	-0.000039348
setUp2	T	0	-800	-800	-400	H	H	1790	16.3093	0.404138	-1.42019
setUp3	T	0	-800	-800	0	H	H	1790	15.117	0.404796	2.84887
setUp4	T	0	-800	-800	400	H	H	1790	14.9937	0.40495	4.2701
setUp5	T	0	-800	-800	800	H	H	1790	14.7409	0.40482	5.69112
setUp6	T	0	-800	-400	-800	H	H	1790	14.3123	0.404995	-1.42139
setUp7	T	0	-800	-400	-400	H	H	1790	13.3536	0.40493	-0.000059940
setUp8	T	0	-800	-400	0	H	H	1790	14.6425	0.403768	1.42385
setUp9	T	0	-800	-400	400	H	H	1790	14.2392	0.404224	2.84976
setUp10	T	0	-800	-400	800	H	H	1790	14.0017	0.404379	4.27123
setUp11	T	0	-800	0	-800	H	H	1790	13.5185	0.404614	-2.84859
setUp12	T	0	-800	0	-400	H	H	1790	14.6640	0.40561	-1.42448
setUp13	T	0	-800	0	0	H	H	1790	14.9768	0.405143	-0.000119393
setUp14	T	0	-800	0	400	H	H	1790	13.715	0.40604	1.42143
setUp15	T	0	-800	0	800	H	H	1790	13.7012	0.406688	2.85084
setUp16	T	0	-800	400	-800	H	H	1790	14.8883	0.40509	-4.27066
setUp17	T	0	-800	400	-400	H	H	1790	14.2369	0.404139	-2.85002
setUp18	T	0	-800	400	0	H	H	1790	13.7551	0.406629	-1.42129



Motor Model by FEA II

2. Create a Motor Model

- Motor Model : Lookup Table + Equations
- Equations : VHDL-AMS

Lookup table

Setup	Order	Angle	ix	iy	iz	Node	Order	Coordinate	Energy (J)	Energy (%)	Temp (Deg)
ansys1	T	0	-90	-90	-90	X	X	2760	17.3124	0.402912	-0.9993936
ansys2	T	0	-90	-90	-90	X	X	2760	16.3055	0.404130	-1.42021
ansys3	T	0	-90	-90	-90	X	X	2760	15.3171	0.405706	-2.14487
ansys4	T	0	-90	-90	-90	X	X	2760	14.3677	0.408021	-3.17021
ansys5	T	0	-90	-90	-90	X	X	2760	13.4769	0.411482	-4.49922
ansys6	T	0	-90	-90	-90	X	X	2760	12.6523	0.416495	-6.14219
ansys7	T	0	-90	-90	-90	X	X	2760	11.8936	0.424502	-8.097096
ansys8	T	0	-90	-90	-90	X	X	2760	11.2007	0.435970	-10.2670
ansys9	T	0	-90	-90	-90	X	X	2760	10.5742	0.451224	-12.6670
ansys10	T	0	-90	-90	-90	X	X	2760	10.0047	0.470779	-15.3123
ansys11	T	0	-90	-90	-90	X	X	2760	9.49164	0.495014	-18.2489
ansys12	T	0	-90	-90	-90	X	X	2760	9.03490	0.524502	-21.5148
ansys13	T	0	-90	-90	-90	X	X	2760	8.63470	0.559706	-25.1420
ansys14	T	0	-90	-90	-90	X	X	2760	8.29104	0.601482	-29.1624
ansys15	T	0	-90	-90	-90	X	X	2760	7.99408	0.650000	-33.6084
ansys16	T	0	-90	-90	-90	X	X	2760	7.74500	0.705600	-38.5166
ansys17	T	0	-90	-90	-90	X	X	2760	7.53400	0.769600	-43.9300
ansys18	T	0	-90	-90	-90	X	X	2760	7.35100	0.842400	-49.8900

+

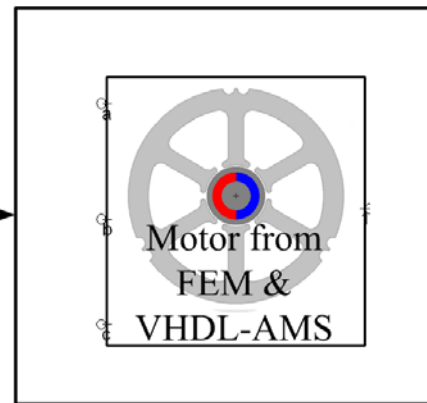
$$V_{a,b,c} = R_{i,a,b,c} + \frac{dF_{a,b,c}}{dt}$$

$$\omega = \frac{1}{J} \int \tau dt$$

voltage and motion equations

VHDL-AMS

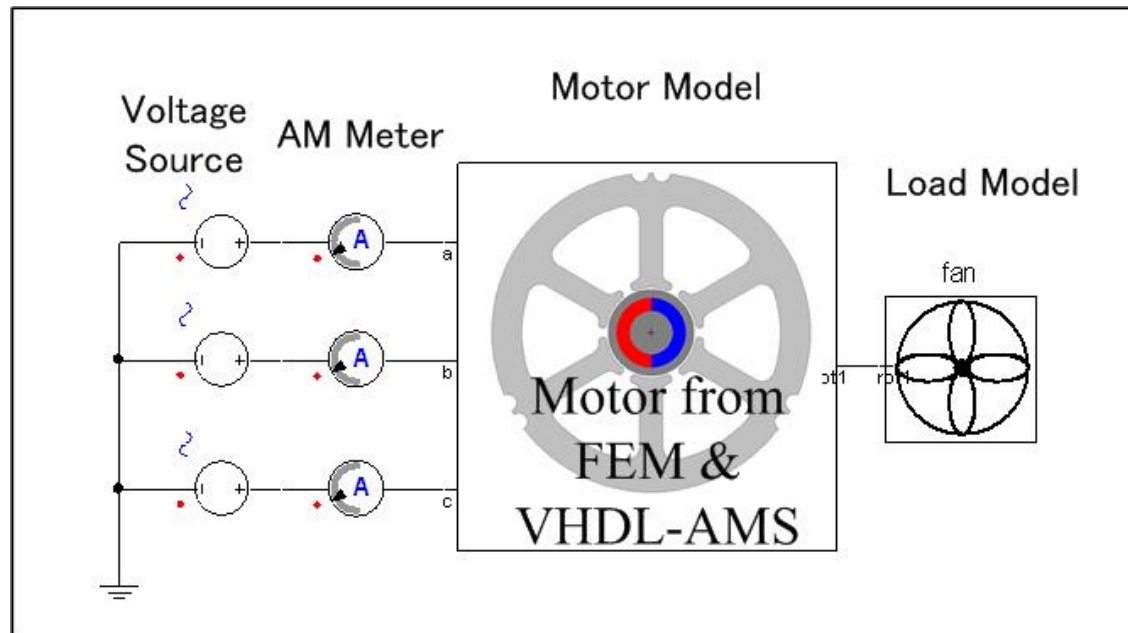
Motor model





Motor Model (Validation)

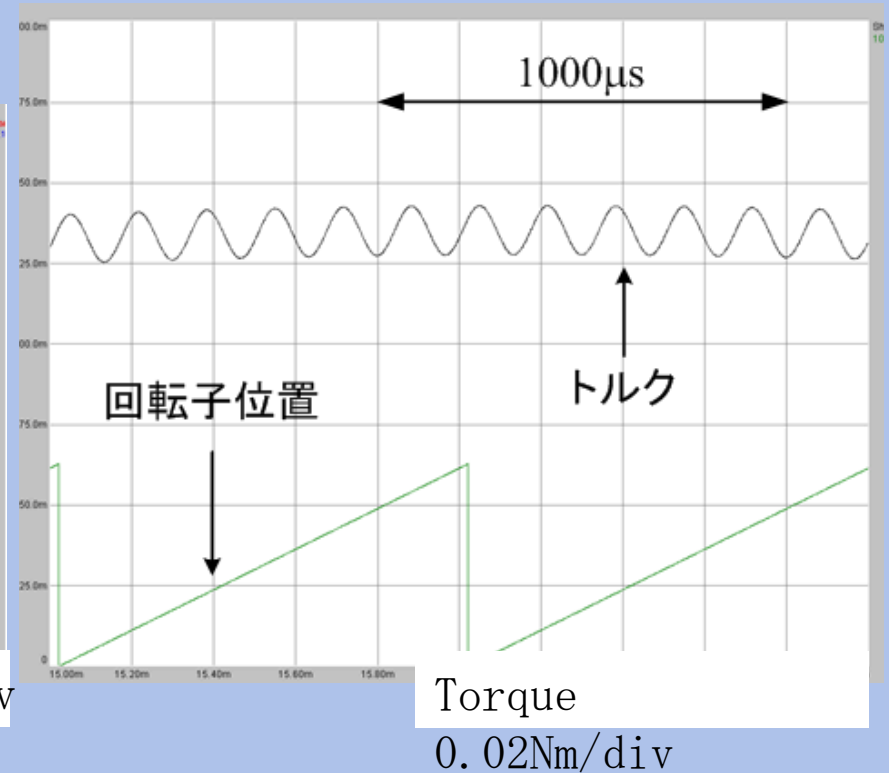
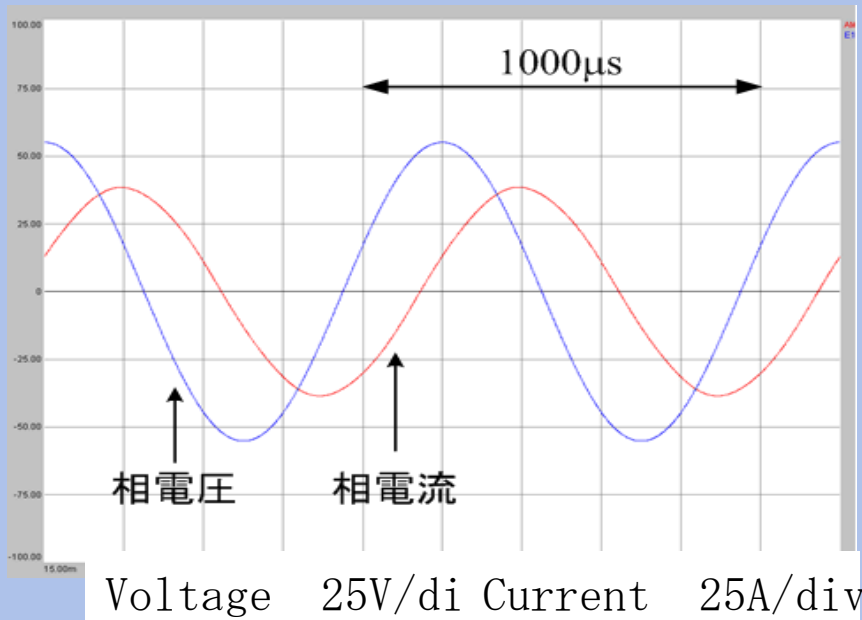
- Test Circuits by using SIMPLORER
- Input : Three phase voltage source





Motor Model (Validation)

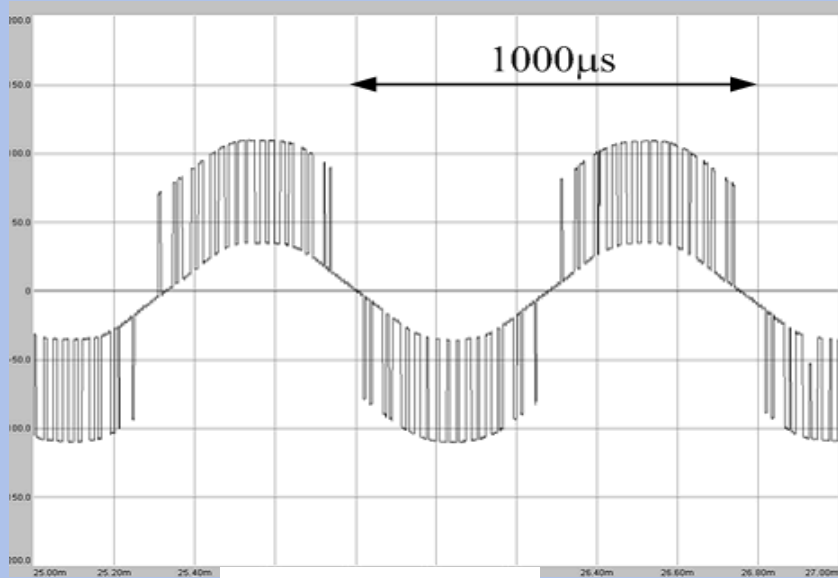
@60,000rpm



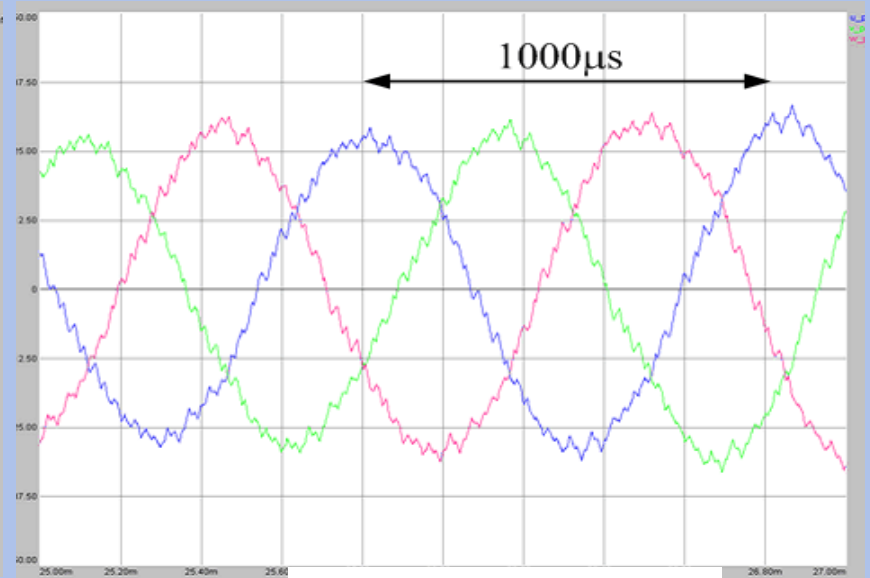


Results

@60,000rpm



Vab 50V/div



Current 12.5A/div





Summary(1)

- In this presentation, the ultra-high speed drive system and the ultra-high speed motor modeled by using VHDL-AMS and the lookup table from FEM analysis.
- The drive system model did almost the same operation as the experiment system.



Engine Cranking System

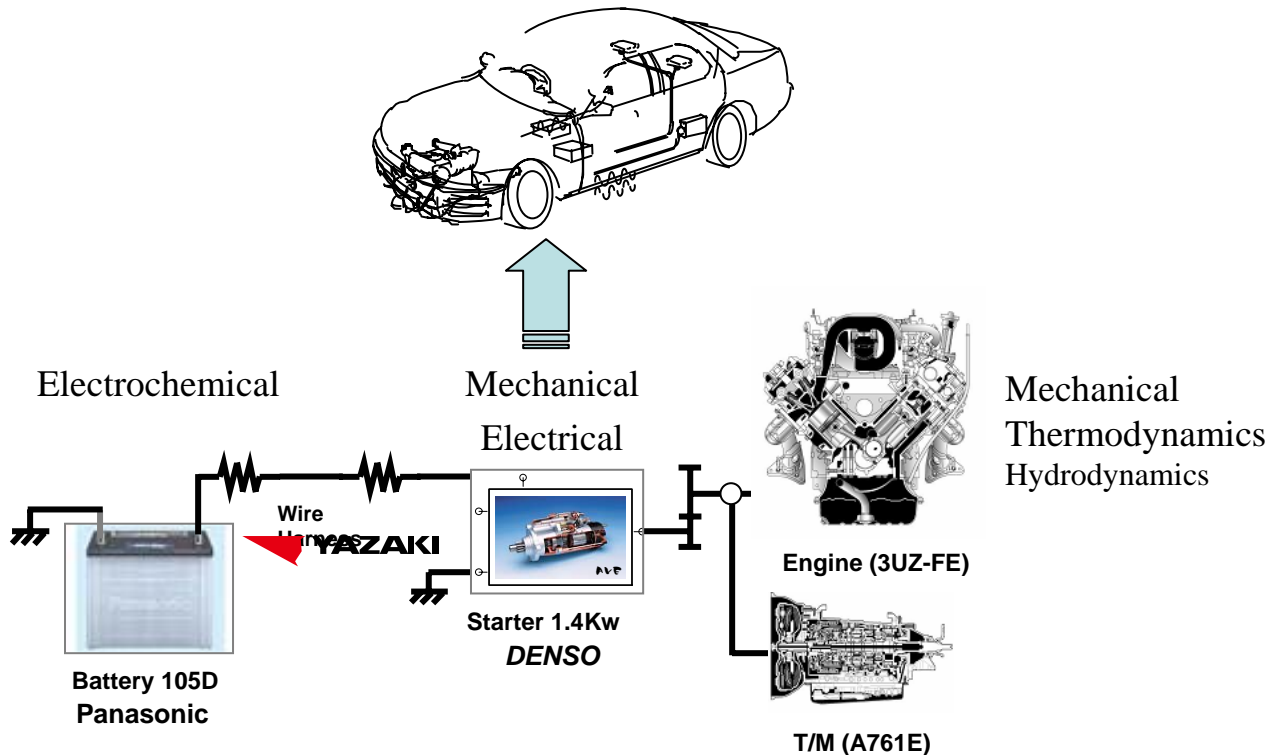
Analysis of the Battery Voltage Behavior

- How much is the rest of battery voltage in the engine cranking ?
 - The guarantee for the lowest battery voltage is the primary criteria for an engine cranking system operation.
- How much is the engine cranking speed?
 - The engine cranking speed gives the quasi combustion criteria.

This analysis uses Mechanical, Electrical, Thermodynamics, Hydrodynamics and Electrochemical models.



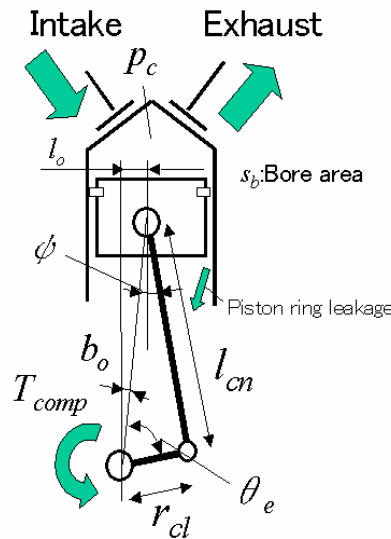
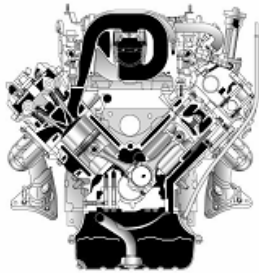
Engine Cranking System



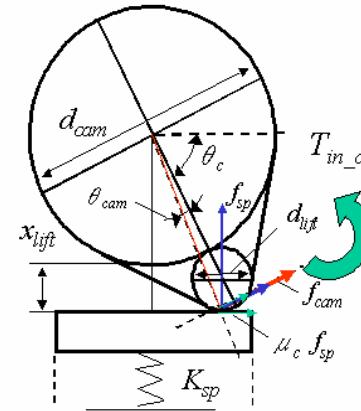
All sub-Models are represented by VHDL-AMS and Circuits components in SIMPLORER



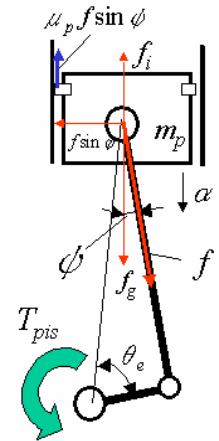
Subsystem (1) : Engine



Compression Model



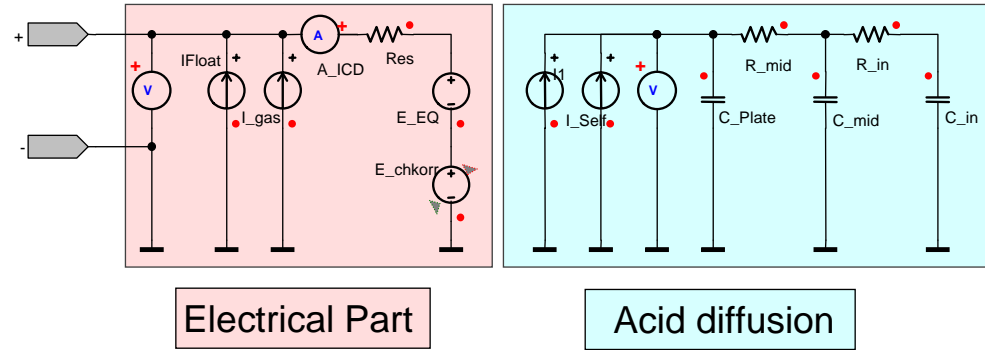
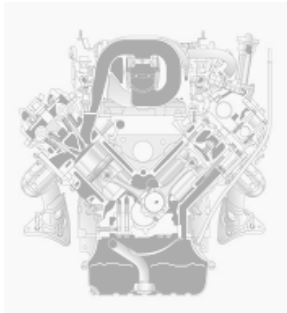
Cam/piston Friction Model



Detail Engine model



Subsystem (2) : Battery



$$I_{self} = \frac{sdpd}{100} \cdot \frac{cap}{24hrs} \cdot e^{\frac{T-T_0}{sd_t}}$$

$$I_{gass} = r_curr \cdot \left[\exp\left(\frac{V_{cell} - gass_th'}{gass_sl}\right) - 1 \right]$$

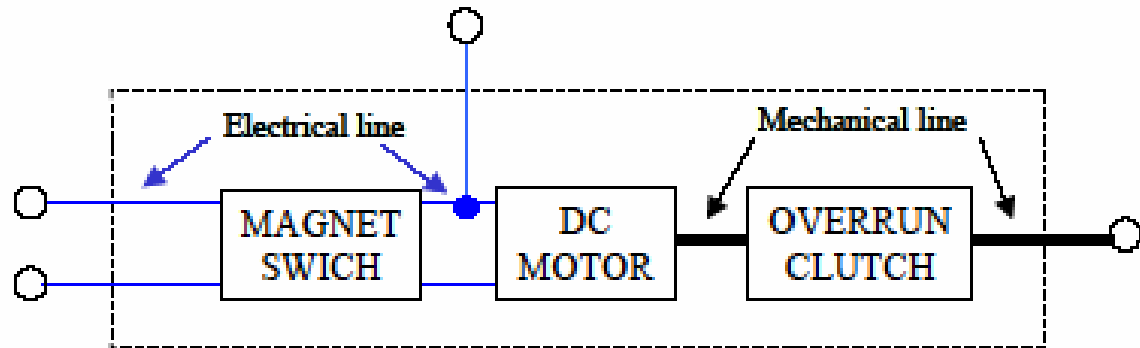
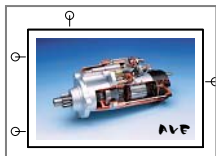
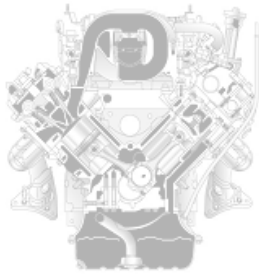
Automotive Lib.

$$[E_d] = \frac{RT}{2F} \ln\left(\frac{[H^+]^4 [SO_4^{2-}]^2}{[H_2O]^2} \frac{[H_2O]_0^2}{[H^+]_0^4 [SO_4^{2-}]_0^2}\right)$$

Polarisation Effects

SIMPLOER Automotive Lib + polarisation effects

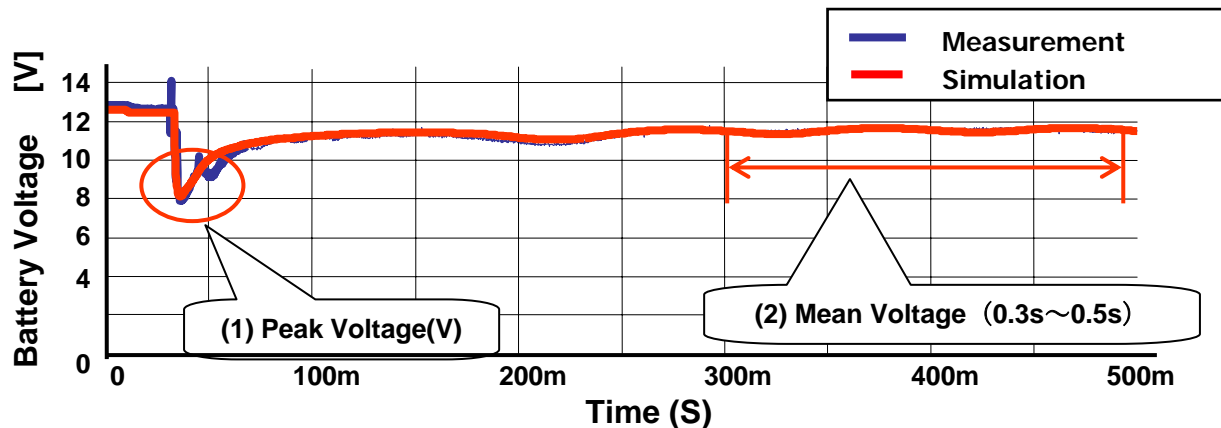
Subsystem (3) : Starter



Mechanical and Electrical behavior



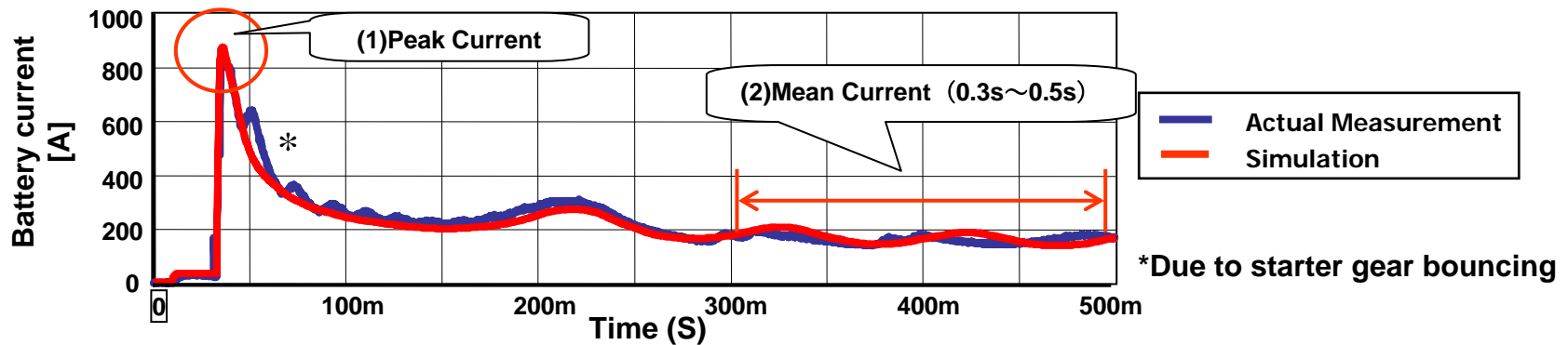
Battery Voltage (V) vs. Time



Temp. & SOC	Measurement	Simulation	Error(%)	
20.0°C SOC 65.6%	(1) Peak	7.9	8.1	2.8
	(2) Mean	11.5	11.6	0.5
20.0°C SOC 2.5%	(1) Peak	7.3	7.2	0.9
	(2) Mean	10.9	10.9	0.1
-25.0°C SOC 77.2%	(1) Peak	6.7	6.9	3.1
	(2) Mean	9.7	10.1	3.9
-25.0°C SOC 34.6%	(1) Peak	6.5	6.5	0.2
	(2) Mean	9.3	9.6	3.6



Battery Current (A) vs. Time



Temp. & SOC	Measurement	Simulation	Error(%)	
20.0°C SOC 65.6%	(1) Peak	855	880	2.9
	(2) Mean	164	160	2.9
20.0°C SOC 2.5%	(1) Peak	808	786	2.7
	(2) Mean	157	158	0.2
-25.0°C SOC 77.2%	(1) Peak	840	867	3.2
	(2) Mean	290	255	12 *
-25.0°C SOC 34.6%	(1) Peak	819	821	0.2
	(2) Mean	315	252	20.2 *

*Due to phase difference



Summary (2)

- Multi domain simulation using modeling language VHDL-AMS was applied to the system verifications.
- Battery Voltage Behavior in Conventional Engine Cranking were examined.
 - The results attained sufficient accuracy (within 5%) in practical use (-25deg to ambient temperature).



Conclusion

V

V

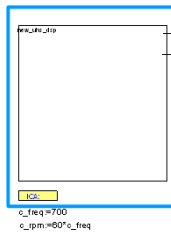
V

• Process “V”

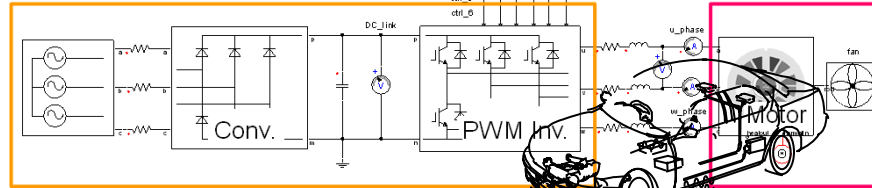
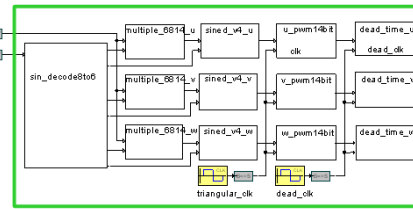
• “V” HDL-AMS

• “V” ictory!

DSP Model



FPGA Model



PWM inverter Model

UHS Motor Model

