

# A Power-hardware-in-the-Loop Test Bench for Electric Machine Emulation

Amitkumar K. S and Prof. Pragasen Pillay

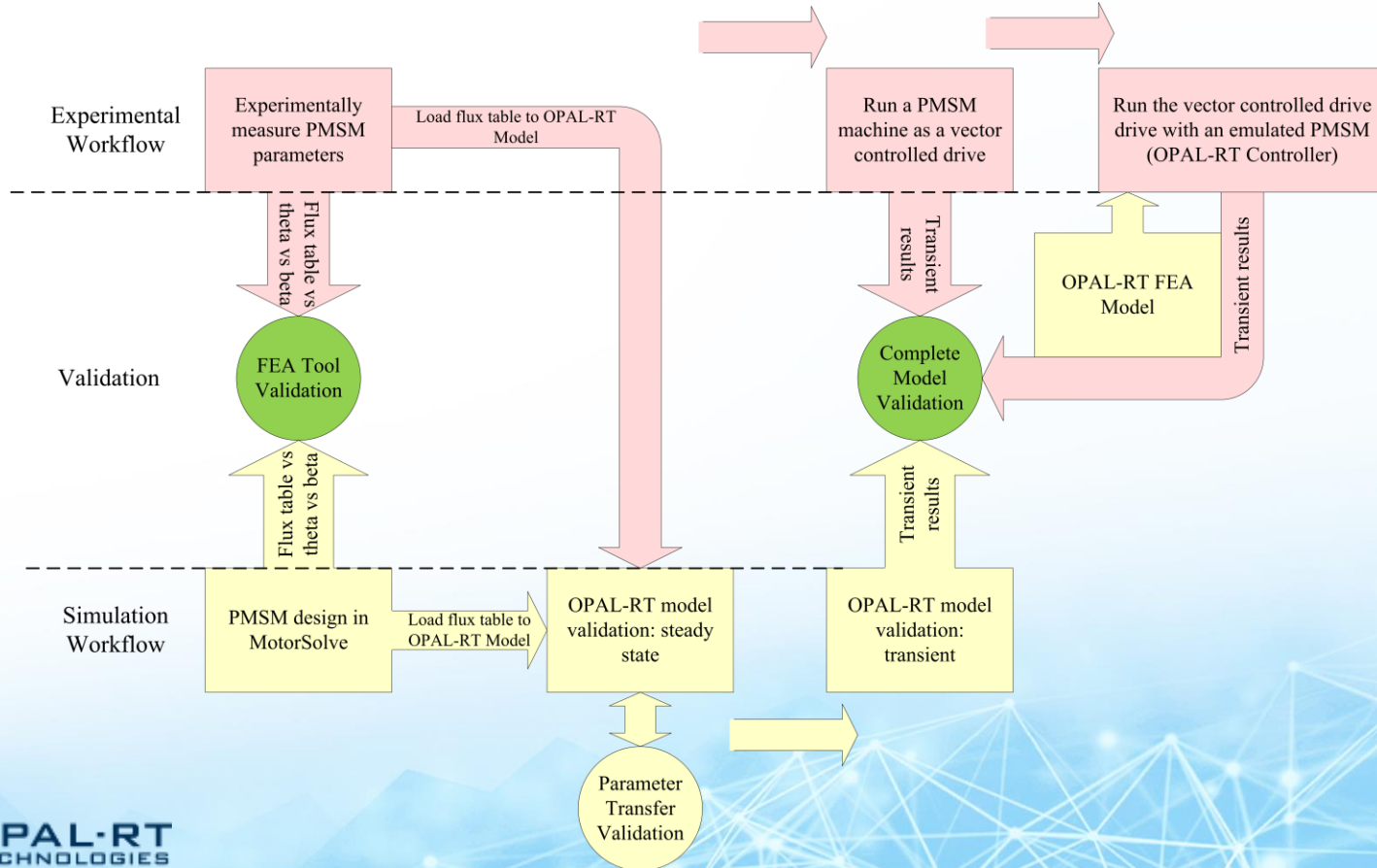
Power Electronics and Energy Research (PEER Group)

Concordia University

# Outline

- Motor model validation: tool-flow
- MotorSolve data import
- Machine emulator structure and control
- Experimental setup (switched and linear machine emulators)
- Summary

# Motor model validation: tool flow



# Motor data export: MotorSolve to OPAL-RT

The screenshot displays the Motor Explorer software interface. The left sidebar shows a tree view with 'Motor Results' expanded, and 'PWM analysis' selected. The main window is titled 'Input: PWM analysis' and contains several sections: 'General', 'Operating Point', 'Result Export Options', and 'Resolution & Accuracy'. A 'Specifications' table is also visible.

Input: General Settings	
Supply voltage	400
Rated current	22.04540769
Rated speed	1200

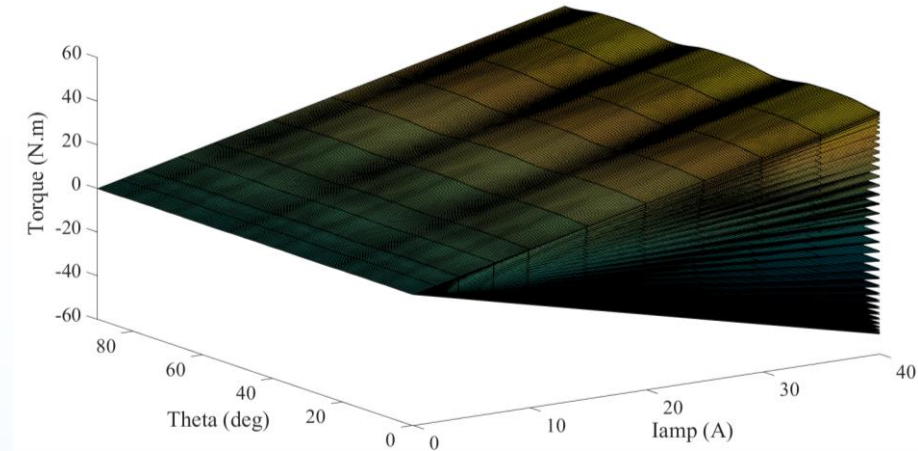
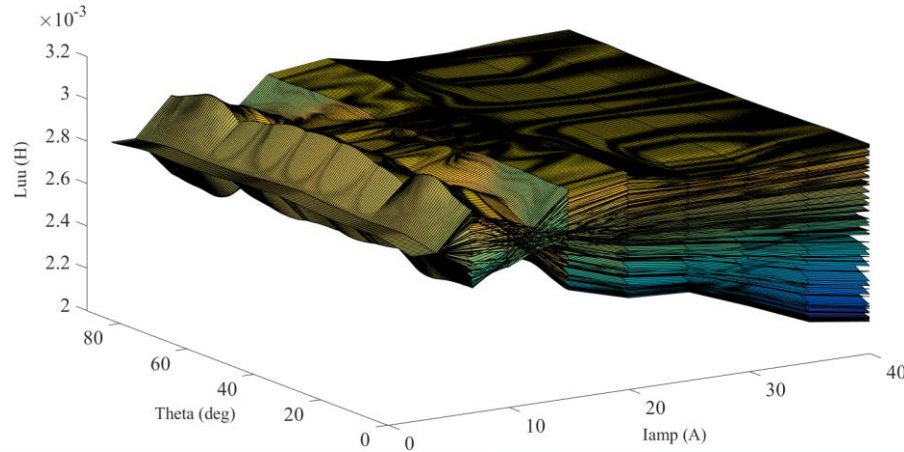
Annotations with callouts provide specific details:

- Current, DC bus voltage and speed settings:** Points to the Specifications table.
- Set to nonlinear to account for multiple currents:** Points to the 'Model type' dropdown set to 'Nonlinear'.
- Current Settings: The linear BH curve region should have a lower number of current set points, when compared to the nonlinear region. Hence the use of list is preferred to save time:** Points to the 'FEA currents percentages' list: '0, 10, 20, 30, 70, 90, 100, 110, 120, 130, 140, 150'.
- Advance angle settings: Change the step size as list or range, but keep the angles between 0 to 360 degs:** Points to the 'FEA advance angles' range: '0, 360, 10'.
- Number of samples per electric cycle:** Points to the 'Number of FEA sample points' value: '24'.
- Accuracy depends on model complexity and results:** Points to the 'Resolution & Accuracy' section.
- After setting up, "Save as type" to generate the model:** Points to the 'View Result' button.
- Enables the inclusion of core losses:** Points to the 'Include iron loss' checkbox, which is checked.

A motor cross-section diagram is shown on the right side of the interface.

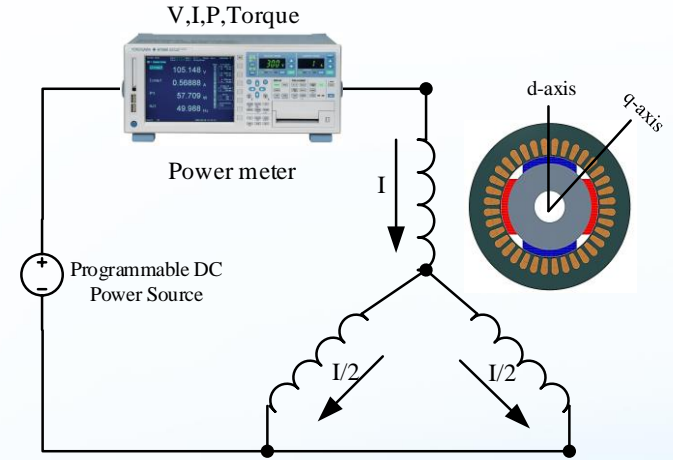
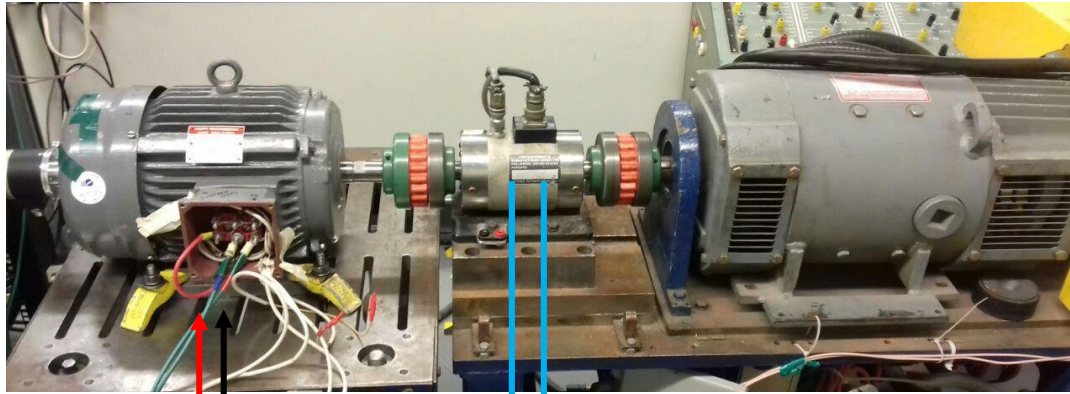
- Process of data export from MotorSolve

# Motor data export: MotorSolve to OPAL-RT



- Machine geometric and magnetic data exported from the FEA software MotorSolve, to the behavioural model in OPAL-RT

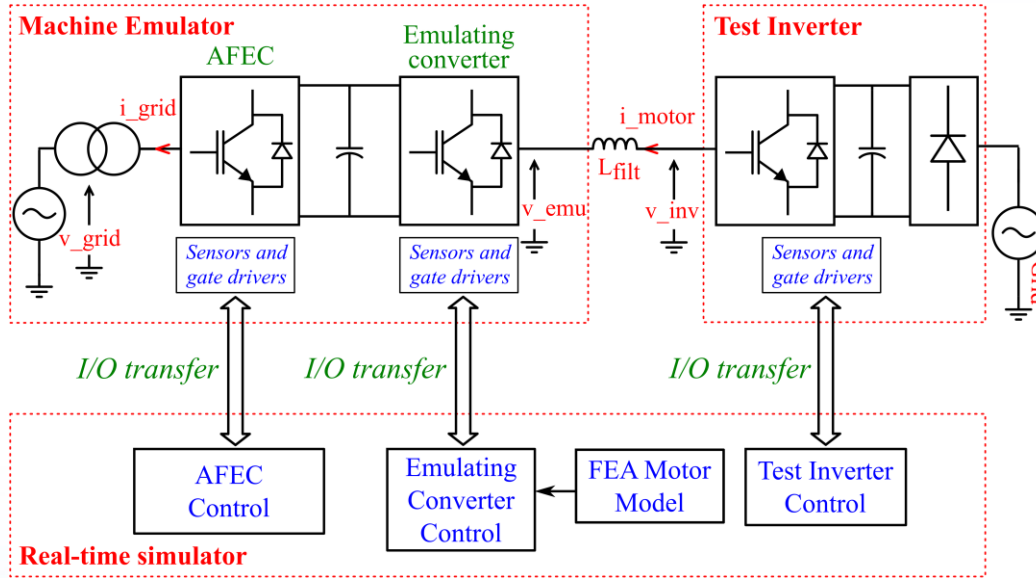
# Physical measurement of machine data\*



- Experimental setup for measuring machine geometric and magnetic data

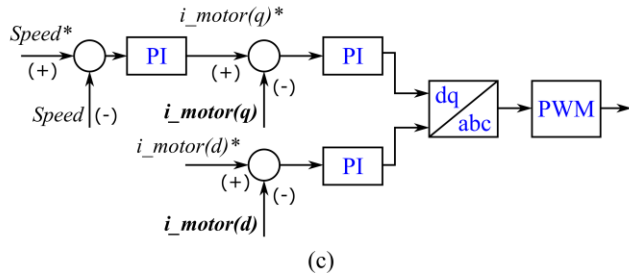
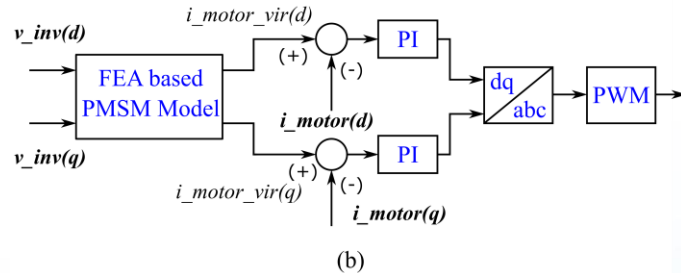
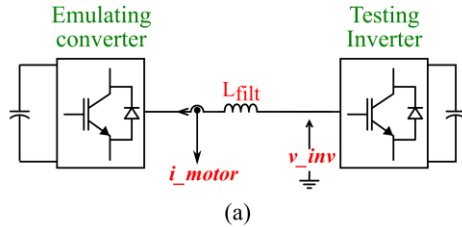
\* Courtesy: Chirag Desai

# Machine emulator structure



- The active front end converter and the emulating converter connected in a back-back fashion works as a power amplifier, emulating the machine behaviour

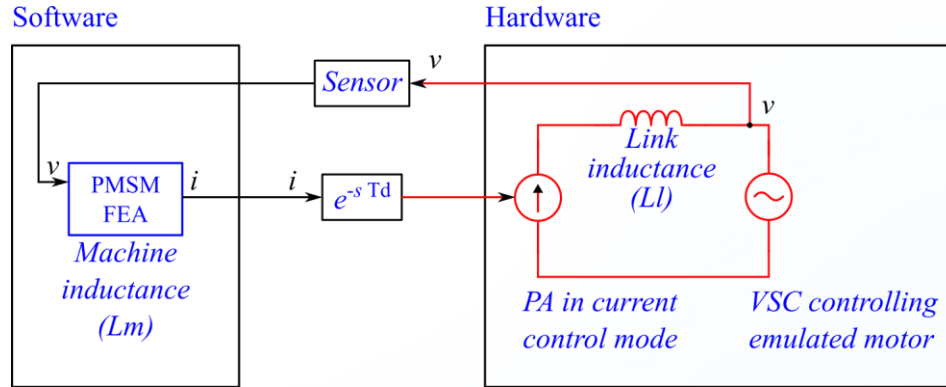
# Machine emulator – control structure



- The emulating converter and the test inverter both work in current control mode
- Controller instability of the system, is avoided by keeping the bandwidth of the emulating converter much higher than the test inverter
- The L-filter (in the figure) is just a link filter used for interconnection of the machine emulator with the test inverter

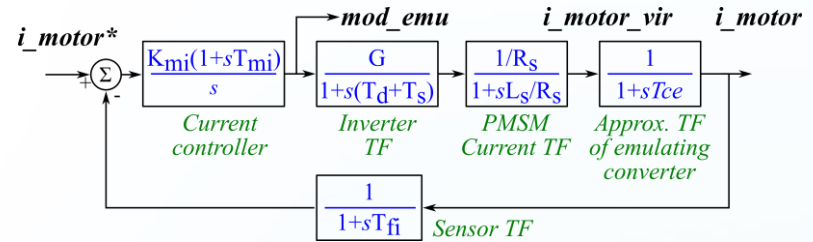
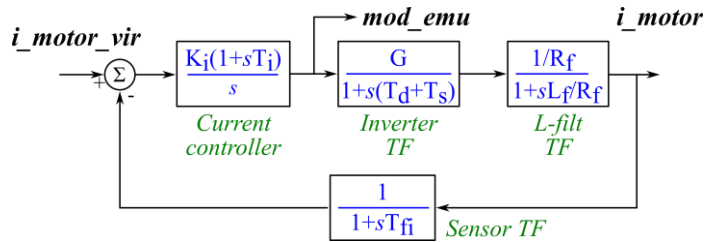


# Machine emulator - interface algorithm



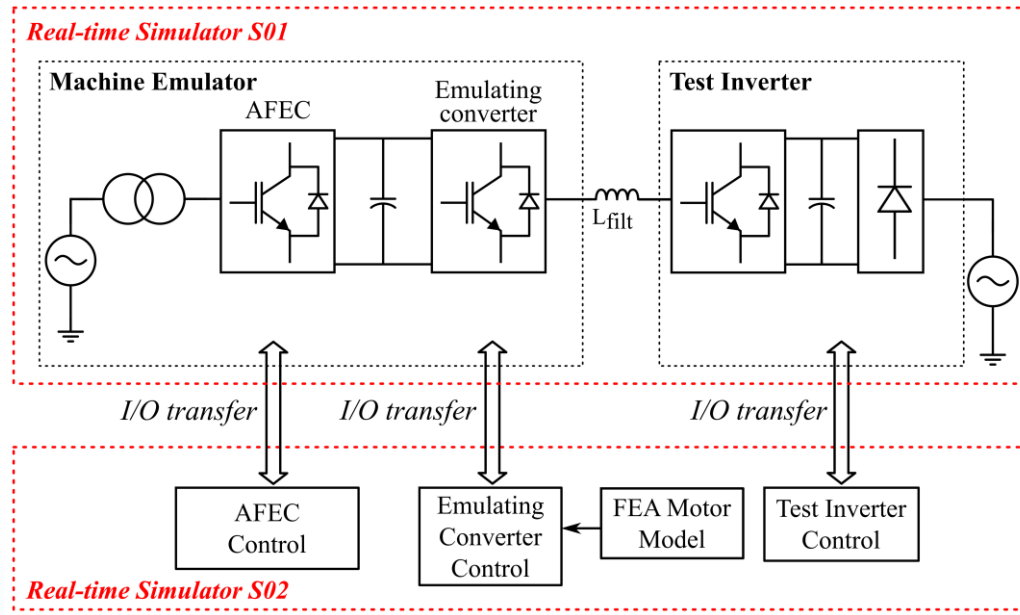
- The interface algorithm used is current-type ideal transformer model (ITM)
- The delay ' $T_d$ ' is inclusive of the power amplifier delay and the time-step of the real-time simulator; power amplifier delay (if linear) is almost negligible
- $L_l$  needs to be smaller than  $L_m$  to ensure absolute stability; however the PA current control loop BW and the test inverter current control loop BW have a role as well

# Machine emulator – control structure



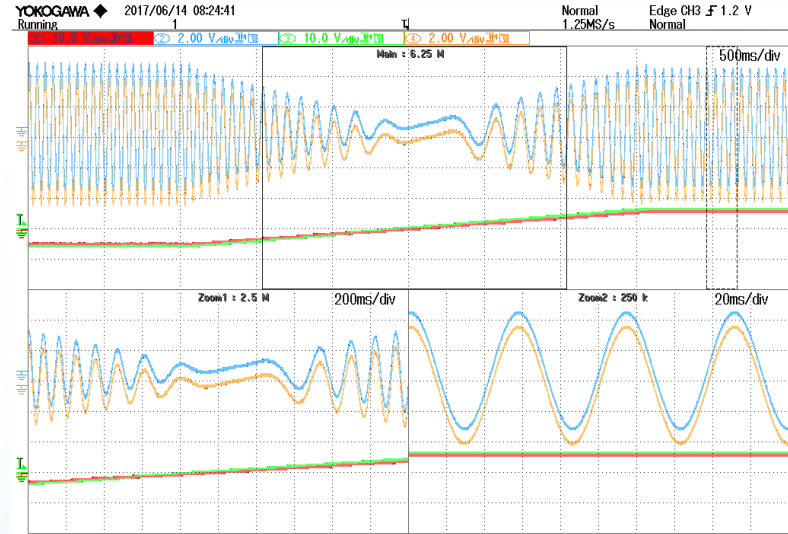
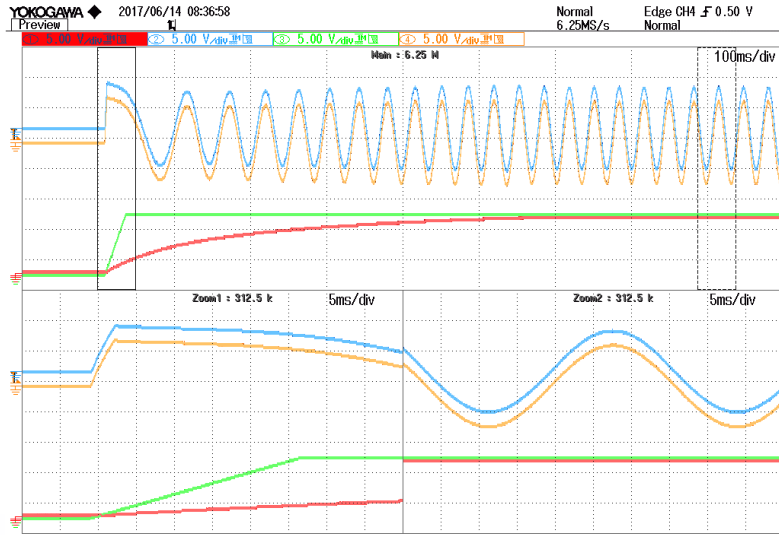
- Emulating converter working in current control mode, cancels dynamics associated with the link inductor
- Emulating converter current control loop needs to be much faster (at least five times) than the test inverter inner current loop to ensure stable operation

# Machine emulator – real-time simulation



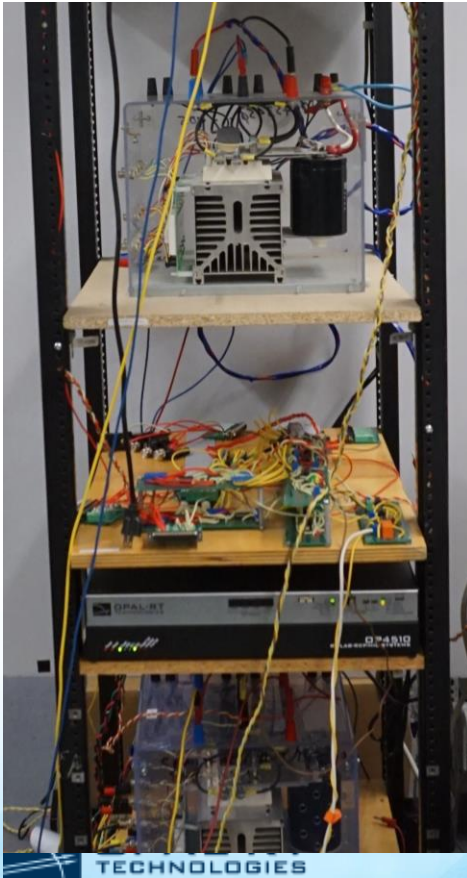
- System implemented in a C-HIL simulation on two OPAL-RT simulators (OP4510s)
- The PMSM-SH model uses MotorSolve flux and torque tables

# Machine emulator – real-time simulation



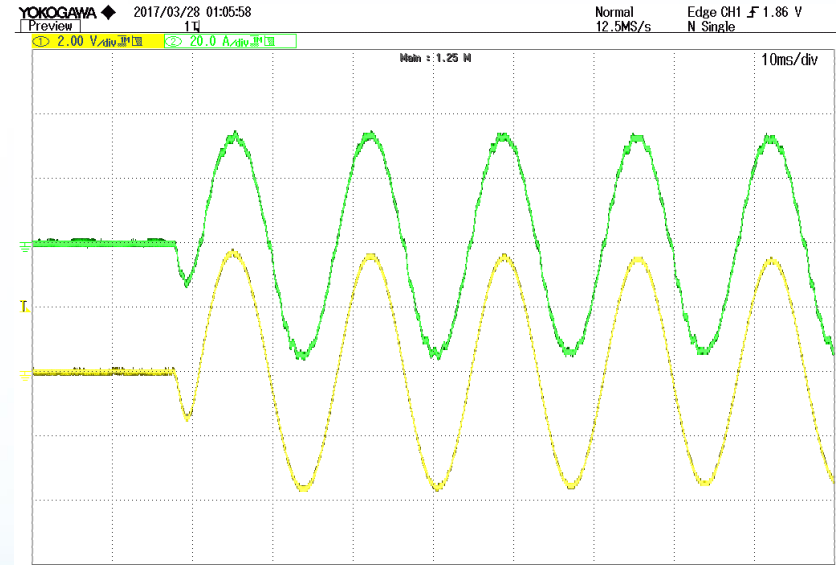
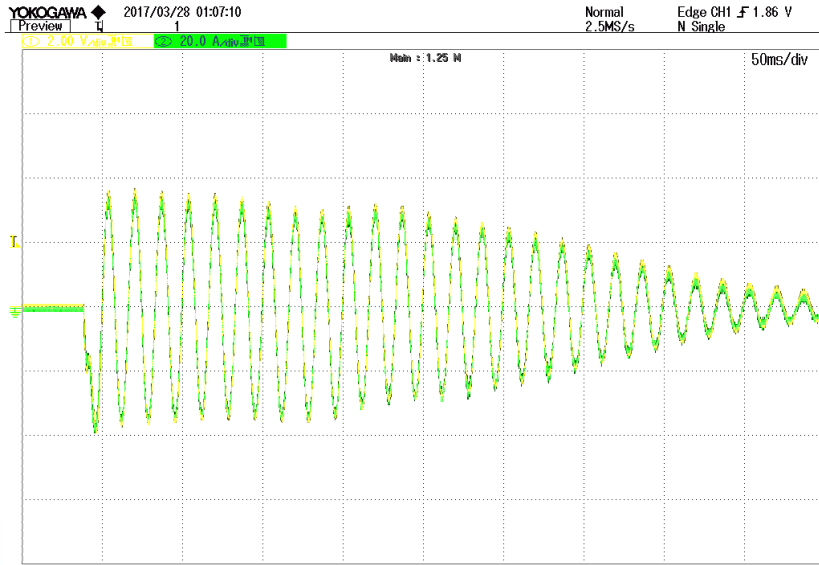
- Results show a stable real-time simulation validating of the individual constituent converters. The same control can be further used for the experimental PMSM setup as well, when developed

# Power amplifier - switched



- The power amplifier developed using simple 6-pack VSC based converters, each switching at 20 kHz
- The power amplifier has an emulation capability of 15 kVA (implying a machine emulation of around 12-15 hp as well).
- Machine amplifier designed to have a current loop bandwidth of around 2 kHz
- Protection circuitry is developed for the power amplifier/machine emulator to protect against overcurrent and overvoltage faults, transformer for isolation

# Power amplifier - switched



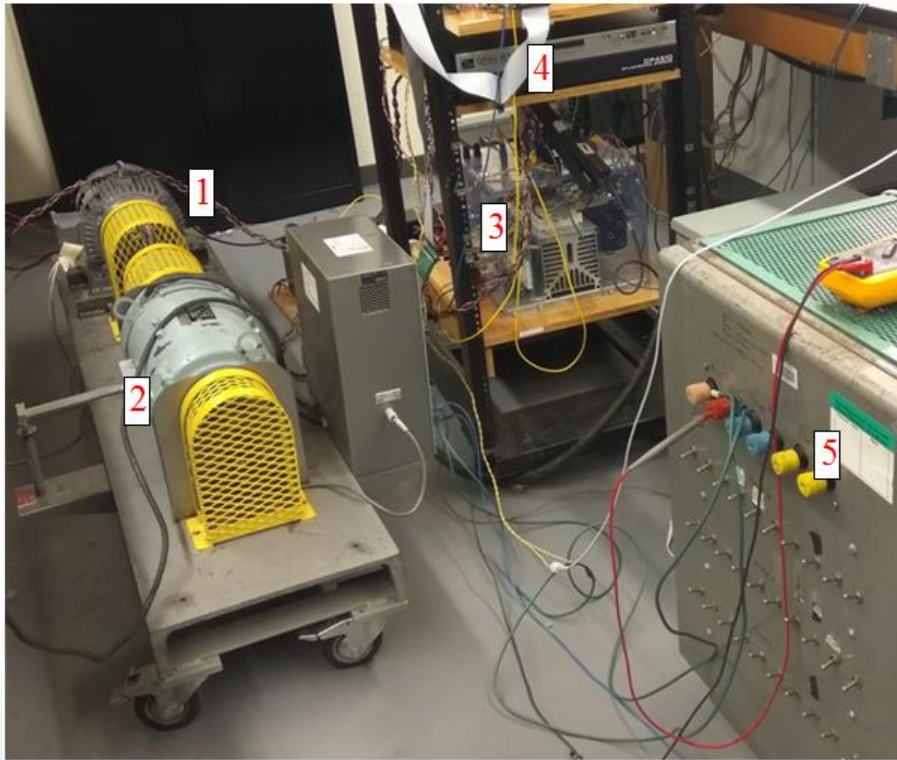
- Preliminary results relating to induction motor direct online startup
- Emulated machine draws a peak inrush current of up to 40 A and mimics the simulated machine model (yellow trace)

# Power amplifier- linear



- 1 amplifier per phase – AETechron 7548
- 3.3 kW sourcing and 1.2 kW sinking power per phase; bandwidth DC-40 kHz -  $\pm 180$  Vpk
- Possibility to operate in both current control and voltage control mode
- Amplifiers operated in software current control mode with modeled machine current acting as reference

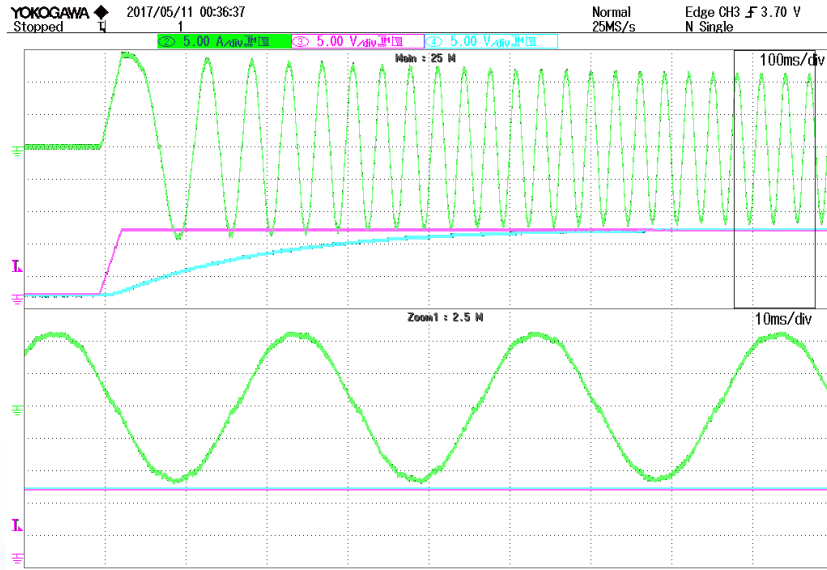
# Results with a physical PMSM drive



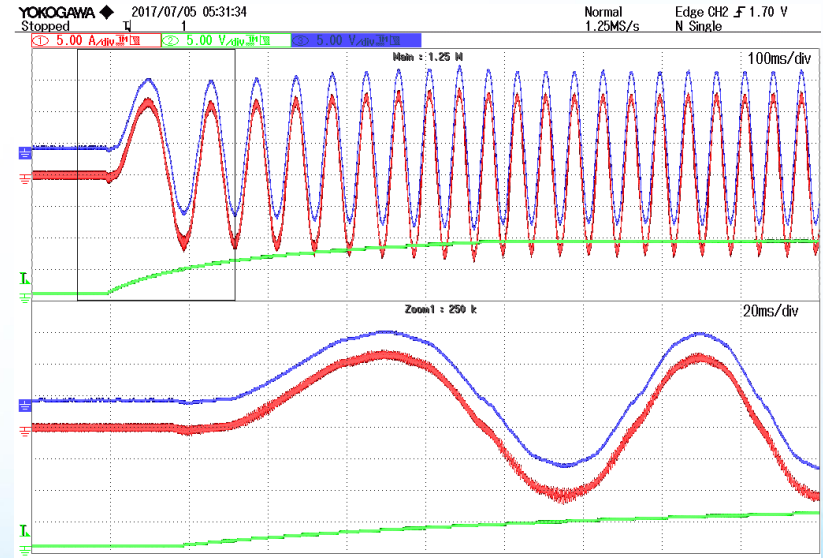
- Experimental setup consists of a physical surface-mounted PMSM coupled to a DC dynamometer
- A simple vector control algorithm used for controlling the PMSM



# Dynamometer/ emulator comparison

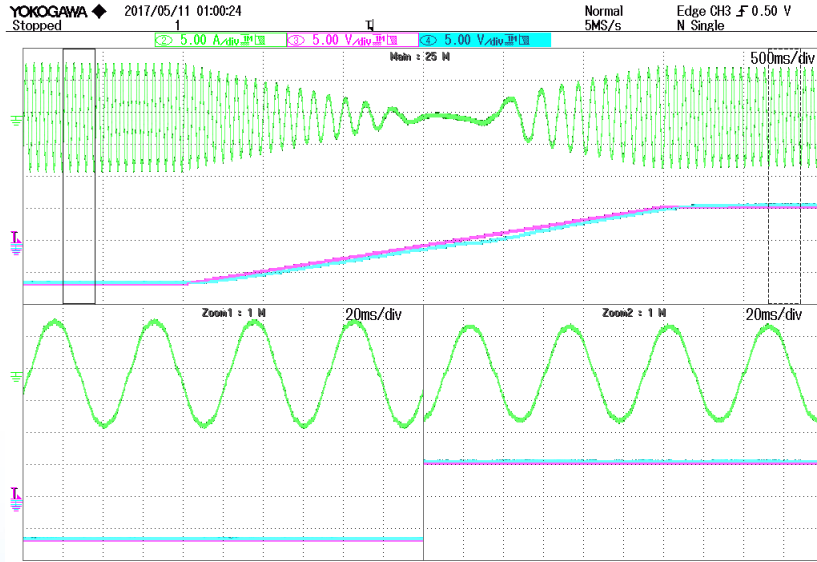


Dynamo-meter

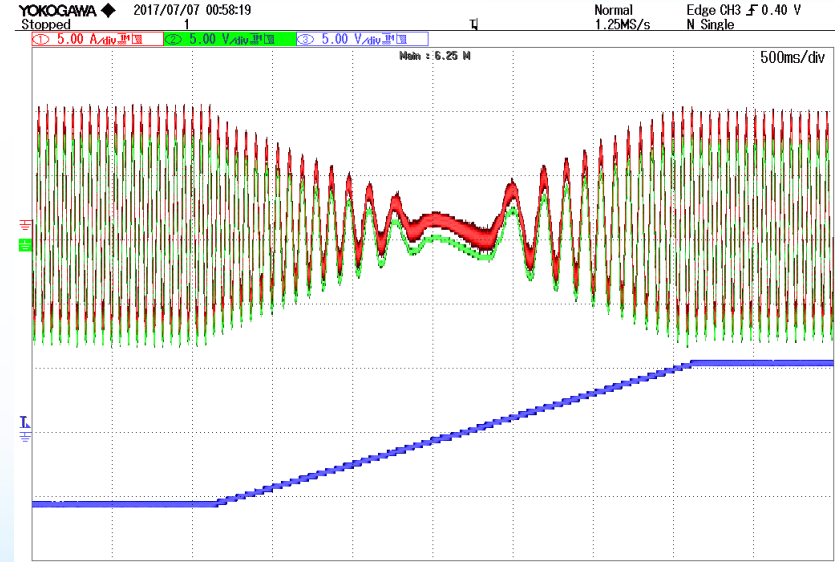


Machine emulator

# Dynamometer/ emulator comparison



Dynamo-meter



Machine emulator

# Summary

- Design files of a surface mounted PMSM from MotorSolve used to generate flux and torque tables for OPAL-RT PMSM models
- Experimental setup being developed for a 4-quadrant 6-switch power amplifier and a linear amplifier to perform power-hardware-in-loop machine emulation
  - Results obtained being compared with a physical experimental dynamo-meter
- Once developed completely the machine emulator system can also be used to validate other machine modes

# Acknowledgement

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# THANK YOU

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Questions???