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

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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

**Experimental Workflow**
- Experimentally measure PMSM parameters
  - Flux table vs. theta vs. beta
- Load flux table to OPAL-RT Model

**Validation**
- FEA Tool Validation
  - Flux table vs. theta vs. beta

**Simulation Workflow**
- PMSM design in MotorSolve
  - Load flux table to OPAL-RT Model

**OPAL-RT Workflow**
- Run a PMSM machine as a vector controlled drive
- Complete Model Validation
  - Transient results
  - OPAL-RT FEA Model
- OPAL-RT model validation: steady state
- OPAL-RT model validation: transient

**Parameter Transfer Validation**

**Run the vector controlled drive drive with an emulated PMSM (OPAL-RT Controller)**
- Transient results
Motor data export: MotorSolve to OPAL-RT

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

Questions???