DEVELOPMENT OF A CUSTOM INDUCTION MACHINE COMPONENT FOR COMPUTATIONALLY EFFICIENT FLYWHEEL ENERGY STORAGE SIMULATION

DAMIAN S. VILCHIS-RODRIGUEZ

THE UNIVERSITY OF MANCHESTER

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INTRODUCTION

Background information

- Effect of distributed energy storage devices with dissimilar response times is investigated
- A medium voltage test network, with embedded energy storage systems (ESS), central controller and telecommunications emulation is considered
- A modified version of the CIGRE European MV distribution network, with number of ESS is to be implemented
- A combination of at least 12 ESS will be included
- A delay model for telecommunications emulation will be included
- Real-time simulation should be realised
- A set of two racks with 5 PB5 are available for testing

INTRODUCTION

Motivation

- A low-speed flywheel energy storage system (FESS) is to be used
- An ideal, symmetric induction machine is sufficient for the FESS
- Saturation effects and zero-sequence components can be neglected
- A detailed representation of the FESS transient response is required for benchmarking
- Multiple FESS (up to twelve) are to be considered
- Local connection to the MV network buses is assumed
- Time-step of the system need to be compatible with the rest of the system

INTRODUCTION

Induction Machine models in RTDS

- DQ0 model
  - Highly efficient
  - Known to have poor accuracy at large time-steps
- Phase-Domain (PD) model
  - More accurate than the DQ model at large time-steps
  - Its time-varying inductance matrix make it considerably more computing intensive
- Phase-Domain Light (PD-L) model
  - Analytically inverted matrix improves computer efficiency over the PD model
  - Less efficient than the DQ model

INTRODUCTION

Hybrid IM models

- Combine PD and DQ0 quantities on their formulation to improve on the PD model efficiency
- Depending on choice of state-space variables of the differential equation from where the model is derived, different numerical properties are obtained: they may be more accurate than the PD model at large time-steps.
- Machine speed may still be present in some hybrid model's conductance matrix. Approximation can be used to eliminate speed dependency with negligible error.
- Hybrid models derived from the classical PD model (using stator and rotor flux linkages as state variables) have a constant conductance matrix, with no approximations, if saturation is neglected.

MACHINE MODEL DESCRIPTION

Hybrid custom model – base differential equations

- Saturation effects are neglected

$$\boldsymbol{V} = p\boldsymbol{\psi} + \boldsymbol{R}\boldsymbol{I}$$

State-space form

$$p\boldsymbol{\psi} = -\boldsymbol{R}\boldsymbol{L}^{-1}(\theta)\boldsymbol{\psi} - \boldsymbol{V}$$

Where:

$\boldsymbol{V} = [\boldsymbol{V}_{abcs}\boldsymbol{V}_{abcr}]^T$

$\boldsymbol{\psi} = [\boldsymbol{\psi}_{abcs}\boldsymbol{\psi}_{abcr}]^T$

$\boldsymbol{I} = [\boldsymbol{I}_{abcs}\boldsymbol{I}_{abcr}]^T$

$\boldsymbol{R} = diag[\boldsymbol{R}_s\boldsymbol{R}_r]$

MACHINE MODEL DESCRIPTION

PD Inductance matrices

And:

$$\mathbf{L}(\theta) = \begin{bmatrix} \mathbf{L}_{ss} & \mathbf{L}_{sr}(\theta) \\ \mathbf{L}_{sr}^{T}(\theta) & \mathbf{L}_{rr} \end{bmatrix}$$

$$\mathbf{L}_{ss} = \begin{bmatrix} L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} & -\frac{1}{2}L_{ms} \\ -\frac{1}{2}L_{ms} & -\frac{1}{2}L_{ms} & L_{ls} + L_{ms} \end{bmatrix}$$

$$\mathbf{L}_{rr} = \begin{bmatrix} L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & L_{lr} + L_{mr} & -\frac{1}{2}L_{mr} \\ -\frac{1}{2}L_{mr} & -\frac{1}{2}L_{mr} & L_{lr} + L_{ms} \end{bmatrix}$$

$$\mathbf{L}_{sr}(\theta) = \begin{bmatrix} L_{sr}\cos\theta_r & L_{sr}\cos\left(\theta_r + \frac{2\pi}{3}\right) & L_{sr}\cos\left(\theta_r - \frac{2\pi}{3}\right) \\ L_{sr}\cos\left(\theta_r - \frac{2\pi}{3}\right) & L_{sr}\cos\theta_r & L_{sr}\cos\left(\theta_r + \frac{2\pi}{3}\right) \\ L_{sr}\cos\left(\theta_r + \frac{2\pi}{3}\right) & L_{sr}\cos\left(\theta_r - \frac{2\pi}{3}\right) & L_{sr}\cos\theta_r \end{bmatrix}$$

MACHINE MODEL DESCRIPTION

Custom model - EMTP-Type form

Voltage equations

$$\mathbf{V}_{abcs}(t) = \mathbf{R}^{FF}_{equ}\mathbf{I}_{abcs}(t) - \frac{3}{2}\frac{2}{\Delta t} Z_M \mathbf{I}_0 + \mathbf{E}^{FF}_{equ}(t)$$

$$\mathbf{R}^{FF}_{equ} = \frac{2}{\Delta t}\mathbf{L}^{FF}_{eq} + \mathbf{R}_s \qquad \mathbf{I}_0 = [i_0 \quad i_0 \quad i_0]^T$$

$$\mathbf{L}^{FF}_{eq} = \begin{bmatrix} L_{ls} + Z_M & 0 & 0 \\ 0 & L_{ls} + Z_M & 0 \\ 0 & 0 & L_{ls} + Z_M \end{bmatrix}$$

$$\mathbf{E}^{FF}_{equ}(t) = \frac{2}{\Delta t}\mathbf{T}^{-1}(t)\mathbf{L}_{srdq}\mathbf{E}_{rhis} - \mathbf{E}_{shis}$$

Auxiliary expressions

$$i_0 = \frac{i_a + i_b + i_c}{3}$$

$$\mathbf{E}_{shis} = \mathbf{V}_{abcs}(t - \Delta t) - \mathbf{R}_s\mathbf{I}_{abcs}(t - \Delta t) + \frac{2}{\Delta t}\mathbf{\Psi}_{abcs}(t - \Delta t)$$

$$\mathbf{E}_{rhis} = \mathbf{E}^{-1}_{rr}\mathbf{L}_{rsdq}\mathbf{I}_{dq0s}(t - \Delta t) + \frac{\Delta t}{2}\mathbf{E}^{-1}_{rr}\left(\mathbf{V}_{dq0r}(t) + \mathbf{V}_{dq0r}(t - \Delta t) + \frac{2}{\Delta t}\mathbf{E}^{*}_{rr}\mathbf{I}_{dq0r}(t - \Delta t)\right)$$

$$\mathbf{E}_{rr} = \mathbf{L}_{rrdq} + \frac{\Delta t}{2}\mathbf{R}_r \qquad \mathbf{E}^{*}_{rr} = \mathbf{L}_{rrdq} - \frac{\Delta t}{2}\mathbf{R}_r$$

$$Z_M = L_M(1 - Z_{mm}) \qquad Z_{mm} = \frac{L_M}{L_M + L_{rns}} \qquad L_{rns} = L_{lr} + \frac{1}{\Delta t}r_r$$

DQ matrices

$$\mathbf{L}_{ssdq} = \begin{bmatrix} L_{ls} + L_M & 0 & 0 \\ 0 & L_{ls} + L_M & 0 \\ 0 & 0 & L_{ls} \end{bmatrix} \qquad \mathbf{L}_{srdq} = \begin{bmatrix} L_M & 0 & 0 \\ 0 & L_M & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

$$\mathbf{L}_{rrdq} = \begin{bmatrix} L_{lr} + L_M & 0 & 0 \\ 0 & L_{lr} + L_M & 0 \\ 0 & 0 & L_{lr} \end{bmatrix} \qquad \mathbf{L}_{rsdq} = \mathbf{L}^{T}_{srdq}$$

Mechanical equations

$$T_e = \frac{3}{2}\frac{P}{2}(\psi_{ds}i_{qs} - \psi_{qs}i_{ds})$$

$$\omega_r(t) = \omega_r(t - \Delta t) + \frac{\Delta t}{2}\frac{P}{2J}[T_e(t) + T_e(t - \Delta t) - 2T_m]$$

$$\theta_r(t) = \theta_r(t - \Delta t) + \frac{\Delta t}{2}[\omega_r(t) - \omega_r(t - \Delta t)]$$

D. S. Vilchis-Rodriguez and E. Acha, "Nodal Reduced Induction Machine Modeling for EMTP-Type Simulations," in *IEEE Transactions on Power Systems*, vol. 27, no. 3, pp. 1158-1169, Aug. 2012, doi: 10.1109/TPWRS.2012.2186987.

MACHINE MODEL DESCRIPTION

Custom model - RSCAD implementation

Neglecting zero-sequence component, the model is interfaced by using:

$$\mathbf{I}_{abcs}(t-\Delta t) = \boldsymbol{G}\mathbf{V}_{abcs}(t-\Delta t) + \boldsymbol{IH}_s$$

Where:

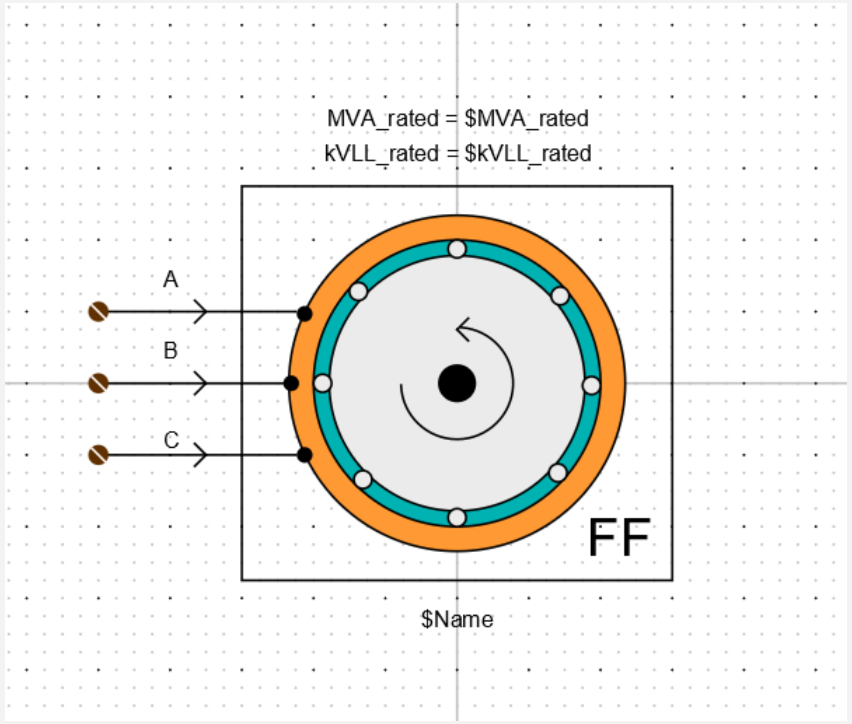
$$\boldsymbol{G} = {\boldsymbol{R}_{equ}^{FF}}^{-1}$$

and the injected currents are defined by

$$\boldsymbol{IH}_s = -\boldsymbol{G}\ \mathbf{E}_{equ}^{FF}(t-\Delta t)$$

MACHINE MODEL DESCRIPTION

Custom model - RSCAD implementation



- Angle prediction-correction scheme is employed in the model solution

$$\theta_r(t) = 2\theta_r(t-\Delta t) - \theta_r(t-2\Delta t)$$

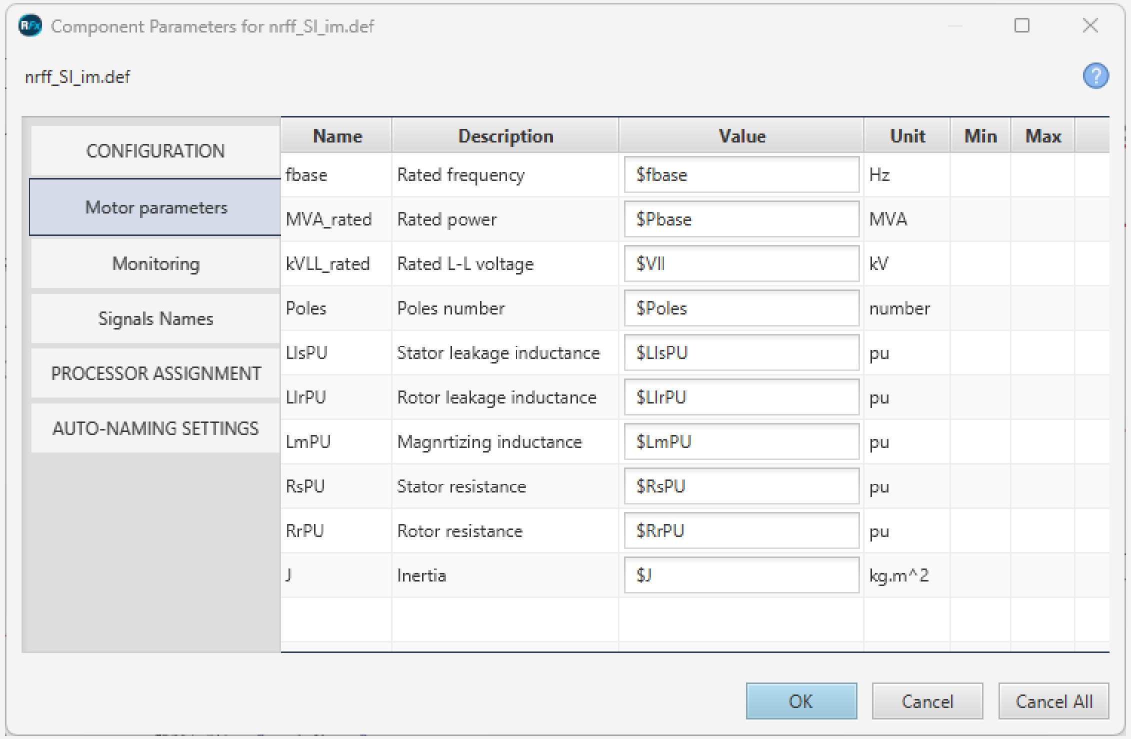
$$\theta_r(t) = \theta_r(t-\Delta t) + \frac{\Delta t}{2}[\omega_r(t) - \omega_r(t-\Delta t)]$$

- 94 flops (+, - , x) required for the model solution. Divide operations are completely avoided

- 2 trigonometric functions are also required

MACHINE MODEL DESCRIPTION

Custom model - RSCAD implementation

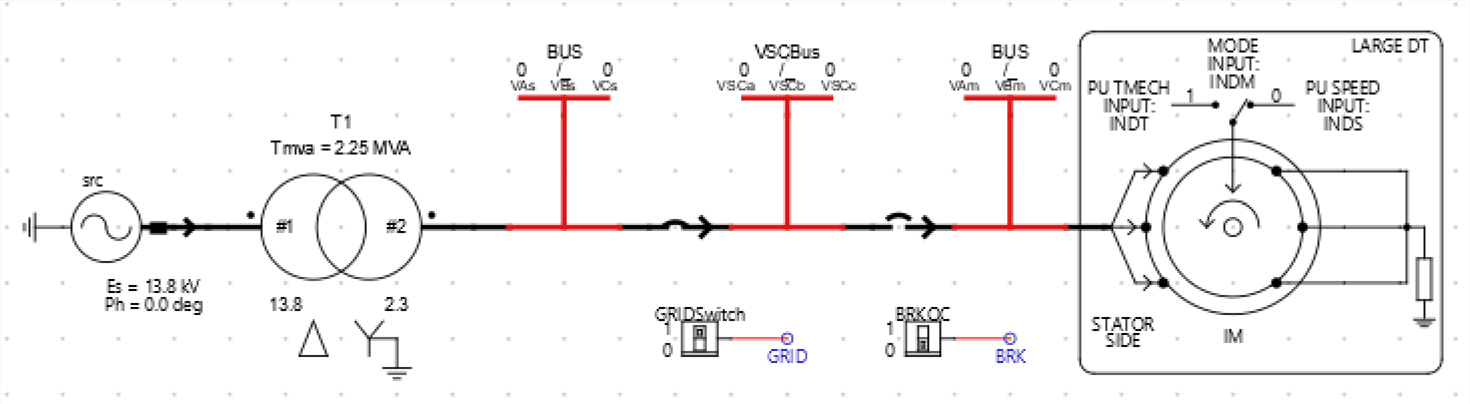


Name	Description	Value	Unit	Min	Max
fbase	Rated frequency	$fbase	Hz		
MVA_rated	Rated power	$Pbase	MVA		
kVLL_rated	Rated L-L voltage	$Vll	kV		
Poles	Poles number	$Poles	number		
LlsPU	Stator leakage inductance	$LlsPU	pu		
LlrPU	Rotor leakage inductance	$LlrPU	pu		
LmPU	Magnrtizing inductance	$LmPU	pu		
RsPU	Stator resistance	$RsPU	pu		
RrPU	Rotor resistance	$RrPU	pu		
J	Inertia	$J	kg.m^2		

- Machine parameters are provided in p.u.
- Stator currents, electromagnetic torque, machine speed and rotor angle can be monitored.
- To avoid additional calculations, input/output voltages and currents are handled natively in kV and kA.
- Calculation of rotor currents is omitted to reduce flop count.

MODEL EFFICIENCY

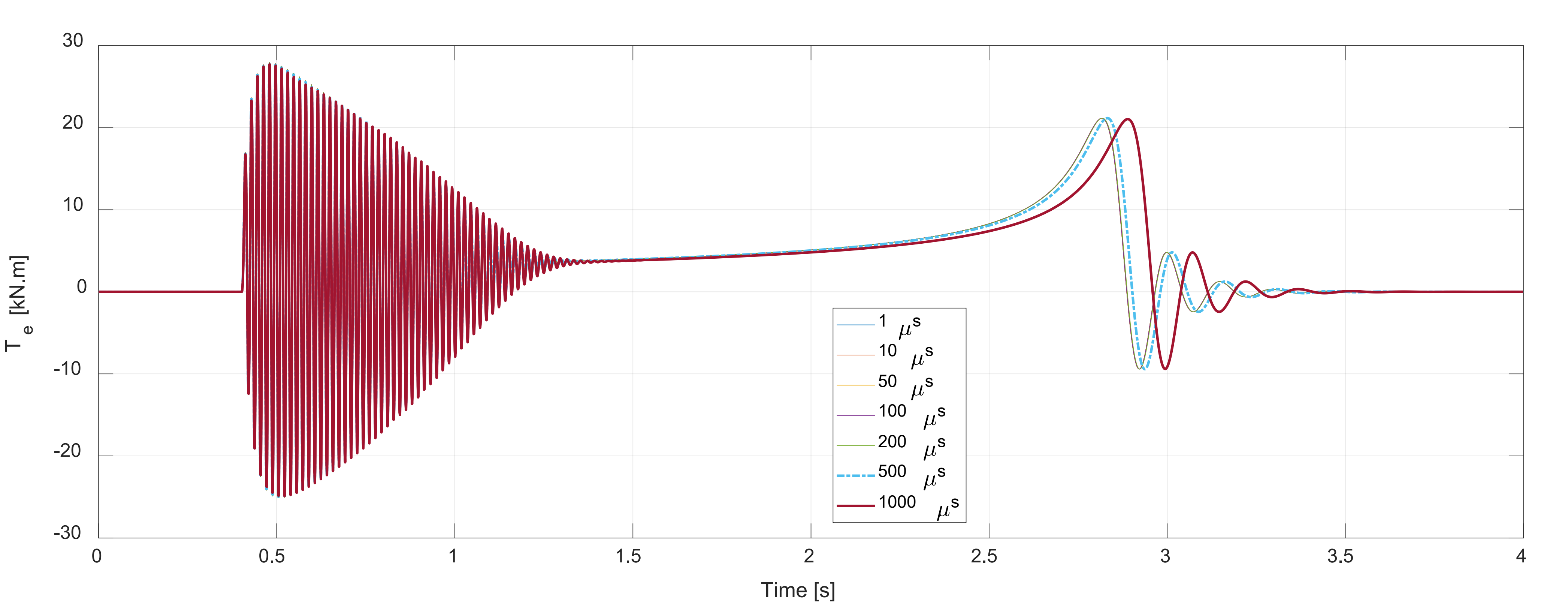
Test system



- Simple system used to verify the custom model results and performance. Startup transient is used for the assessment.
- An RTDS stack with five PB5 was used in the tests.
- For the case under test, identical load was reported for the custom model and RSCAD's DQ0 model (15% of a PB5), 22% for PD and 18% for PD-light.
- Minimum time-step at which real-time simulation was achievable for the custom and RSCAD's DQ0 model was identical (8μs), PD-light 14μs and 15μs for the PD.

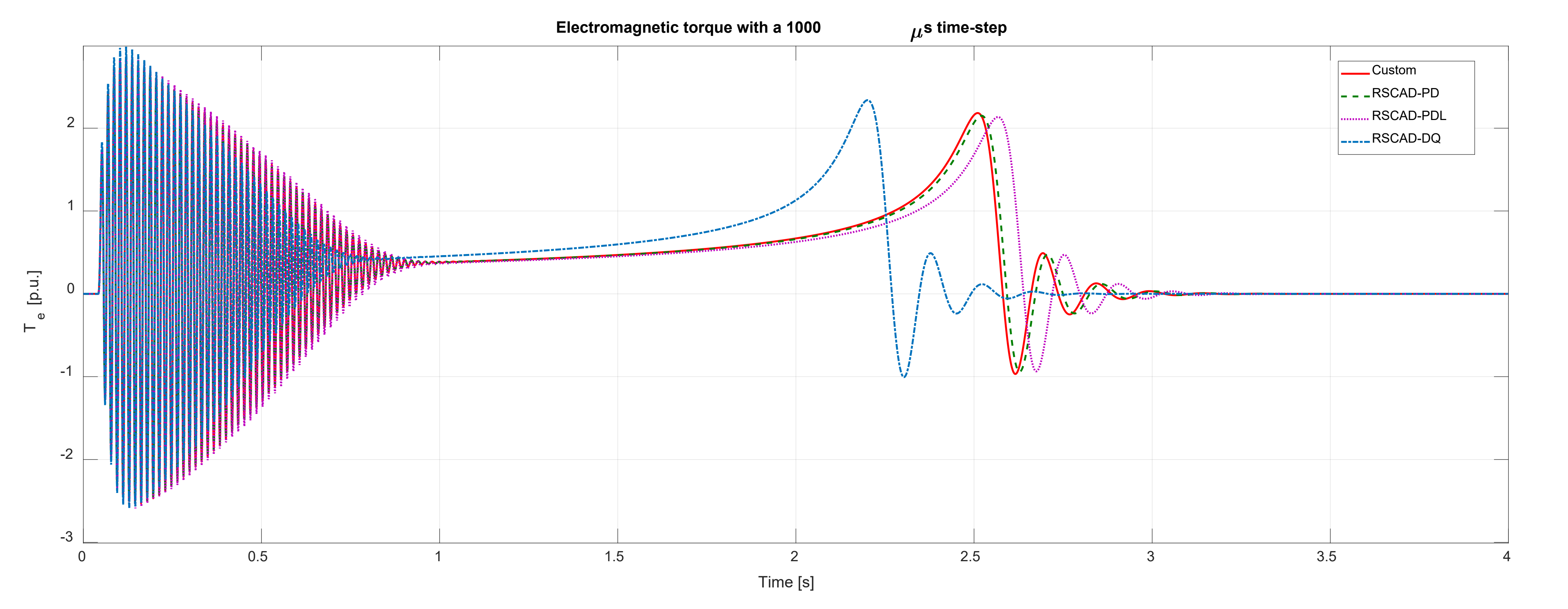
SIMULATION RESULTS

Time-step length effect



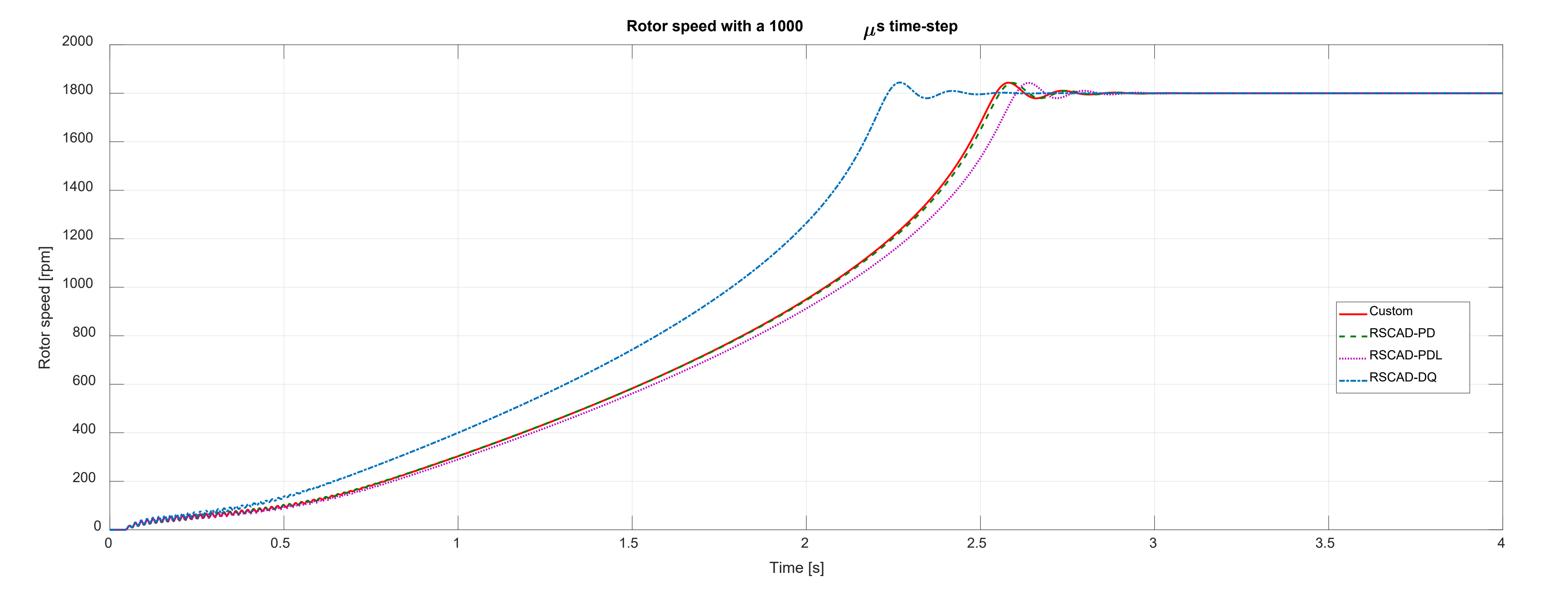
SIMULATION RESULTS

Time-step length effect



SIMULATION RESULTS

Time-step length effect



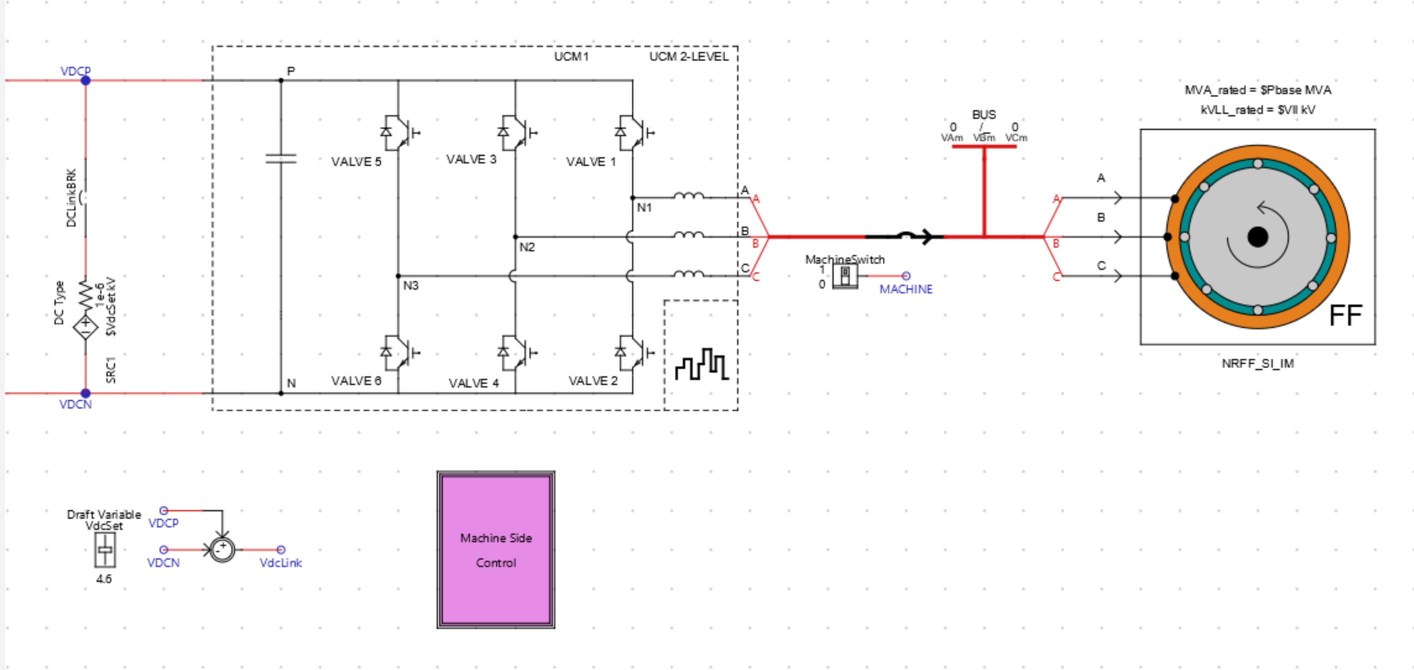
MODEL EFFICIENCY

Summary - models performance

Model	Load [%]	Time-step [µs]	Notes
PD	22 (+47%)	15 (+88%)	The most computing intensive
PD-L	18 (+20%)	14 (+75%)	Slightly more efficient than the PD model, diverges from the PD model at large time-steps
DQ0	15 (base)	8 (base)	Very efficient but poor accuracy at large time-steps
Custom	15 (+0%)	8 (+0%)	As efficient as the DQO and as accurate as the PD model

SIMULATION RESULTS

Custom model - FESS integration



- The custom model has been incorporated into a FESS
- Computing load is identical to that of the FESS using RSCAD's DQ model (27% of a PB5), the PD model uses 35%.
- Minimum time-step at which real-time simulation is realizable is identical to that of the DQ0 model (16μs) . The PD model requires 23 μs (+44%).
- Computing time (off-line), to complete an 18.5 s simulation at 1μs time-step with the UCM in improved firing pulse mode is similar to the obtained using the DQ model.

CONCLUSIONS

- A custom induction machine component for RSCAD/RTDS, with direct interface with the power network, was implemented.
- By neglecting magnetic saturation and zero sequence components a constant, diagonal conductance matrix is obtained.
- The model was found to have similar computing performance to that of RSCAD's DQ model.
- Error propagation with increase in time-step length was found to be very similar to RSCAD's PD model
- RSCAD's PD-L results were found to diverge from that of the conventional PD model for large time-steps.
- The combined use of PD and DQ quantities, and avoiding non-essential calculations, resulted in an efficient and accurate IM model implementation, that preserves the combined strengths of the DQ and PD formulations.