Advanced Dynamic Model of E-motor for Control Rapid Prototyping

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***Abstract*- The thesis aims at developing a unified circuital Simulink and PLECS model of an e-Drive, including e-motor, inverter and control blocks, suitable for Permanent Magnet Synchronous Machines (PMSMs) and Synchronous Reluctance (SyR) machines. The work includes the drive simulation under healthy and faulty conditions. Two motor modelling approaches are considered, evaluating the respective computational times and accuracy. The results are experimentally validated by comparing the simulated and measured waveforms in steady-state conditions and under a controlled fault transient. Additionally the Simulink model is validated against transient FEA simulations in the Infolytica-Magnet environment. The obtained model will be embedded into SyR-e, the open source software for e-Drives design available on GitHub.**

I. Introduction and goal of the thesis

The design of a traction e-Motor involves two main steps: (1) magnetic, mechanical and thermal design of the motor based on design rules and Finite Element Analysis (FEA) and (2) simulation of the e-Drive for torque control calibration. Step 1 is the original purpose of the *SyR-e* (Synchronous Reluctance-evolution) open source design environment. Recently, an add-on called SyreDrive was introduced, whose purpose is to automatically generate a Simulink model of the designed machine for control calibration and accurate waveform simulation, starting from the results of Step 1. The starting point of the thesis is the non-circuital, discrete-time average Simulink model available in SyreDrive, used as benchmark.

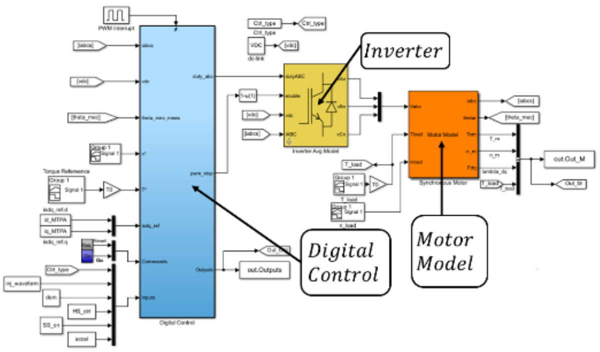

Figure 1. Simulink benchmark model.

The benchmark model (Fig.1) consists of three main blocks: 1) *Digital Control*: includes a discrete-time executed ANSI C-script, with configurable torque/speed control, 2) *Inverter Model*: average non-circuital model accounting for voltage drops and dead time effects and 3) *Motor Model*: continuous time, voltage fed non-circuital model. The benchmark model has four main limitations: 1) it is *time averaged* and neglects the instantaneous PWM evolution, 2) being *non-circuital*, it cannot be used for faults analysis, uncontrolled scenarios or open circuit simulations, 3) the inverter voltage drop is mathematically emulated and not circuitally simulated, 4) the motor model requires *the flux-map tables inversion* $\boldsymbol{i_{dq}}(\boldsymbol{\lambda_{dq}})$ derived from direct flux maps $\boldsymbol{\lambda_{dq}}(\boldsymbol{i_{dq}})$. About this latter point, the inversion of FEA computed or experimentally measured flux maps reduces the operating domain (e.g. the current and torque domain) of validity of the model.

The goal of the thesis is to set up a new circuital model of the e-Drive, valid for both instantaneous and average simulation, covering faulty operating conditions on inverter and motor sides, and compatible with both Simulink and PLECS environments.

II. Description of the work

Two modeling approaches are considered for the e-motor:

a) Controlled Current Generators (CCG) model (Fig.2);
b) Voltage Behind Reactance (VBR) model (Fig. 3).

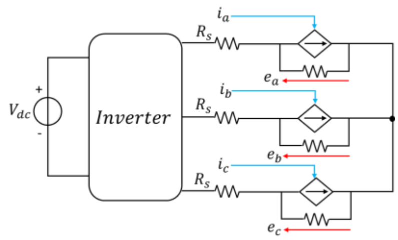

Figure 2.Controlled Current Generators (CCG) model.

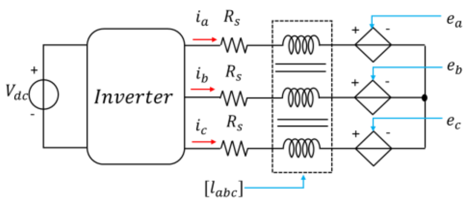

Figure 3. Voltage Behind Reactance (VBR) model.

The CCG model uses three controlled current generators, where the phase currents are computed according to measured phase voltages and the motor equations and maps. This model requires the inverse flux maps $\boldsymbol{i_{dq}}(\boldsymbol{\lambda_{dq}})$. The VBR model represents the motor as an RLE load, with coupled inductors and controlled voltage generators imposing the back EMF voltages computed by the motor model. This requires both the direct flux maps and incremental inductance maps. Both CCG and VBR models were comparatively implemented in Simulink/Simscape and PLECS. The validation consists of the following steps:

1. Comparison of output waveforms and computational time;
2. Experimental validation of the results, using an automotive PMSM, in steady-state operating and in commanded Active Short Circuit (ASC) transient conditions.

III. Simulation Results

The CCG and VBR models have been simulated in PLECS and Simulink, under FOC torque control. The simulated motor is a SyR machine rated 4.9kW, 18.82 Nm, 2500 rpm. An example of simulation is given in Fig.4, showing perfect overlap with the exception of the torque reversal transient. Fig.5 indicates that the VBR model is computationally slower than the CCG model, which is comparable with the benchmark model.

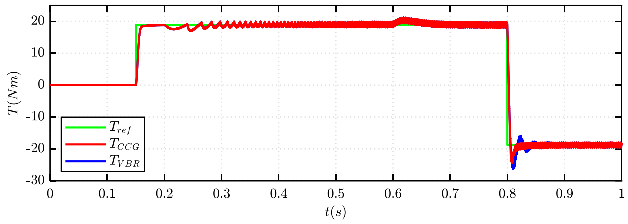

Figure 4. Torque response of the CCG and VBR models.

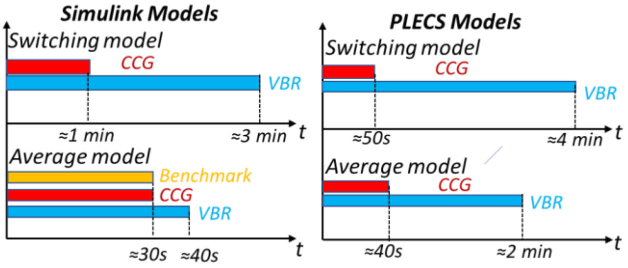

Figure 5. Execution time of the models for 1s of simulation time.

IV. Comparison with Finite Element Analysis

An Open Phase Fault (OPF) was simulated in Simulink and in FEA. The phase current waveforms obtained with the two methods are very similar, as shown in Fig.9. In this case, CCG and VBR models provide overlapping waveforms.

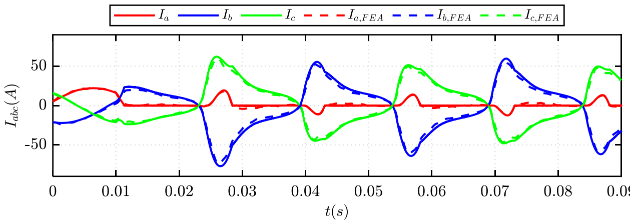

Figure 6. Phase current obtained with Simulink and Magnet during the OPF.

V. Experimental validation

The experimental validation was performed using an automotive PMSM, rated 70 kW, 130 Nm, 4200 rpm, coupled with a speed controlled driving machine (Fig. 6). The tested motor was current-controlled, using dSPACE 1202 MicroLabBox and a three-phase inverter. An HBM data recorder measured the electrical and mechanical quantities.

At first, accurate flux maps of the machine were experimentally measured using state-of-art techniques. Such flux maps were implemented in the simulation models.

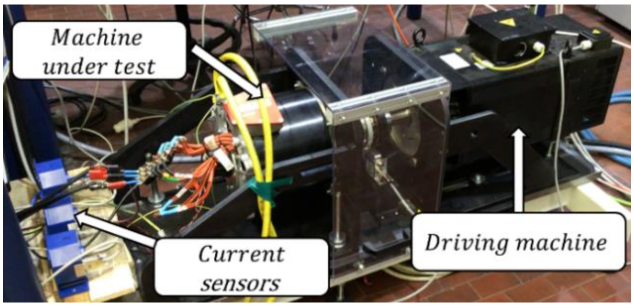

Figure 7. View of the test rig used for the experimental validation.

A. PWM current ripple analysis

The measured phase current is compared with the current obtained with CCG model (Fig.6) and VBR model (Fig.7), at the nominal torque and 2000 rpm. It can be noted that both models are very accurate in simulating the real phase current of the motor, including PWM ripple.

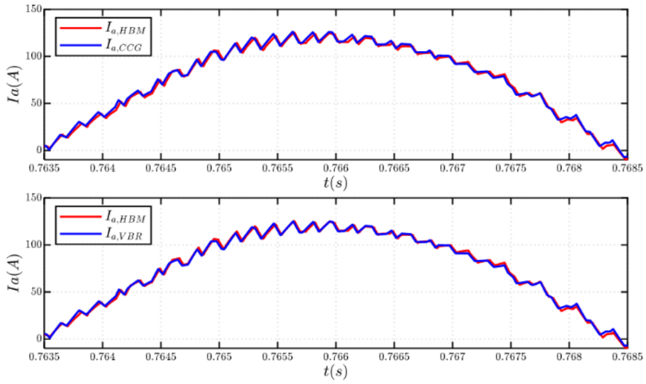

Figure 8.Phase current measured by HBM data recorder and simulated current with a) CCG and b) VBR models.

B. Active Short Circuit (ASC)

A controlled ASC at different speeds was experimentally implemented, comparing the measured currents with the ones computed by CCG and VBR models. An example is given in Fig.8, with the motor rotating at 500 rpm. It can be noted that the models provide equal currents at steady state but not during the transients, with CCG model more accurate that the VBR model. It should be noted that the operating point exceeds the domain of the experimental direct and inverse flux maps, so analytical extrapolation was required for both approaches.

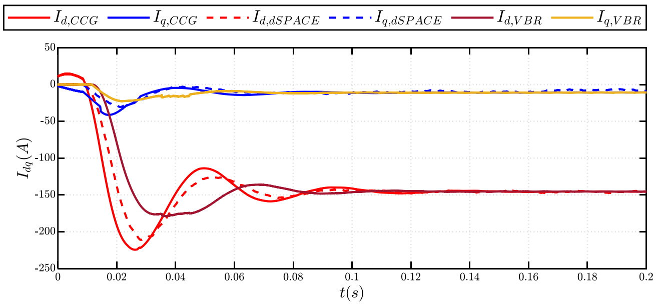

Figure 9. Rotor frame dq currents obtained by dSPACE and by the CCG and VBR models during the ASC.

VI. Conclusions

The thesis contributed to set up a circuital model compatible with instantaneous and time-averaged simulations, and with healthy and fault conditions. The CCG model is based on the inverse flux maps, which limit the operating domain with respect to the direct flux maps, but the simulation is much faster. The VBR model uses the direct flux maps, but it is heavier computationally. The CCG model is thus selected as the new approach of SyreDrive for circuital and instantaneous simulations, with limited computation increase (1 minute vs 30 secs of the benchmark).