The SmartElectricDrives Library – Powerful Models for Fast Simulations of Electric Drives

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Abstract

In this work the SmartElectricDrives (SED) library Release 1.0.1 is presented. The SED library is a tool for simulating and tuning of electric drives in complex electromechanical systems. This library is specifically designed for simulations of electric drive systems with a *Modelica* development platform. Besides a variety of elementary components for simulating modern electric drives the SED library also contains powerful 'ready-to-use' drive models. These 'ready-to-use' drive models include all features and characteristics of full modern electric drives in only one single component. Furthermore, the SED library facilitates simulations on different levels of abstraction. By choosing the right level of abstraction the user can save processing power and therefore computing time. This work outlines all the specific features and design considerations of the SED library. Three simulation examples are presented. Based on the results of these examples the performance of the applied SED models is assessed and analysed.

Keywords: electric drives; electromechanical systems; quasi stationary simulation; signal bus systems; parameter estimation functions;

1 Electric drives applications – the scope of the SED library

The SED library facilitates simulations of any electric drive application. Drives such as machine tools, robotics, mining drives, traction drives and auxiliary drives in vehicles and hybrid electric vehicles (HEV) are good examples for typical applications [1], [2], [3]. These applications require high static control precision, fast dynamic response, overload capability and sometimes speed ranges significantly above nominal speed. Conventional asynchronous induction machines used for such high performance applications are usually controlled by exploiting the principle of field oriented control (FOC) [4]. FOC can also be applied to synchronous induction machines and is widely used in respective drive applications. Since FOC is the most popular method to control ac machines it is implemented in all 'ready-to-use' ac drive models in the current version of the SED library.

2 Structure of the SED library

All components needed for modern electric drives can be found in the SED library. In Figure 1 the arrangement of the packages is shown.

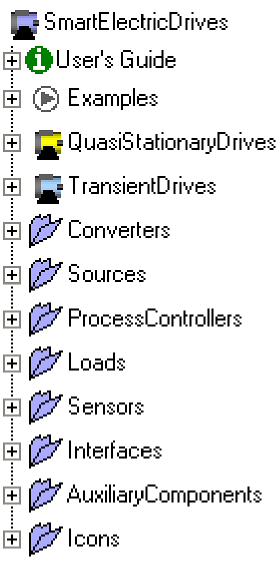

Figure 1: Screenshot of the SED library in the *package browser*.

2.1 The `QuasiStationaryDrives` package

In the `QuasiStationaryDrives` package, shown in Figure 2, only models of full torque controlled drives with a dc supplied converter are included. These models are designed such way that all electrical transients in the machines are neglected. Mechanical transients due to the inertia of the rotor are considered, however. Consequently these models cannot be used for the simulation of electric transient effects such as current spikes due to converter switching, for instance. However, as long as only the energy consumption or the efficiency of the drive is of interest it is very advantageous to use `QuasiStationaryDrives` models because they are remarkably faster than models considering electrical transient effects in machines. Another benefit of `QuasiStationaryDrives` models compared to conventional drive models is that current controllers, flux controllers and torque controllers do not have to be parameterized since these components do not appear in the quasi stationary equations of electrical drive systems. It can be shown that if electrical transient effects get neglected in electrical machines then simple feed forward control can achieve a system performance that can only be reached by feed back control in systems, which take the electrical transients into account. This fact leads to shorter simulation times of the `QuasistationaryDrives` models compared to their counterparts in the `TransientDrives` package.

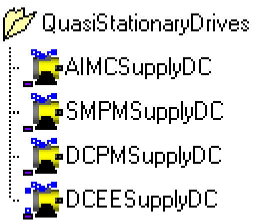

Figure 2: Screenshot of the `QuasiStationary-Drives` package in the *package browser*.

2.2 The `TransientDrives` package

The `TransientDrives` package, shown in Figure 3, contains all drive components that are needed to build a simulation of an electric drive considering transient electric effects in machines. This package is split up into four machine type specific packages containing 'ready-to-use' models of full torque controlled drives as well as the respective elementary control components of these models. Each 'ready-to-use' drive model consists of a dc/dc or dc/ac converter considering power balance, a machine model and the elementary drive components, such as controllers, a measurement device, a flux model, bus connectors, etc. Figure 4 shows the internal set-up of the 'ready-to-use' asynchronous induction machine drive model. In order to facilitate a very easy switching between `QuasiStationaryDrives` models and `TransientDrives` models the connector naming and coding is standardized.

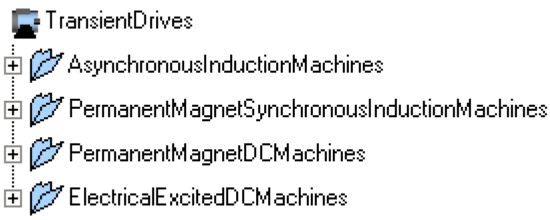

Figure 3: Screenshot of the `TransientDrives` package in the *package browser*.

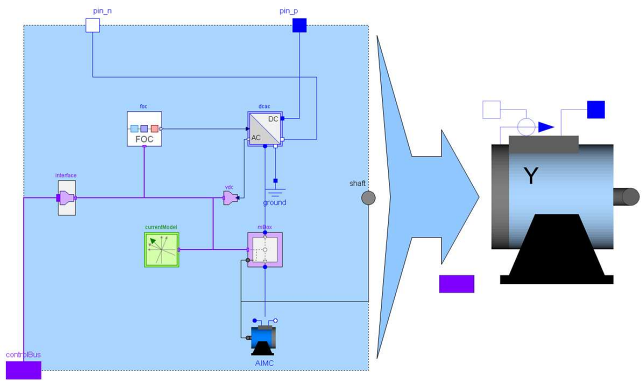

Figure 4: Screenshot of the `TransientDrives` model of a dc supplied asynchronous induction machine.

2.3 The `AuxiliaryComponents` package

In the `AuxiliaryComponents` package a number of primary transformations such as space phasor transformations and line/phase transformations are available. Moreover, in this package the user has some functions for controller parameter estimation at ones disposal. The opened sub-package containing these functions is shown in Figure 5.
These controller parameter estimation functions help the user to adjust the whole set of controller parameters in speed controlled drive simulations for any machine type. Since drive control systems have a

cascaded structure deploying many elementary controllers it can be quite time consuming to find proper values for this big set of controller parameters. By using the provided parameter estimation functions the process of controller adjustment can be accelerated considerably. With regard to specific controller optimization criteria the estimation functions generate controller values based on the parameters that define the machine model such as nominal current, nominal speed, stator resistance etc. Furthermore, the control system behaviour can be tuned by the choice of specific dynamic gains in the estimation functions.

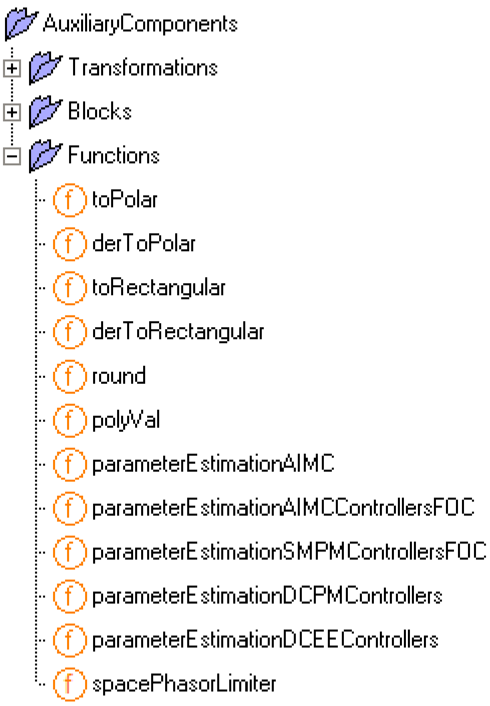

Figure 5: Screenshot of the `AuxiliaryComponents.Functions` package in the *package browser*.

2.4 The `Examples` package

A large selection of examples for applications of the SED library components is given in the `Examples` package shown in Figure 6. In order to ease starting up with the SED library eight specific tutorial examples are included in the `Examples` package. Step by step, these tutorial examples explain the most important models and their correct application in drive simulations. More sophisticated examples can be found in the `Examples.AutomotiveApplications` package. In this package some possibilities for the use of electric drives in vehicular applications are presented. Further examples are included in order to give details concerning the correct use and application of major SED library components such as controllers, converters, sources and loads.

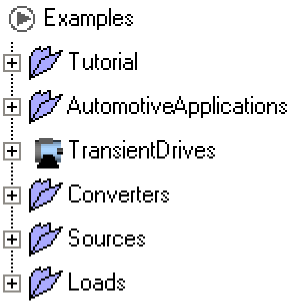

Figure 6: Screenshot of the `Examples` package in the *package browser*.

2.5 Further important packages

Apart from models representing full torque controlled drive setups the SED library also offers some different models of dc energy sources. There are two battery models, a supercap model and a proton exchange membrane (PEM) fuel cell model available. These models can be found in the `Sources` package.

The `Converters` package contains converters on two different levels of abstraction. On one hand the user can choose the so called *power balance converters* and on the other hand there are converters modeled with ideal switches available. *Power balance converters* are designed for simulations in which switching effects do not have to be considered. Their big plus is that simulations work much faster with these models since the calculation effort for the power balance equation is much smaller compared to processing a large number of switching events.

In the `Sensors` package there are different meters for the generation of specific measuring values available. One important component in this package is the RMS model, which transforms an instantaneous signal to the respective RMS value within a certain measuring periode.

The `Load` package contains different models that can be used for electric power dissipation. The components of this package allow the simulation of dc power loads and the modeling of constant or variable efficiencies in dc circuits.

3 The bus concept

In order to group control signals and measuring signals most SED components are featured with a bus connector. For the internal use of each type of machine control system in the `TransientDrives` package there is a specific internal bus system available since each type of machine has a particular set of control parameters and variables. There is also a general `ControlBus` connector in the `Interfaces` package available that is used to build an external bus system by connecting torque controlled drive systems with further controllers, such as speed controllers, position controllers or drive strategy controllers. Figure 7 illustrates that the external bus system and the internal bus system must be connected via an `Interface` that is also available in the SED library.

A big advantage of bus concepts in *Modelica* is that when programming in a *diagram layer* the model stays manageable because the number of connections gets minimized. Another plus is that during the simulation of the model all variables that are on the bus get grouped together in the *variable browser* of the *simulation tab*. The buses used in the SED library are designed such way that the most important variables for basic analyses of the drive system can be selected on first sight in the variable browser. Some of these very important variables are the shaft speed, the shaft angle, the stator current, the stator voltage and the dc-link voltage.

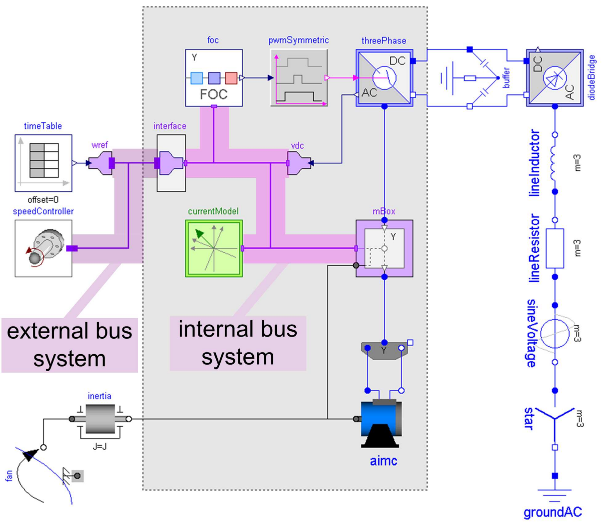

Figure 7: An SED simulation of a speed controlled asynchronous induction machine with an internal and an external bus system.

4 Examples

In order to point out the basic advantages of using standardized 'ready-to-use' models and models on different levels of abstraction three simulations get compared. These three simulations can be found in the `Examples.Tutorial` package of the SED library. All three simulations represent the same drive system with identical component parameters. The drive system simulated, is a speed controlled asynchronous induction machine driving an industrial fan. The machine is sourced via a six pulse diode bridge that converts three phase ac voltages to a rippled dc voltage in the dc-link circuit. A capacitive grounding component smoothens the ripple of the dc voltage and assures system stability when calculating results with *Dymola*. FOC is used to control the asynchronous induction machine. The fan modelled with a quadratic speed dependent torque and an inertia component is directly connected to the shaft of the machine. The parameters of the simulations are as follows:

- Three phase ac supply:
  - Supply Voltage $\hat{V}_{AC} = 660\,\mathrm{V}$
  - Line Resistor $R_{line} = 1\,\mathrm{m\Omega}$
  - Line Inductance $L_{line} = 0.1\,\mathrm{mH}$
- dc-Link:
  - Buffer resistance $R_{buffer} = 0.01\,\mathrm{m\Omega}$
  - Buffer capacitance $C_{buffer} = 0.01\,\mathrm{F}$
- Asynchronous induction machine:
  - Number of pole pairs $p = 4$
  - Nominal frequency $f = 50\,\mathrm{Hz}$
  - Nominal phase voltage $V_N = 400\,\mathrm{V}$
  - Nominal phase current $I_N = 416\,\mathrm{A}$
  - Rotor's moment of inertia $J_r = 35\,\mathrm{kg\,m^2}$
  - Stator resistance $R_s = 8.086\,\Omega$
  - Stator stray inductance $L_{s\sigma} = 300.1\,\mu\mathrm{H}$
  - Main field inductance $L_m = 8.231\,\mathrm{mH}$
  - Rotor stray inductance $L_{r\sigma} = 502\,\mu\mathrm{H}$
  - Rotor resistance $R_r = 4.934\,\Omega$
  - Stator phases star-connected
- Fan:
  - Nominal speed $\omega_N = 78\,\frac{\mathrm{rad}}{\mathrm{s}}$
  - Nominal torque $\tau_N = 5227\,\mathrm{Nm}$
  - Inertia $J = 50\,\mathrm{kg\,m^2}$

4.1 Simulations with 'ready-to-use' models

In Figure 8 a quasi stationary simulation, designated as case A, is presented. The 'ready-to-use' model `aimcqs` contains a torque controlled asynchronuos induction machine drive considering only quasi stationary effects. Also the dc/ac converter is included in this component. The reference torque is generated by a speed controller and fed to the FOC in the 'ready-to-use' model via the external bus system and an interface model `wRef`. The reference speed curve for the drive is defined by a time table. This time table contains a `RealOutput` connector, which doesn't match the `ControlBus` connectors of the drive model and the speed controller. That is why a bus adaptor must be used to connect the reference speed signal to the external bus system. This bus adaptor also provides the correct physical unit accordingly. In Figure 9 another transient simulation setup, designated as case B, is shown. The difference to case A is that in case B the electric transients are considered by using a 'ready-to-use' `TransientDrives` model of a torque controlled asynchronous induction machine, called `aimcfoc`.

Figure 10, a simulation result of case B, illustrates that the reference speed, w_{Ref}, matches the real shaft speed, $w_{Mechanical}$, in small speed regions whereas at the instant $t = 3\,\mathrm{s}$, when the speed is higher, the torque limit of the drive is reached and therefore the acceleration of the inertia is limited. The speed curves in case A are very similiar to the ones displayed in Figure 10.

In Figure 11, Figure 12 and Figure 13 case A and case B are compared. From the beginning of the simulations until $t = 1.2\,\mathrm{s}$ the stator phase current in case B, $i_{Machine,caseB}$, deviates significantly from the stator phase current in case A, $i_{Machine,caseA}$. This is because the flux controller in the `TransientDrives` model creates a very high flux by generating a reference current to magnetize the machine very fast. In case A this magnetizing effect is neglected, because transient electric effects are not considered in the quasi stationary model. At $t = 3.45\,\mathrm{s}$ the current $i_{Machine,caseB}$ deviates from $i_{Machine,caseA}$ because the flux weakening function in the FOC triggers a demagnetization of the iron core in the machine model in case B whereas in case A this effect is not considered. Furthermore there are larger overshoots of current, torque and voltage in case B whenever the reference speed, w_{Ref}, triggers a significant torque change.

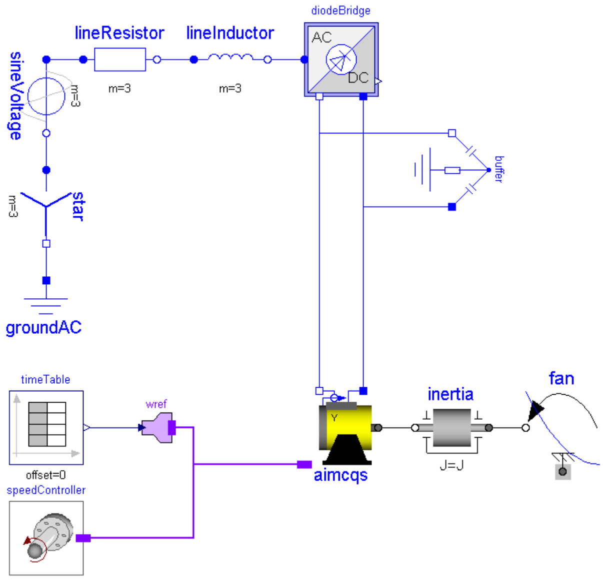

Figure 8: Case A; quasi stationary simulation of the speed controlled fan drive with a 'ready-to-use' SED model.

4.2 Simulating ideal switching effects

Figure 14 shows a simulation model considering switching effects, which is designated as case C. In case A and case B the dc/ac converter is modelled by considering the power balance between supply circuit and load circuit. However, in case C a converter modeled with ideal switches and controlled by a symmetric pulse width modulation (PWM) algorithm is used to simulate the effects of pulsed stator voltages in the drive. The basic differences between case C and the simulations using power balance converters are shown in Figure 15 and in Figure 16. Due to the converter switching the current and the electric torque of the machine have a significant ripple.

4.3 Performance comparison of the simulations

The three simulations are developed and simulated on a conventional 1 GHz, 512 MB PC with a 5400 rpm hard drive with Dymola 6.0a using the DASSL solver. Processing the quasi stationary simulation, case A, is the fastest since it contains the smallest set of differential equations and algebraic equations among the three investigated cases. After translation, case A has only 16 differentiated variables and 333 equations. Processing the presented results takes less than 1 s processing time. Case B shows a simulation considering also electrical transient effects in the machine. Consequently, the model of the control system applied in

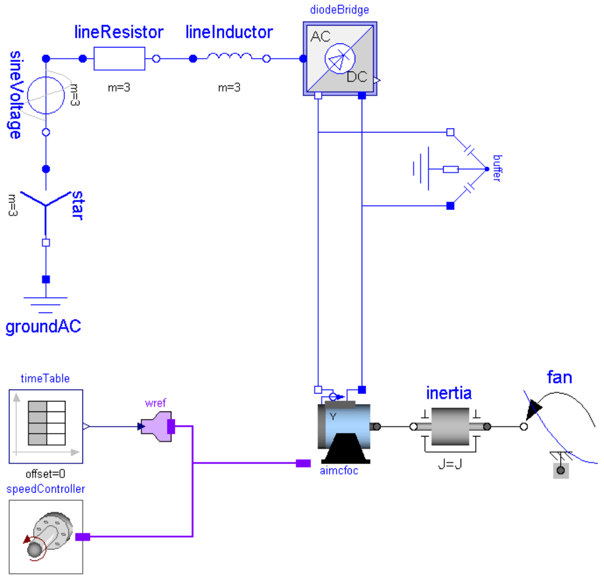

Figure 9: Case B; electrical transients simulation of the speed controlled fan drive with a 'ready-to-use' SED model.

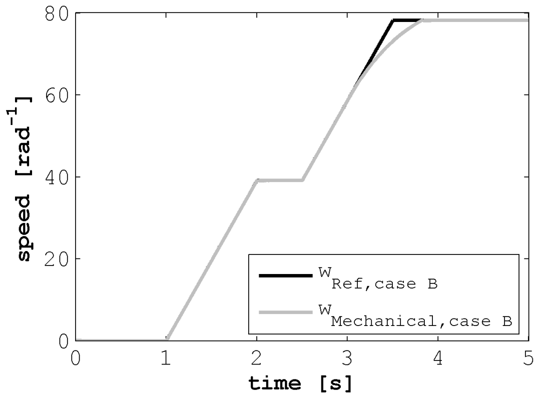

Figure 10: Reference speed and real fan speed in case B.

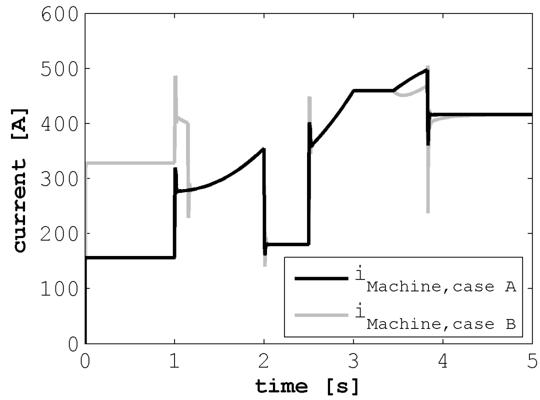

Figure 11: RMS values of the stator phase currents of the machine in case A and case B.

case B is more complex. Case B contains 42 differentiated variables and 867 equations, which is the reason for a processing time increase of 50% for the presented results. However, processing case B takes still a much smaller effort than processing case C. Calculating the presented results of case C takes around 5 min 30 s. The reason for this tremendous computation time is that the solver iterates each event in order to find the precise switching instant. Since the converter in case C works with a 2 kHz PWM the processing effort is considerably. Case C contains 41 differentiated variables and 849 equations, which indicates a smaller system than case B. Still, case B can be solved much faster because the dc/ac converter in the 'ready-to-use' drive model is modeled by only considering the power balance between supply circuit and load circuit.

5 Conclusions

The scope, the structure and the most important packages of the SED library are described. Three simulation setups with similiar parameter settings on different levels of abstraction are presented and the results are compared. The comparison shows that the 'ready-to-use' `QuasiStationaryDrives` models of the SED library have the best performance. However, they don't show all the physical effects that can be analysed with a simulation considering electric transient effects and converter switching effects. Typical applications for `QuasiStationaryDrives` models are energy balance analyses of electromechanical systems, such as HEV or electric vehicle concepts. In such applications switching effects and electrical transient effects can be neglected. The models in the `TransientDrives` package can be used when system responses on fast transient events have to be investigated or if controller optimization is the focus of investigation. Furthermore, it is shown that the application of power balance converter models helps saving a considerable amount of computer resources when simulating electric drives with *Modelica*.

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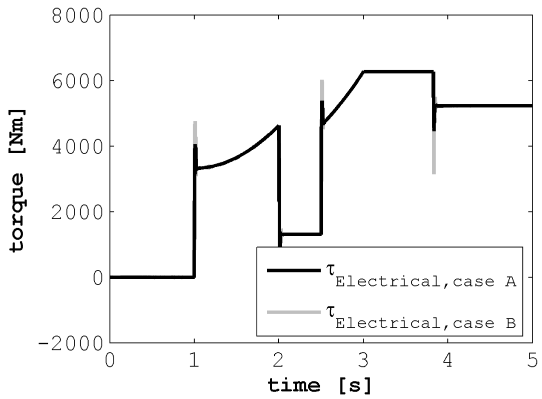

Figure 12: Electrical torque of the machine in case A and case B.

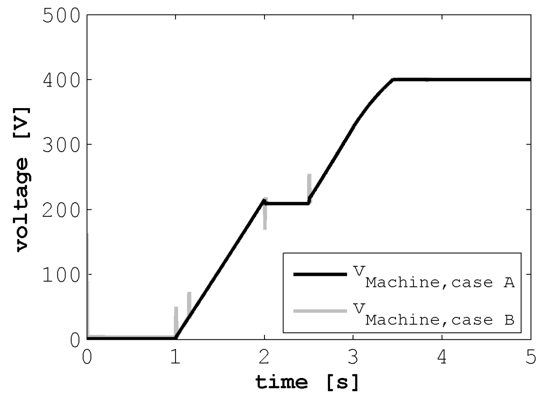

Figure 13: RMS values of the stator phase currents of the machine in case A and case B.

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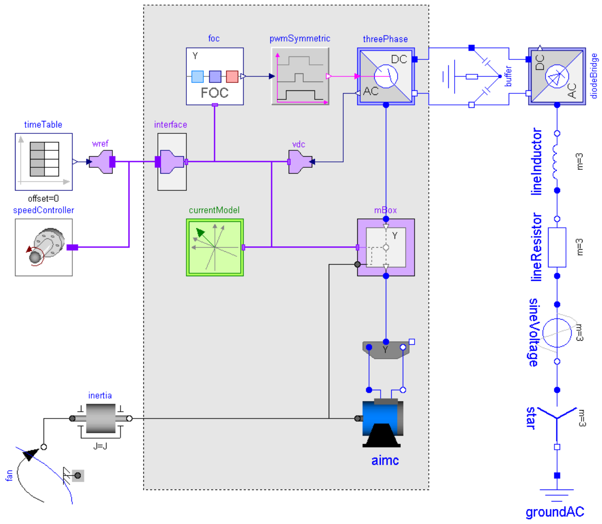

Figure 14: Case C; electrical transients and switching effects simulation of the speed controlled fan drive with elementary SED models.

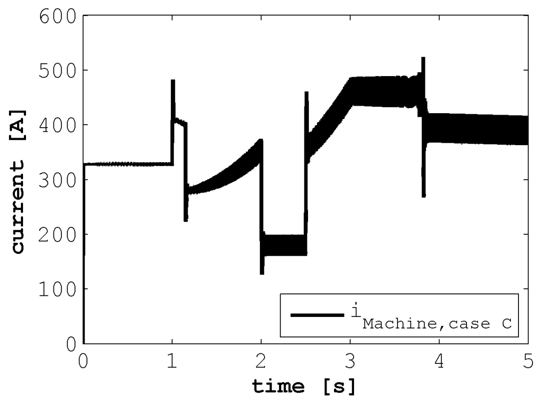

Figure 15: RMS value of the stator phase current of the machine in case C.

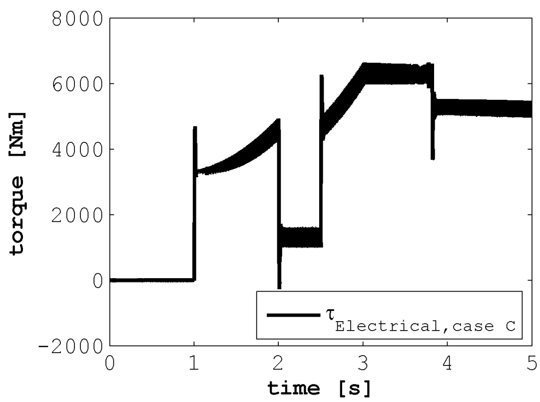

Figure 16: Electrical torque of the machine in case C.