Object Oriented Modeling of Rotating Electrical Machines

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1. Introduction

The simulation of electric machines is required in many fields of applications. For the simulation of electric vehicles or hybrid electric vehicles it is often important to take multi physical effects into account. Only the full coupling of different physical domains allows a systemic analysis of the entire power train. The electric energy storage, power electronics, control and electric machines may have some kind of forced air or liquid cooling. The cooling circuits of each of the electric devices may be coupled or not. Depending on the complexity of the vehicle, the mutual coupling of thermal, mechanical and electrical effects may be crucial when the entire electric power train shall be designed. A flexible and open environment for modeling the electric energy storage, the power electronics, the electric machines, gears and clutches is thus very beneficial in the design phase.

In this book chapter object oriented models of rotating electric three phase machines will be presented. To these machines will be referred with the general term *induction machines*. Particular machines handled in this paper are

- asynchronous induction machines with squirrel cage,
- asynchronous induction machines with slip rings,
- synchronous reluctance machines,
- electrical excited synchronous machines and
- permanent magnet synchronous machines.

For modeling the machines the language Modelica is used. The presented models are summarized in a library, which is available open source. This library takes the following loss mechanisms into account: temperature dependent copper (ohmic) losses, core losses, friction losses, stray load losses and brush losses which is certainly suitable for most applications. However, the motivation for developing the presented electric machines library is also the expandability of the library, being very powerful for a wide range of advanced drive applications. The expandability of the library enables an extension by considering additional effects, e.g., saturation, deep bar effects, thermal behavior, etc.

2. Modelica

The Modelica Association is a non-profit and non-government association which is developing and maintaining the Modelica language, see Fritzson (2004). Modelica is an object

oriented equation based language for modeling multi physical systems, e.g., analog electrical, digital, mechanical, thermal, magnetic, hydraulic, pneumatic, control, etc.

A Modelica library is a very convenient and reliable way to summarize and maintain developed and tested Modelica models (classes). The most prominent model library is the Modelica Standard Library, which contains a huge set of models (classes) out of many scientific fields. This library is also maintained by the Modelica Association. The entire Modelica Standard Library is open source and can be freely used, distributed and modified. The authors of the proposed book chapter are members of the Modelica Association and contributed to the control, thermal, mechanical, electrical multiphase, and electric machines packages of the Modelica Standard Library.

Modelica allows the modeling of multi physical systems in an object oriented way. Most models (classes) define interfaces and the model equations only refer to the interfaces and internal variables. The interfaces may either be signal connectors as they are used in control, or physical connectors as they are used for physical models. These connectors consist of pairs of potential and flow variables, e.g., the electric potential and the electric current in case of an electric connector. A more complex model can be accomplished by connecting the connectors of different objects to a a a more complex object. The potential variables of connected interfaces are set equal as implied by Kirchhoff's voltage law. According to Kirchhoff's current law the sum of flow variables of the connected connectors is set to zero.

The relations between connector variables—describing the behavior of the component—are formulated in an acausal way, i.e., independent of the later usage of the component. Instead of using assignments,

```
v:=R*i; // assign resistance multiplied by current to voltage drop
```

as in most programming languages, equations are used:

```
v/R=i;  // voltage drop divided by resistance equals current
```

A software tool gathers all (ordinary) differential and algebraic equations, simplifies the set of equations (e.g. solving some of the algebraic equations analytically), and numerically integrates and solves the simplified set of equations. Thus the formulation of e.g. Ohm's law (for a resistor model) is independent on whether current flowing through the component or voltage applied to its terminals is prescribed by the system.

The advantage of the object oriented approach is that redundant model code can be avoided. This increases the maintainability and reduces the fault liability of the code. In Modelica the generalization of the term model is a class, which may be, e.g., a model, a function or a package—which is a container for additional classes, like, e.g., a directory in a file structure. A tested class can be re-used in other models through inheritances. Modelica supports two different kinds of inheritance. First, the extension of code, i.e., the inserting (extending) of code or code fragments in classes. The second kind of inheritance is instantiation which creates instances of classes which can be accessed through their instance names. For example, when modeling an electrical network of concentrated elements, different instances of, e.g., resistors and inductors may be used.

```
model Network
  Modelica.Electrical.Analog.Basic.Resistor R1(R=1);
  Modelica.Electrical.Analog.Basic.Resistor R2(R=10);
  Modelica.Electrical.Analog.Basic.Inductor L1(L=0.01);
  ...
end Network;
```

The class names starting with `Modelica.Electrical.Analog.Basic.` refer to standard components of the Modelica Standard Library. The dots in the name nomenclature separate different hierarchical levels. The class definitions of the resistor and inductor inherit code through extension from the partial model `OnePort`, which contains the interface connectors and basic variable definitions.

```
partial model OnePort
  Modelica.SIunits.Voltage v;
  Modelica.SIunits.Current i;
  Modelica.Electrical.Analog.Interfaces.PositivePin p;
  Modelica.Electrical.Analog.Interfaces.NegativePin n;
equation
  v = p.v - n.v;
  0 = p.i + n.i;
  i = p.i;
end OnePort;
```

The keyword **partial** in this model indicates that the number of variables and equations is not balanced. Different models and partial models may be recursively access code through extension. A non-partial model extending from one or more partial models needs to provide additional equations (and variables) such that the numbers of variables and equations are balanced.

In Modelica physical dimensions of parameters and variables can be assigned. In the Modelica package `Modelica.SIunits` all the base SI units and many derived SI units are provided. When translating a model for the simulation of a particular problem, a unit check of all of the involved equations is performed. This way it can be ensured, that consistency problems of physical equations can be avoided.

3. Electric machine components

An electric machine is an electro mechanical energy converter. The object interfaces are the (electrical) terminal connections of the windings, the (rotational) shaft end and housing, as well as a thermal connector incorporating the significant thermal regions and loss sources of the machine. With reference to asynchronous and synchronous induction machines two different implementations of electric machine models are included in the Modelica Standard Library. The first implementation relies on space phasor theory and this is the library that is presented in this book chapter. The second implementation is based on magnetic fundamental wave models—with respect to the spatial electro magnetic field. The space phasor based machines library was originally released in 2004 and was heavily improved over the last years. The other machines library is included in the Modelica Standard Library since version 3.2, which has been released in 2010. Both machine implementations are fully compatible and model the transient behavior of induction machines in the time domain. For DC machines and transformers a time transient (and an electrically stationary) implementation is also included in the Modelica Standard Library, which will, however, not be addressed in this book chapter. The basic idea of the object oriented modeling in electric machines is that each effect which can be separated from others is encapsulated in an object. Typical machine specific objects are winding resistances, winding stray inductances, cage models and the air gap model, which takes the electro mechanical power conversion and the magnetic main field into account. Other objects are the inertia, and loss models related to mechanical friction, eddy currents in the core, stray load effects and brush contact. Each loss model takes a consistent power

balance into account, such that all dissipated losses are always considered in a respective thermal connector. The loss models have been presented and validated against measurements in Haumer et al. (2009). For the mechanical components *actio et reactio* applies. For each torque acting on the stator and rotor side of, e.g., the air gap and friction model, the torques have the same numeric values, but different signs. Different machines, such as asynchronous induction machines with squirrel cage and slip ring rotor, and synchronous machines with permanent magnets, electrical excitation, etc., are modeled out of a minimal subset of components. This way the object oriented Modelica models of electric machines become code and run-time efficient and certainly very robust.

3.1 Assumptions

The induction machine models are summarized in the package `Modelica.Electrical.Machines` of the Modelica Standard Library. For these machine models the following assumptions apply:

- the number of phases is restricted to three

- the phase windings are fully symmetrical

- the inductances are constant and thus the relationships between flux linkages and currents are linear

- saliency effects, represented by different inductances of the *d*- and *q*-axis are considered for the synchronous machines models

- cross coupling of inductances is not modeled

- deep bar effects are not taken into account

- only (spatial) fundamental wave effects of the magnetic field are taken into account

- time transients of electrical, mechanical and thermal quantities are not restricted

3.2 Electrical concept

The interface definition of the electric pin in `Modelica.Electrical.Analog.Interfaces.Pin` consists of the electric potential and the current being a flow quantity.

```
connector Pin
  Modelica.SIunits.Voltage v;
  flow Modelica.SIunits.Current i;
end Pin;
```

In order to model multi phase machines an electric plug is defined in `Modelica.Electrical.MulitiPhase.Interfaces.Plug`. This plug contains `m=3` pins by default:

```
connector Plug
  parameter Integer m=3;
  Modelica.Electrical.Analog.Interfaces.Pin pin[m];
end Plug;
```

In all instances of the plug, `m` is finally set to three when applied in the machines package, since only three phase machines are modeled.

3.3 Mechanical concept

For the rotating electric machine models only rotating one dimensional effects need to be taken into account. The rotational interfaces definitions of `Modelica.Mechanics.Rotational.Interfaces.Flange_a` are:

```
connector Flange_a
  Modelica.SIunits.Angle phi;
  flow Modelica.SIunits.Torque tau;
end Flange_a
```

In the rotational package the rotational angle `phi` servers as potential quantity and torque `tau` is the flow quantity.

3.4 Thermal concept

Each loss component is equipped with a heat port which carries the heat flow as flow variable and the accessory operating temperature as potential quantity. The connector definition of `Modelica.Thermal.HeatTransfer.Interfaces.HeatPort` is:

```
connector HeatPort
  Modelica.SIunits.Temperature T;
  flow Modelica.SIunits.HeatFlowRate Q_flow;
end HeatPort;
```

Each machine model has a conditional super heat port, which consists of as many heat ports as loss effects are considered. If the super heat port of a machine is enabled, the heat ports of the loss components are connected with this super heat port. This way the machine model can be coupled with an external thermal model. If the heat port of a machine is disabled the loss components are thermally connected to internal temperature sources representing fixed (operating) temperatures. In this case, the losses are entirely dissipated in internal temperature sources. The concept of coupling an external thermal model with the electro-mechanical model is presented in detail in Haumer et al. (2010).

3.5 Resistance

The resistor objects applied in the machine models are directly taken from the Modelica package `Modelica.Electrical.Analog.Basic.Resistor`, see resistor in tab. 1. This model consists of two electrical pins and one thermal connector. This resistance is modeled temperature dependent

```
R = RRef*(1+alphaRef*(T-TRef));
```

where `RRef` is the reference resistance at the reference temperature `TRef` and `alphaRef` is the linear temperature coefficient at `TRef`. The actual resistance `R` is dependent on the operating temperature `T` which is obtained from the thermal connector of this model.

Three phase resistors are directly taken from the Modelica package `Modelica.Electrical.MultiPhase.Basic.Resistor`, see resistor in tab. 1. This model consists of two electrical three phase plugs, one thermal connector and three single phase resistors. Since the machine models are assumed to have symmetrical phase windings the individual reference resistances for each phase are set to equal values in the machine models.

Icon	Class name	Comment
	Resistor	Temperature dependent single phase resistor with heat port
	Resistor	Temperature dependent three phase resistor with heat port
	StrayLoad	Stray load losses with heat port and rotor and stator rotational flange
	Friction	Friction losses
	Brushes	Carbon brush losses
	SpacePhasor	Transforms multi phase quantities to space phasors and zero sequence components
	Inductor	Linear single phase inductor
	Inductor	Linear space phasor inductor
	Core	Core losses (without hysteresis losses)
	SquirrelCage	Symmetrical squirrel cage with heat port
	DamperCage	Salient damper cage with heat port
	ElectricalExcitation	Transforms excitation voltage and current to space phasors
	PermanentMagnet	Transforms permanent magnet excitation to an equivalent space phasor
	Inertia	Rotating mass

Table 1. Components of the electric machines library

3.6 Stray load losses

The stray load loss model applied to all the induction machine models is originally inspired by the standard 60034-2 (1998) and extended by a thesis of Lang (1984). The stray load losses are modeled to be proportional to the square of the root mean square (RMS) current and to a particular power of speed. In order to consistently cover the loss balance in the machine, stray load losses are considered as an equivalent torque, acting on the rotor (and stator housing, respectively).

```
tau = tauRef*(I/IRef)^2*(w/wRef)^power_w;
```

The term `wRef*tauRef` represents the reference stray load losses at rated current `IRef` and rated angular speed `wRef`. The parameter `power_w` is a positive real quantity in this model.

The stray load loss model consists of two plugs and two mechanical flanges. One mechanical flange is supposed to be connected with the rotor and the other one shall be connected with the stator (housing). The torques of the two mechanical flanges have the same numeric values but different signs. The electrical connectors are part of the stator (winding) circuit. The RMS value of the current is actually computed from the instantaneous values of the phase currents. The actual losses dissipated by this model are equal to the heat flow of thermal connector:

```
heatPort.Q_flow = tau*w;
```

The heat flow and losses, respectively, are independent of the temperature of the heat port. Yet for operating this model an (arbitrary) operating temperature has to be provided at the heat port (see tab. 1).

3.7 Friction losses

The friction losses are modeled by:

```
tau = tauRef*(w/wRef)^power_w;
```

In this equation `wRef*tauRef` represent the reference friction losses at reference angular velocity `wRef`. The exponent `power_w` is a positive real quantity.

In order to avoid numerical problems the torque speed relationship is approximated as a linear curve around the zero crossing. The linear speed region is, however, much smaller than the reference reference speed.

```
tau = if w >= +wLinear then
        +tauRef*(+w/wRef)^power_w
     else if w <= -wLinear then
        -tauRef*(-w/wRef)^power_w
     else
        tauLinear*(w/wLinear);
```

This model requires two mechanical flanges to be connected with the rotor and stator (housing), respectively. The thermal connector dissipates the losses

```
heatPort.Q_flow = tau*w;
```

independent of the actual operating temperature, which has to be provided externally due to consistency reasons, see tab. 1.

3.8 Brush losses

In the induction machine models carbon brush losses (see tab. 1) are currently taken into account only for the excitation circuit of the electrical excited synchronous machine model. The brush model considers three regions. For large positive currents `i>ILinear` the voltage drop is constant and equal to `V`. For currents less than `-ILinear` the voltage drop is equal to `-V`. In between these regions the voltage versus current characteristic is linear.

```
v = if (i>+ILinear) then
       +V
    else if (i<-ILinear) then
       -V
    else
       V*i/ILinear;
```

The brush loss model has only two electrical connectors and one thermal connector. The heat dissipated by the brushes is:

```
heatPort.Q_flow = -v*i;
```

independent of the actual operating temperature.

3.9 Space phasor transformation

The machine models presented in this book chapter rely on the space phasor equations. In literature—instead of space phasor—also the terms space vector or Park's vectors are used. The reason for applying space phasor theory is that the equations are simpler compared to the individual phase equations. When the model equations refer to the rotating reference frame, time transients have lower characteristic frequencies which gives also rise to significant simulation speed advantages.

Space phasor transformation is used to transform the phase voltages and currents of the three plug connectors into voltage and current space phasor—and the zero sequence voltage and current, according to Kleinrath (1980):

$$\underline{v} = \frac{2}{3} \left(v_1 + \underline{a} v_2 + \underline{a}^2 v_3 \right)$$

$$\underline{a} = e^{j\frac{2}{3}\pi} = -\frac{1}{2} + j\frac{\sqrt{3}}{2}$$

$$v_0 = \frac{1}{3} \left(v_1 + v_2 + v_3 \right)$$

In the presented machines package the space phasor is implemented as an array of two elements, representing real and imaginary part, respectively. The space phasor connector is thus defined by:

```
connector SpacePhasor
  // First component [1] represents real part,
  // second component [2] represents imaginary part
  Modelica.SIunits.Voltage v_[2];
  flow Modelica.SIunits.Current i_[2];
end SpacePhasor;
```

In the space phasor transformation model the following equations apply for the voltages:

```
v_[1] = (2/3)*(v[1]-v[2]/2-v[3]/2);
v_[2] = (1/sqrt(3))*(v[2]-v[3]);
```

The zero sequence connector `zero` is modeled as a regular electrical pin. The respective zero sequence voltage is determined by the following acausal relationship:

```
3*zero.v = v[1]+v[2]+v[3];
```

The same relationships also apply for the space phasor currents and the zero sequence current. In each of the presented machines the zero sequence inductance of the respective (stator or rotor) winding is then connected to the zero sequence connector of the space phasor transformation model, see section 4 and tab. 1.

3.10 Zero inductance

In the presented machines package the zero inductances are modeled by means of single phase inductors which are taken directly from the Modelica package `Modelica.Electrical.Analog.Basic.Inductor` (see inductor model in tab. 1). The same inductor model is used for the stray inductance of single phase excitation windings.

3.11 Stray inductance

In the presented machines package stray inductances are modeled by means of inductors with space phasor connectors and components (see inductor model in tab. 1).

```
v_[1] = L[1]*der(i_[1]);
v_[2] = L[2]*der(i_[2]);
```

The operator `der()` represents the time derivative and the inductances `L[1]` and `L[2]` are the inductances in the two axes of the actual space phasor reference frame.

3.12 Core losses

In the current implementation of the core loss model only eddy current losses are taken into account (tab. 1). Therefore, the actual core conductance `Gc` is assumed to be constant, calculated from reference core losses at given reference voltage. The electrical interfaces of the model are space phasor connectors. The space phasor relationship between voltages and currents is simply

```
i_ = Gc*v_;
```

and dissipated losses are:

```
heatPort.Q_flow = -3/2*(+v_[1]*i_[1]+v_[2]*i_[2]);
```

Hysteresis losses are not considered in the actual implementation, since hysteresis losses are usually modeled in the frequency domain as presented by Lin et al. (2003), but the presented model is strictly a time domain approach.

3.13 Air gap, magnetizing inductance and torque

The air gap model takes the magnetizing inductance and the electro mechanical power conversion into account. The stator and rotor side of the model have space phasor connectors representing the voltage and current phasors with respect to the stator and rotor fixed reference frame. Additionally the air gap model has one rotor and one stator (housing) related rotational flange.

In the proposed machine models the entire magnetic circuits are represented by equivalent air gap inductances. In order to express the relationship between stator and rotor currents and magnetizing inductance, the stator and rotor space phasors have to refer to one common reference frame. It is thus required to either

1. transform the stator space phasors to the rotor fixed reference frame or

2. transform the rotor space phasors to the stator fixed reference frame.

For both cases an air gap model is available in the presented machines library. In the following only the first implementation will be discussed, as this represents the more general approach. In the following the rotor fixed rotor current space phasor is referred to as i_rr. The first letter after the underscore represents the rotor side and the second letter indicates the reference frame—in this case the rotor fixed reference frame. The stator fixed stator current space phasor i_ss is transformed to the rotor fixed reference frame by means of a rotation by the negative angle gamma. This quantity is the difference of angular position of the stator and rotor rotation flange, multiplied by the number of pole pairs. The rotor fixed stator current space phasor i_sr and the rotor current space phasor i_rr add up the magnetizing current phasor:

```
i_mr = i_sr+i_rr;
```

The main flux linkage phasor psi_mr of the air gap is thus determined by

```
psi_mr[1] = Lmd*i_mr[1];
psi_mr[2] = Lmq*i_mr[2];
```

where Lmd and Lmq are the magnetizing inductances in the direct (d) and quadrature (q) axis of the rotor. The different inductances in both axis allow the consideration of saliency effects of the magnetic reluctance of the rotor.

The inner (electrical) torque of the air gap model is determined by the vector product of the magnetizing flux and the stator current space phasor:

```
tauElectrical = 3/2*p*(i_sr[2]*psi_mr[1] - i_sr[1]*psi_mr[2]);
```

In this equation p represents the number of pole pairs. As for all mechanically interacting models, the torque at rotor shaft and the stator (housing) have the same numeric quantities but different signs to correctly consider *actio et reactio*; see tab. 1.

3.14 Squirrel and damper cage

For asynchronous induction machines symmetrical squirrel cages are used, whereas synchronous machines use damper cages with different equivalent resistances and stray inductances in direct (d) and quadrature (q) axis. In this sense, the symmetrical squirrel cage is a restricted damper cage with equal parameters in the two axis; see tab. 1. The relationship between the two axis components of the voltages and current spaces phasors are:

```
v_[1] = Rrd * i_[1] + Lrsigmad * der(i_[1]);
v_[2] = Rrq * i_[2] + Lrsigmaq * der(i_[2]);
```

The resistances Rrd and Rrq are again temperature dependent, and the model is equipped with a heat port. The constant inductances Lrsigmad and Lrsigmaq are the stray inductances of the cages in the direct (d) and quadrature (q) axis.

3.15 Electrical excitation

For electrically excited synchronous machines, excitation voltage and current have to be transformed to equivalent space phasors (direct axis components), taking the conversion factor between rotor and stator into account:

```
ve = v_[1]*turnsRatio*3/2;
i_[1] = -ie*turnsRatio;
i_[2] = 0;
```

With given main field inductance in d-axis `Lmd`, the `turnsRatio` can be calculated from no-load voltage at given speed (frequency) and excitation current `IeOpenCircuit`:

```
sqrt(2)*VsNominal = 2*pi*fsNominal*Lmd*IeOpenCircuit*turnsRatio
```

3.16 Permanent magnet

For permanent magnet synchronous machines, the effect of the permanent magnet can be considered like a constant DC excitation current (providing a constant remanent flux, neglecting the detailed B-H-characteristic of the magnet material):

```
i_[1] = -Ie;
i_[2] = 0;
```

3.17 Inertia

Inertia models are required to model the rotor and stator (housing) inertia effects with respect to one rotational axis. The relationship between torque `tau` and angular position `phi` of the flange is:

```
phi = flange_a.phi;
phi = flange_b.phi;
w = der(phi);
a = der(w);
J*a = flange_a.tau + flange_b.tau;
```

The inertia model has two flanges, `flange_a` and `flange_b` which are rigidly connected. From a modeling point of view the two different connectors are not required, but are used for convenience reasons when graphically connecting components, see tab. 1.

4. Induction machine models

4.1 Partial induction machine model

The partial induction machine model (see Fig. 1) comprises all components that are common to all induction machines models:

- electrical three phase plugs `plug_sp` and `plug_sn` representing the beginning and end of the stator three phase windings; star or delta connection has to be provided outside of the machine model

- stray load losses `strayLoad`: see sec. 3.6

- resistances `rs` of the three phase stator windings: see sec. 3.5

- space phasor transformation `spacePhasorS` of stator voltages and currents: see sec. 3.9

- stator zero sequence inductor `lszero`: see sec. 3.10; the inductance is set equal to the stray inductance by default, but can be parametrized differently

- stray inductance `lssigma` of the three phase stator windings: see sec. 3.11

- stator core losses `statorCore`: see sec. 3.12

- friction losses `friction`: see sec. 3.7

- rotor moment of inertia `inertiaRotor` (see sec. 3.17) and a rotational flange, representing the shaft end

- stator moment of inertia `inertiaStator` (see sec. 3.17) and an optional rotational flange, representing the housing

- a replaceable internal heat port `internalHeatPort`, an optional replaceable thermal ambient `thermalAmbient` and an optional replaceable thermal port `thermalPort` (see sec. 3.4)

For the user's convenience, a boolean parameter `useSupport` determines whether the stator flange of the air gap model is connected to an internal mechanically fixed point `fixed`), or to the stator moment of inertia and the rotational flange `support`. If the user chooses `useSupport` = **true**, the flange `support` has to be connected to an external mechanical circuit, e.g., representing an elastic mounting.

All induction machine models extend from this partial model, i.e., they inherit all common components, replacing the thermal ports and thermal ambient by machine specific components and add all other specific components (e.g. air gap model).
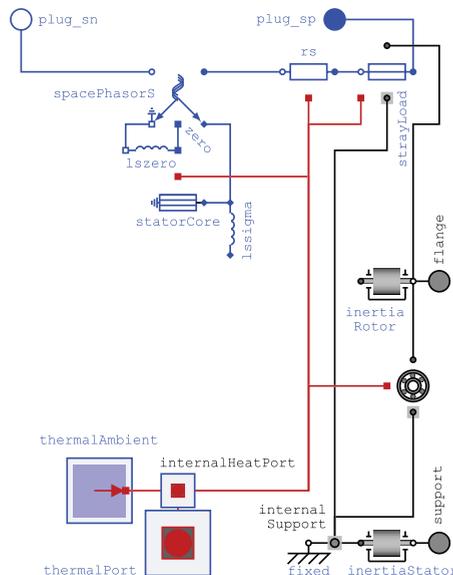

Fig. 1. Partial model of induction machines

4.2 Asynchronous induction machine with squirrel cage
The asynchronous induction machine with squirrel cage (see fig. 2) inherits from the partial induction machine model (see sec. 4.1) and adds the following machine specific components:

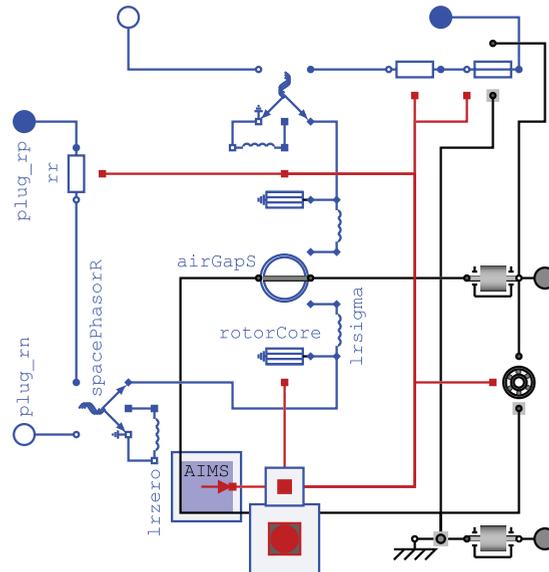- air gap model `airGapS` in the stator fixed reference frame: see sec. 3.13
- squirrel cage `squirrelCageR` in rotor fixed reference frame: see sec. 3.14

4.3 Asynchronous induction machine with slip ring rotor
The asynchronous induction machine with slip ring rotor (see fig. 3) inherits from the partial induction machine model (see sec. 4.1) and adds the following machine specific components:

- air gap model `airGapS` in the stator fixed reference frame: see sec. 3.13

Fig. 2. Asynchronous induction machine with squirrel cage

- electrical threephase plugs `plug_rp` and `plug_rn` for beginning and end of the rotor three phase windings; star or delta connection has to be provided outside of the machine model

- resistances `rr` of the three phase rotor windings: see sec. 3.5

- space phasor transformation `spacePhasorR` of rotor voltages and currents: see sec. 3.9

- rotor zero sequence inductor `lrzero`: see sec. 3.10; the inductance is set equal to the rotor stray inductance by default, but can be parametrized differently

- stray inductance `lrsigma` of the three phase rotor windings: see sec. 3.11

- rotor core losses `rotorCore`: see sec. 3.12

- brush losses (see sec. 3.8) are neglected, since standards consider brush voltage drop dependent on root mean square of current; during transient operation RMS current cannot be calculated; the dependency of brush voltage drop on instantaneous current will be investigated

The space phasor transformation of rotor voltages and currents has to take into account additionally the turns ratio between stator and rotor winding:

$$\frac{v_r'}{v_r} = \frac{\text{effective number of stator turns}}{\text{effective number of rotor turns}}$$

This parameter can either be determined from a pre-processing calculation of the machine, or calculated from the measured locked-rotor voltage v_{r0}:

$$\frac{v_{r0}'}{v_{r0}} = \frac{v_s}{v_{r0}} \cdot \frac{|j\omega_s L_m|}{|r_s + j\omega_s L_s|}$$

Fig. 3. Asynchronous induction machine with slip ring rotor

4.4 Synchronous reluctance machine

The synchronous reluctance machine (see fig. 4) inherits from the partial induction machine model (see sec. 4.1) and adds the following machine specific components:

- air gap model `airGapR` in the rotor fixed reference frame (see sec. 3.13), since saliency of the rotor has to be taken into account

- optional damper cage model (see sec. 3.14) which can be enabled/disabled by means of the boolean parameter `useDamperCage`; since the damper cage can be disabled (machine without damper cage), an auxiliary heat flow sensor has to be used for connection to the thermal port

4.5 Electrical excited synchronous machine

The electrical excited synchronous machine (see fig. 5) inherits from the partial induction machine model (see sec. 4.1) and adds the following machine specific components:

- air gap model `airGapR` in the rotor fixed reference frame (see sec. 3.13), since saliency of the rotor has to be taken into account

- optional damper cage model (see sec. 3.14) which can be enabled/disabled by means of the boolean parameter `useDamperCage`; since the damper cage can be disabled (machine without damper cage), an auxiliary heat flow sensor has to be used for connection to the thermal port

- electrical single-phase pins `pin_ep` and `pin_en` for beginning and end of the excitation winding

- brush losses `brush` (see sec. 3.8) for modeling losses and the voltage drop due to brushes; if a brushless excitation system is considered, the brush loss equations can be disabled by setting the reference voltage drop to zero
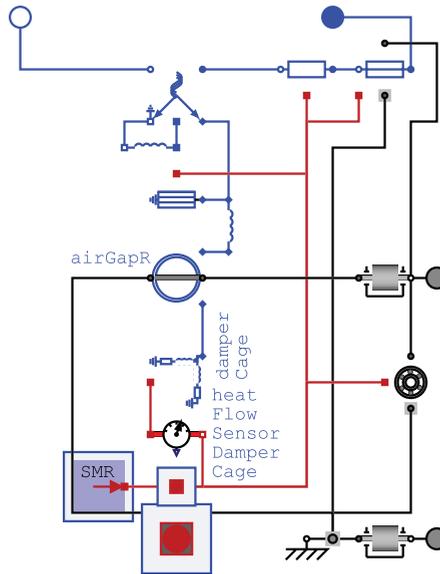
Fig. 4. Synchronous machine with reluctance rotor and optional damper cage

- resistance `re` (see sec. 3.5) of the excitation winding
- stray inductance `lesigma` (see sec. 3.10) of the excitation winding
- electrical excitation: see sec. 3.15
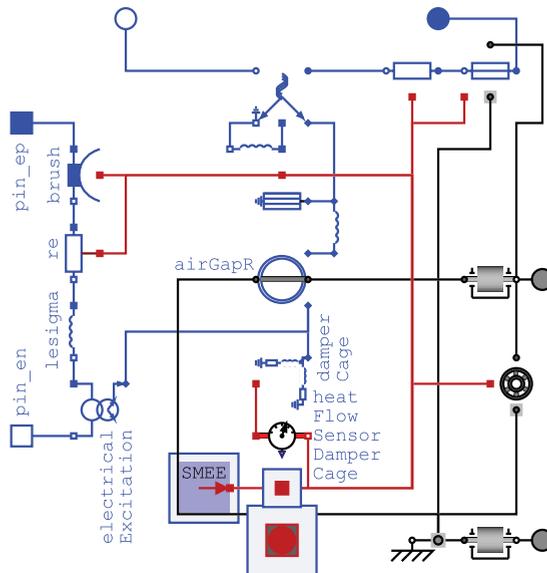
Fig. 5. Electrical excited synchronous machine with optional damper cage

4.6 Permanent magnet synchronous machine

The permanent magnet synchronous machine (see fig. 4.6) inherits from the partial induction machine model (see sec. 4.1) and adds the following machine specific components:

- air gap model `airGapR` in the rotor fixed reference frame (see sec. 3.13), since saliency of the rotor has to be taken into account

- optional damper cage model (see sec. 3.14) which can be enabled/disabled by means of the boolean parameter `useDamperCage`; since the damper cage can be disabled (machine without damper cage), an auxiliary heat flow sensor has to be used for connection to the thermal port

- permanent magnet (see sec. 3.16): the equivalent excitation current `Ie` is calculated from the given no-load voltage at given speed
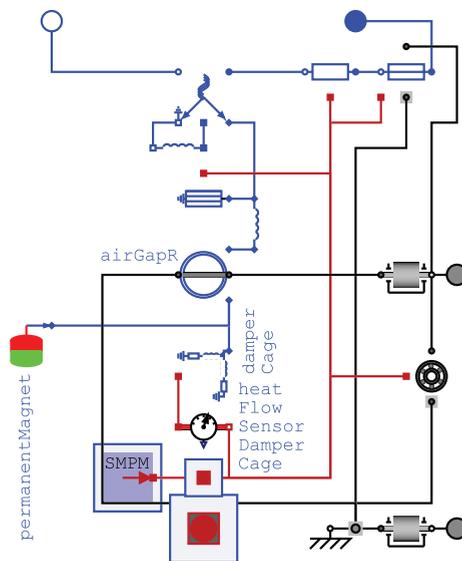
Fig. 6. Permanent magnet synchronous machine with optional damper cage

4.7 Parametrization of machine models

The parameters needed for the machine models have to be taken from pre-processing design software, or calculated from measurement reports:

- number of pole pairs

- nominal frequency: used to calculate inductances from reactances

- rotor moment of inertia

- stator moment of inertia: only relevant if the user chooses to connect an external mechanical circuit to the stator mounting (see sec. 4.1)

- winding resistances (see sec. 3.5):

  – reference resistance at reference temperature

- – reference temperature
- – temperature coefficient at reference temperature
- – operational temperature: only relevant if the user chooses to dissipate the losses to an internal thermal temperature source instead of connecting an external thermal circuit (see sec. 3.4)

- • stray inductance
- • zero inductance of three phase windings
- • magnetizing inductance (see sec. 3.13)
- • stray load losses (see sec. 3.6):
  - – reference loss power at reference current and reference speed
  - – reference current
  - – reference speed
  - – exponent of stray load torque with respect to speed
- • friction losses (see sec. 3.7):
  - – reference loss power at reference speed
  - – reference speed
  - – exponent of friction torque with respect to speed
- • brush losses (see sec. 3.8):
  - – voltage drop
  - – current limit (linear changeover around current = 0)
- • core losses (see sec. 3.12):
  - – reference loss power at reference voltage and reference frequency
  - – reference voltage
  - – reference frequency

If it is desired to neglect losses, the reference loss power (stray load losses, friction losses, core losses) respectively the voltage drop (brush losses) can be set to zero.

Resistances and inductances have to be specified per phase as they are accessible for measurements at the respective winding terminals, except squirrel cage and damper cage. Cage parameters (see sec. 3.14) have to be specified with respect to an equivalent three phase stator winding. If temperature dependency shall be neglected, either the temperature coefficient can be set to zero or—in case the heat port shall not be connected to an external thermal model (see sec. 3.4)—the operational temperature can be set equal to the reference temperature.

Additional machine specific parameters are:

- • for asynchronous induction machines with slip ring rotor (see sec. 4.3), `turnsRatio` between stator and rotor winding is calculated out of the parameters
  - – nominal stator voltage
  - – locked-rotor voltage
- • for electrical excited synchronous machines (see sec. 4.5 and sec. 3.15), `turnsRatio` between stator and excitation winding as well as excitation stray inductance require the parameters

- – nominal stator voltage
- – open circuit excitation current for nominal stator voltage at nominal frequency
- – stray fraction of total excitation inductance
- for permanent magnet synchronous machines (see sec. 4.6 and sec. 3.16), the calculation of the equivalent excitation current requires the
  - – open circuit stator voltage at nominal speed

5. Examples

5.1 Asynchronous induction machine with squirrel cage, started direct on line

The stator windings of an asynchronous induction machine with squirrel cage (`aimc` in fig. 7) is connected in delta, using the auxiliary model `terminalBox` which allows the selection of either star or delta connection. The `terminalBox` is series connected to an RMS current sensor (which determines the length of the current space phasor) and a switch (which is closed at `time = 0.1 s`). The stiff voltage supply is represented by a purely sinusoidal voltage source (`sineVoltage`). The machine's shaft end is connected to the `loadInertia` and a quadratic speed dependent `loadTorque`. The parameters of the load are selected such way that the machine load torque equals the nominal torque at nominal speed. A summary of the machine parameters is listed in tab. 2. Parameters which are not needed for parametrizing the machine model are listed without parameter name. In the presented example, for simplicity reasons, the temperature dependence of the resistances is neglected. All other than ohmic losses are also not taken into account.
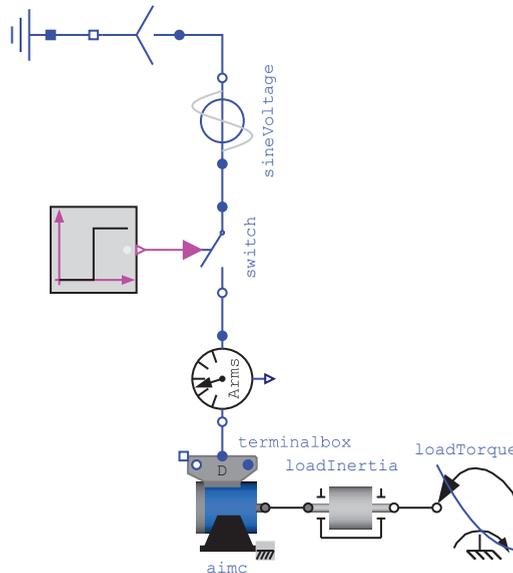
Fig. 7. Asynchronous induction machine with squirrel cage, started direct on line

The line current shown in fig. 8 represents the length of the current space phasor divided by $\sqrt{2}$, which can be interpreted as equivalent RMS value for stationary operation. The current waveform reflects an electro-magnetic transient when the `switch` is closed. Due to
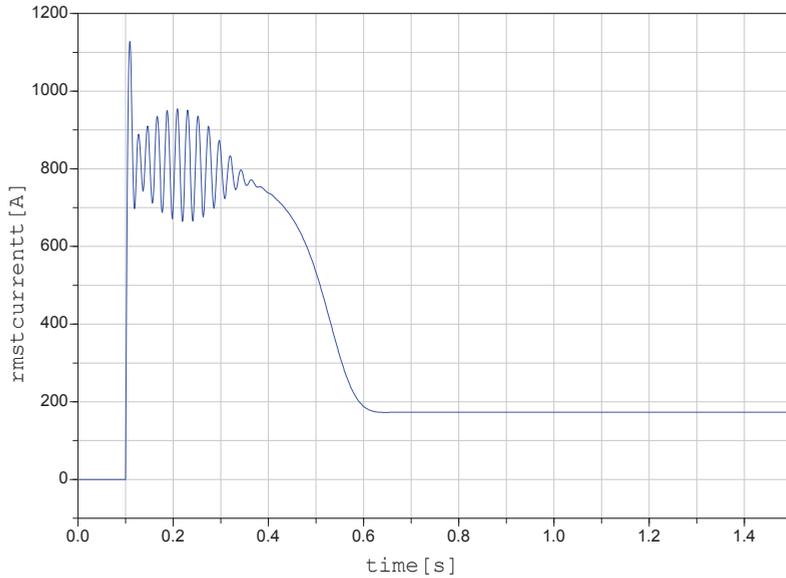
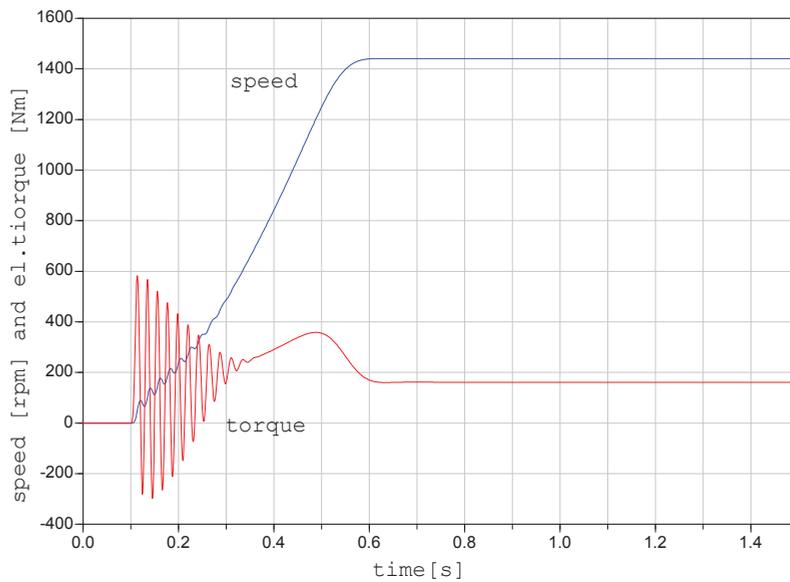Fig. 8. Line current of asynchronous induction machine with squirrel cage

Fig. 9. Speed and electrical torque of asynchronous induction machine with squirrel cage

Comment	Parameter name	Value	Unit
number of pole pairs	p	4	
rotor's moment of inertia	Jr	0.29	$kg \cdot m^2$
nominal RMS voltage per phase		100	V
nominal RMS current per phase		100	A
nominal frequency	fsNominal	50	Hz
nominal torque		161.4	Nm
nominal speed		1440.45	rpm
stator resistance	Rs	0.03	Ω
stator stray inductance	Lssigma	0.3239	mH
stator zero sequence inductance	Lszero	0.3239	mH
main field inductance	Lm	9.2253	mH
rotor stray inductance	Lrsigma	0.3239	mH
rotor resistance	Rr	0.04	Ω

Table 2. Parameters of the asynchronous induction machine with squirrel cage

the electro-magnetic transients the electrical torque developed by the machine also starts with transient oscillations, which causes a speed ripple accordingly (fig. 9). The total moment of inertia (machine plus load) is accelerated by the electromagnetic torque minus the quadratic speed dependent load torque. At approximately 0.6 s the drive reaches nominal operating conditions.

5.2 Asynchronous induction machine with slip ring rotor, started with rheostat
The stator windings of an asynchronous induction machine with slip ring rotor (aims in fig. 10) is connected in delta. The stator starting switch is closed at time = 0.1 s. The machine's shaft end is connected to a loadInertia and a quadratic speed dependent loadTorque with the same parameters settings as in sec. 5.1. The rotor terminals are connected to a rheostat, i.e., an external additional resistor with resistance parameters equal to four times the rotor resistance. This rheostat is shorted during the start procedure after time = 1 s. The parameters of the simulated machine are summarized in tab. 3. For simplicity reasons neither temperature dependent resistances nor other loss phenomena are taken into account.

The current depicted in fig. 11, again, represents the length of the current space phasor divided by $\sqrt{2}$. The transient current is smaller than that of the asynchronous induction machine with squirrel cage due to the external rotor resistance of the rheostat. The electrical torque developed by the machine also starts with transient oscillations, which give rise to speed oscillations (fig. 12). The total moment of inertia of the machine including load is accelerated by the electromagnetic torque minus the quadratic speed dependent load torque. At approximately 0.7 s the drive reaches stationary operation with the rheostat still being switched on. After shorting the rheostat at time = 1 s, the machine accelerates with a short transient to nominal speed.

5.3 Electrical excited synchronous machine, load dump
The stator windings of an electrical excited synchronous induction machine (smee in fig. 13) is connected in star, using the auxiliary model terminalBox. The machine is operated as generator connected to a three-phase resistor and inductor by means of a switch. The electrical load has a nominal power factor of 0.8. At time = 2 s the open circuit
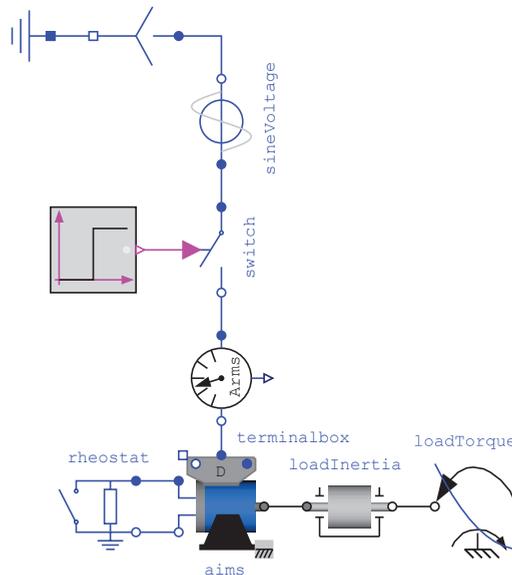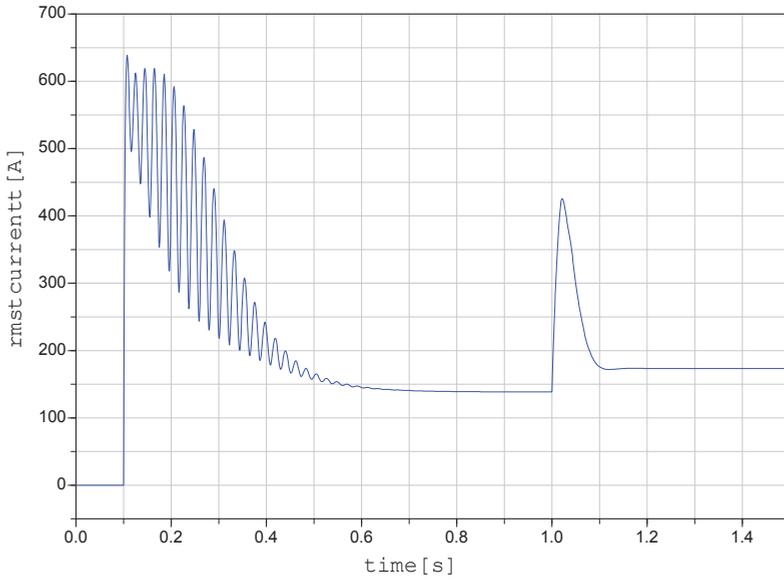
Fig. 10. Asynchronous induction machine with slip ring rotor, started with rheostat

Comment	Parameter	Value	Unit
number of pole pairs	p	4	
rotor's moment of inertia	Jr	0.29	$kg \cdot m^2$
nominal RMS voltage per phase	VsNominal	100	V
nominal RMS current per phase		100	A
nominal frequency	fsNominal	50	Hz
locked rotor RMS voltage per phase	VrLockedRotor	96.603	V
nominal torque		161.4	Nm
nominal speed		1440.45	rpm
stator resistance	Rs	0.03	Ω
stator stray inductance	Lssigma	0.3239	mH
stator zero sequence inductance	Lszero	0.3239	mH
main field inductance	Lm	9.2253	mH
rotor stray inductance	Lrsigma	0.3239	mH
rotor zero sequence inductance	Lrzero	0.3239	mH
rotor resistance	Rr	0.04	Ω

Table 3. Parameters of the asynchronous induction machine with slip ring rotor

Fig. 11. Line current of asynchronous induction machine with slip ring rotor and rheostat
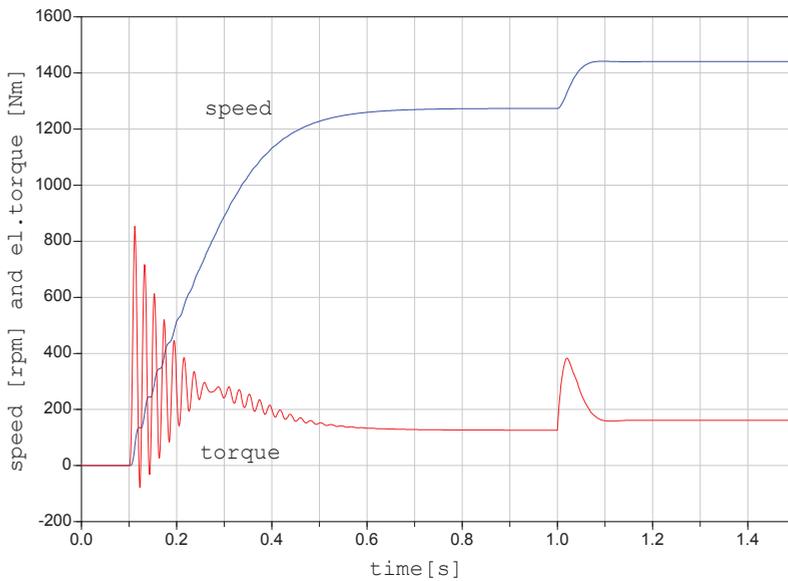
Fig. 12. Speed and electrical torque of asynchronous induction machine with slip ring rotor

of the generator is connected to the load which again is dumped at `time = 4 s`. This procedure is repeated periodically. The machine's shaft end is driven by a prescribed speed representing an ideal turbine. The turbine accelerates the machine within 1 s from standstill to nominal speed. For the remaining simulation time the speed is considered to be constant. The machine excitation is fed by a voltage source, which is controlled by a PI-controller (`voltageController`). The controller reference voltage is defined proportional to speed, the actual RMS voltage of the generator is determined from a voltmeter. The utility record `machineData` calculates the machine parameters (resistances and inductances) from given parameters (transient and subtransient reactances) according to the standard 60034-4 (1998). The parameters of the simulated machine are summarized in tab. 4. In order to simplify the simulation, first, the temperature dependencies of the resistances and, second, all other losses phenomena are not taken into account.
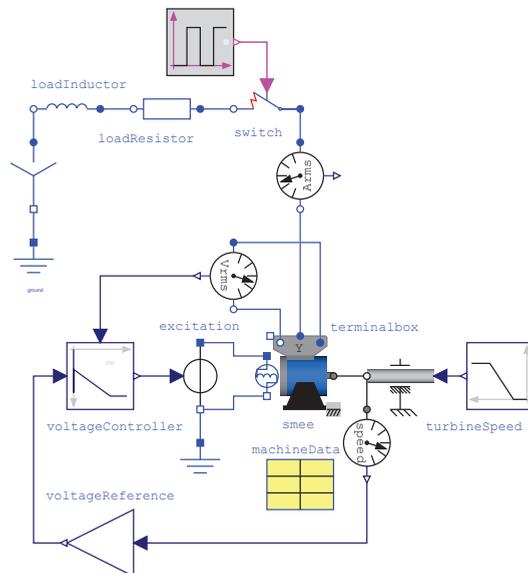
Fig. 13. Electrical excited synchronous machine, behavior during load dump

During starting the generator with `turbineSpeed` the excitation voltage and current as well as the machine terminal voltage increase to no-load operation at nominal voltage. The overshots are due to the settings of the voltage controller. Figure 14 shows the transient changes of line current between no-load and nominal current due to loading and load dump. The terminal voltage—see fig. 15—shows dips during loading and overshots during load dump. The voltage controller increases respectively decreases excitation voltage as shown in fig. 16. The excitation current follows the excitation voltage with a time constant according to total excitation inductance and excitation resistance.

6. Conclusions

The presented electric machines library, which it is part of the Modelica Standard Library, provides comprehensive three phase induction machine models. All relevant loss mechanisms are implemented and encapsulated in Modelica objects. The parametrized machine models

Comment	Parameter	Value	Unit
number of pole pairs	p	4	
rotor's moment of inertia	Jr	0.29	kg · m²
nominal RMS voltage per phase	VsNominal	100	V
nominal RMS current per phase		100	A
nominal frequency	fsNominal	50	Hz
stator resistance	Rs	0.03	Ω
stator stray inductance	Lssigma	0.3183	mH
stator zero sequence inductance	Lszero	0.3183	mH
main field inductance, d-axis	Lmd	4.7746	mH
main field inductance, q-axis	Lmq	4.7746	mH
damper stray inductance, d-axis	Lrsigmad	0.1592	mH
damper stray inductance, d-axis	Lrsigmaq	0.1592	mH
damper resistance, d-axis	Rrd	0.04	Ω
damper resistance, q-axis	Rrq	0.04	Ω
no-load excitation current	IeOpenCircuit	10	A
excitation resistance	Re	2.5	Ω
stray frac. of total exc. inductance	sigmae	2.5	%

Table 4. Parameters of the electrical excited synchronous machine
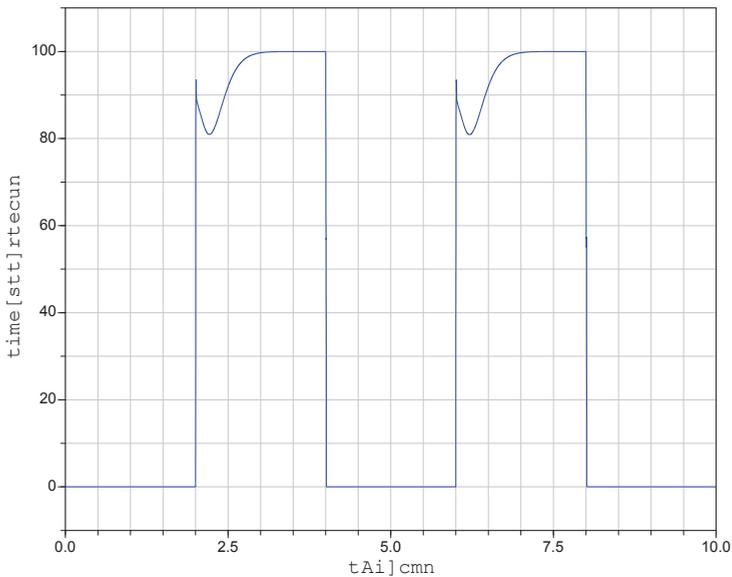
Fig. 14. Current of electrical excited synchronous machine
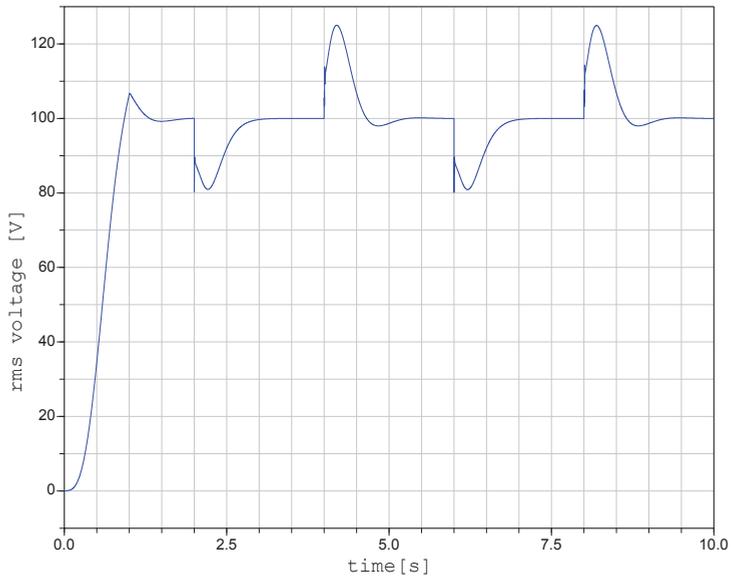
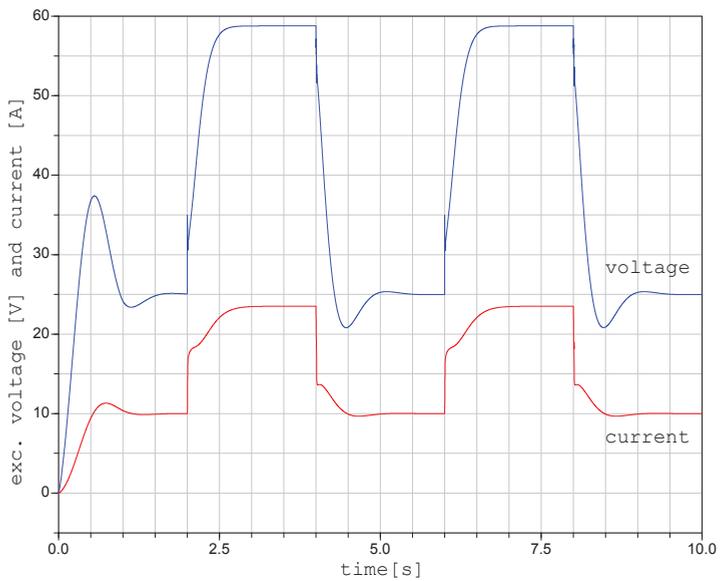Fig. 15. Stator voltage of the electrical excited synchronous machine

Fig. 16. Excitation of electrical excited synchronous machine

can be used together with other models from the Modelica Standard Library for various investigations; examples are presented in sec. 5. Due to the object oriented implementation all machine models can be used as a basis to implement additional phenomena, such as magnetic saturation or deep bar effects. Since the physical connectors are standardized in the Modelica Standard Library, the machine models have the potential to be used together with power electronic circuits, controll models and thermal models.

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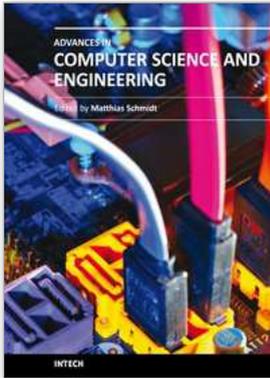
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