Proceedings
of the 4th International Modelica Conference,
Hamburg, March 7-8, 2005,
Gerhard Schmitz (editor)

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pp. 549-558

Paper presented at the 4th International Modelica Conference, March 7-8, 2005,
Hamburg University of Technology, Hamburg-Harburg, Germany,
organized by The Modelica Association and the Department of Thermodynamics, Hamburg University of Technology

Modelica libraries for dc machines, three phase and polyphase machines

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Abstract

This paper presents two libraries, the basic *Machines* library which is released with Modelica standard library 2.1 as well as an *ExtendedMachines* library, both for modelling electric machines. The basic library provides the basic machines types such as dc machines, three phase induction machines, three phase permanent magnet synchronous machines and three phase reluctance machines. The three phase machine models are implemented on basis of space phasor theory. By contrast, the extended machines library models the winding topology of polyphase induction and permanent magnet synchronous machines. Such machine models can be used to simulate machines with arbitrary phase number such as large six phase induction machines or machines with winding asymmetries or even winding faults. The used winding models of the *ExtendedMachines* library are flexible enough to consider even higher field harmonics in future impementations.

1 General

Each of the presented machine models considers linear inductors. This means that neither saturation effects nor skin effects are considered yet. Iron losses such as eddy current and hysteresis losses are not taken into account. All resistive parameters are assumed to be constant, therefore machines are modeled without thermal behavior. Friction and ventilation losses are not considered. For the basic *Machines* library symmetrical three phase windings are assumed for induction machines, synchronous machines and reluctance machines. The extended library supports an arbitrary number of stator and rotor phases including possible asymmetries.
Any leakage inductances and ohmic resistors of the windings are modelled as discrete elements. These elements are connected between machine terminals (*MultiPhase* plugs or regular pins) and the air gap model.
All quantities accessible at the electrical and mechanical connectors are shown in physical units, not as p.u. values. This allows the coexistence of different machines in a complex system model.

2 Basic Machines Library

The basic elements of the *Machines* libraries are the air gap models. These elements model the magnetic main flux in the air gap including induced voltages and the electromagnetic torque generation. This torque is directed to a mechanical `flange` connector representing the shaft as well as to a second mechanical `support` connector, representing the housing respectively the machine legs or flange where the reaction torque is noticeable. The airgap's `flange` is connected to the rotor's inertia, which is connected to the machine's `flange` (i.e. shaft). The airgap's `support` now is implicitly fixed but allows to add a `support` connector for the whole machine in the next release. Adding a `support` connector for the whole machine, besides the rotor's inertia also the stator's inertia will be needed as a parameter.
The Basic *Machines* library is structured as follows:

- `BasicMachines.AsynchronousInduction-Machines` containing machine models
- `BasicMachines.SynchronousInduction-Machines` containing machine models
- `BasicMachines.DCMachines` containing machine models
- `BasicMachines.Components` contains elements like air gaps, squirrel cage and permanent magnet

- `Sensors` provides voltage and current RMS sensors (using space phasor functions), electrical and mechanical power sensor, as well as a sensor calculating the phase angle between the rotor and the rotating field. Voltage and current RMS sensors actually calculate the $\frac{1}{\sqrt{2}}$-fold of the magnitude of the current and voltage space phasor, respectively. The outputs of these sensors equal the RMS values of the currents and voltages for sinusoidal and stationary operation (only).

- `SpacePhasors.Components` provides the basic transformation element between three phase instantaneous voltages and currents and their space phasor representation, including zero sequence system

- `SpacePhasors.Blocks` implements space phasor transformation blocks to support the design of controllers

- `SpacePhasors.Functions` provides the same functionality as blocks but implemented as functions for use in initial equations

- `Interfaces` defines the space phasor connector as described later as well as some partial machine models, defining the common mechanical connectors

- `Examples` demonstrate the usage of the machine models as well as some utilities (used for the examples)

All machine models ensure correct initialization and efficient integration by using appropriate `stateSelect`-modifiers.

2.1 DC Machines

For the dc machines an air gap model is used which evaluates the (perpendicular) two axis equations of the armature and field excitation circuit. The air gap model has two electric pins, for the armature and the field excitation circuit each. The mechanical connectors `flange` and `support` are connected with the rotor's inertia and the implicitly fixed housing, respectively. The equations of the air gap model considers

- the induced voltage of the armature (electromotive force and emf $v_{a.i}$, respectively) due to magnetic field and rotor movement,

- the voltage drop of the excitation winding due to the time derivative of the magnetic main flux, and

- the electromagnetic torque which is directed to `flange` and `support`.

The armature voltage equation reads:

$$v_a = R_a i_a + L_a \frac{\mathrm{d}i_a}{\mathrm{d}t} + v_{a.i} \tag{1}$$

where $R_a i_a$ and $L_a \frac{\mathrm{d}i_a}{\mathrm{d}t}$ are modelled as discrete elements and $v_{a.i}$ is calculated by the air gap model. The excitation voltage equation reads:

$$v_e = R_e i_e + v_{e.i} \tag{2}$$

where $R_e i_e$ is modelled as discrete element and the induced (inner) voltage $v_{e.i}$ is calculated by the air gap model. Excitation voltage equation (2) is used for electrically excited dc machines, only.
The air gap model uses the following voltage equations:

$$v_{a,i} = \texttt{TurnsRatio} \cdot \psi_e \omega \tag{3}$$

$$v_{e,i} = \frac{\mathrm{d}\psi_e}{\mathrm{d}t} \tag{4}$$

as well as the flux linkage equation:

$$\psi_e = L_e i_e \tag{5}$$

and the torque equation:

$$\tau = \texttt{TurnsRatio} \cdot \psi_e i_a \tag{6}$$

Parameter `TurnsRatio` (between armature and excitation winding) is calculated internally from rating plate values. For an electrically excited dc machine the defining equation is:

$$v_{a,\mathrm{nom}} - R_a i_{a,\mathrm{nom}} = \texttt{TurnsRatio} \cdot (L_e i_{e,\mathrm{nom}})\, \omega_{\mathrm{nom}} \tag{7}$$

Therefore the electrical parameters of the dc machine models are the armature resistance R_a and field excitation resistance R_e (except permanent magnet machine), armature inductance L_a, field inductance L_e (except permanent magnet machine) as well as nominal values from the rating plate: $v_{a,\mathrm{nom}}$, $i_{a,\mathrm{nom}}$, ω_{nom} and $i_{e,\mathrm{nom}}$ (only for electrically excited dc machines).
The *Machines* library provides the following types of dc machines:

- `DC_ElectricalExcited`: model of an electrically excited dc machine which can either be connected as separate excited or shunt excited machine.
- `DC_SeriesExcited`: model of an electrically excited dc machine with series excitation; the only to difference to `DC_ElectricalExcited` is a modified assignment of parameters due to different rating plate data.
- `DC_PermanentExcited`: the magnetic field is provided by a permanent magnet which is modelled internally as a constant current source in the field excitation circuit.

2.2 Induction Machines

All three phase machines of the basic *Machines* library rely on space phasor theory [1]. For each system of three instantaneous voltages v_1, v_2 and v_3 a space phasor (indicated by underline) can be defined:

$$\underline{v} = \frac{2}{3}(v_1 + e^{\mathrm{j}2\pi/3} v_2 + e^{-\mathrm{j}2\pi/3} v_3) \qquad (8)$$

The factor $\frac{2}{3}$ in this equation is an arbitrary factor which is due to normalization reasons. Similar to (8) a space phasor of three instantaneous currents can be defined. The current space phasor can be interpreted as a vector representing the fundamental harmonic of the magnetomotive force (mmf) of the three phase currents. The direction of the phasor represents the phase angle, the length of the phasor represents the peak value of the fundamental mmf.
Therefore a space phasor connector is defined in the library. Both the voltage and the current space phasors are combined in the `SpacePhasor` connector. Real and imaginary part of voltage and current are stored in two elements of an array, respectively.
Space phasor theory is not restricted to any waveforms of voltages and currents in the time domain. Due to a given winding topology mainly the fundamental space harmonics of the electromagnetic quantities such as flux density and the mmf are physically present [2]. The harmonics of the electromagnetic quantities refer to the spatial domain along the tangential direction in the air gap. The restriction of space phasor theory is, that it only takes the fundamentals of these quantities into account. Higher harmonic components cannot be considered.

The mathematically correct formalism of space phasor theory requires a third transformed quantity, because the three original quantities (index 1,2 and 3) have to be linearly transformed into three transformed quantities. The third quantity is the zero sequence component:

$$v_0 = \frac{1}{3}(v_1 + v_2 + v_3) \qquad (9)$$

Any zero sequence quantity does not contribute to the fundamental of the main field due to the symmetry of the windings.
From (8) and (9) we determine the equations for back transformation:

$$v_1 = v_0 + \mathrm{Re}\left(\underline{v}\right) \qquad (10)$$

$$v_2 = v_0 + \mathrm{Re}\left(e^{-\mathrm{j}2\pi/3}\underline{v}\right) \qquad (11)$$

$$v_3 = v_0 + \mathrm{Re}\left(e^{\mathrm{j}2\pi/3}\underline{v}\right) \qquad (12)$$

Transformations (8) and (9) and (10)–(12) are modelled in element `SpacePhasors.Components.SpacePhasor`.
To describe the machine's behavior, first we need an equation for the stator voltages of the three phases ($i \in [1, 2, 3]$):

$$v_{Si} = R_S i_{Si} + \frac{\mathrm{d}\psi_{Si}}{\mathrm{d}t} \qquad (13)$$

Applying transformation (8) – neglecting the zero sequence system at the moment – on (13), we obtain the stator voltage space phasor equation in a stator fixed reference (coordinate) system (indicated by index (S)):

$$\underline{v}_{S(S)} = R_S \underline{i}_{S(S)} + \frac{\mathrm{d}\underline{\psi}_{S(S)}}{\mathrm{d}t} \qquad (14)$$

It is possible to split the stator flux linkage $\underline{\psi}_{S(S)}$ into main flux $\underline{\psi}_{m(S)}$ and leakage flux:

$$\underline{\psi}_{S\sigma(S)} = L_{s\sigma} \underline{i}_{S(S)} \qquad (15)$$

This leads to:

$$\underline{v}_{S(S)} = R_S \underline{i}_{S(S)} + L_{S\sigma}\frac{\mathrm{d}\underline{i}_{S(S)}}{\mathrm{d}t} + \frac{\mathrm{d}\underline{\psi}_{m(S)}}{\mathrm{d}t} \qquad (16)$$

Similarly we obtain the rotor voltage equation using space phasors in a fixed rotor reference (coordinate) system (indicated by index (R)):

$$\underline{v}_{R(R)} = R_R \underline{i}_{R(R)} + L_{R\sigma}\frac{\mathrm{d}\underline{i}_{R(R)}}{\mathrm{d}t} + \frac{\mathrm{d}\underline{\psi}_{m(R)}}{\mathrm{d}t} \qquad (17)$$

The main flux linkage depends on the sum of stator and rotor phase current, formulated in a common reference (coordinate) system:

$$\underline{\psi}_m = L_m \left(\underline{i}_S + \underline{i}_R\right) \quad (18)$$

At last we need an equation for the electromagnetic torque; this may be done by setting up power balance:

$$\begin{aligned} p_{el} &= v_{S1}i_{S1} + v_{S2}i_{S2} + v_{S3}i_{S3} \\ &+ v_{R1}i_{R1} + v_{R2}i_{R2} + v_{R3}i_{R3} \end{aligned} \quad (19)$$

After some transformations we obtain:

$$p_m = m_{el}\omega_m \quad (20)$$

$$\tau_{el} = \frac{3}{2} p\,\mathrm{Im}\left(\underline{i}_S \underline{\psi}_m^*\right) \quad (21)$$

In the latter equation p represents the number of pole pairs. This equation is valid in any arbitrary reference frame. To avoid transformation of (16) to the rotor fixed reference frame, or, alternatively to transform (17) to the stator fixed reference frame – obeying the product rule of differentiation – the ohmic resistors R_S and R_R as well as the leakage inductances $L_{S\sigma}$ and $L_{R\sigma}$ are modelled as discrete three phase elements outside the air gap. The next element of the modelled voltage equation transforms the three phase system into space phasors which are connected with the air gap model (fig. 1).
The air gap model using the stator fixed reference frame `BasicMachines.Components.AirgapS` transforms the rotor current space phasor $\underline{i}_{R(R)}$ to the stator fixed reference frame and calculates main flux linkage $\underline{\psi}_{m(S)}$ from (18). Then it is possible to calculate $\frac{\mathrm{d}\underline{\psi}_{m(S)}}{\mathrm{dt}}$ and – after the transformation of $\underline{\psi}_{m(S)}$ to the rotor fixed reference frame – the term $\frac{\mathrm{d}\underline{\psi}_{m(R)}}{\mathrm{dt}}$.
The air gap model using the rotor fixed reference frame `BasicMachines.Components.AirgapR` transforms the stator current space phasor $\underline{i}_{S(S)}$ to the rotor fixed reference frame and calculates main flux linkage $\underline{\psi}_{m(R)}$ from (18). Then it is possible to calculate $\frac{\mathrm{d}\underline{\psi}_{m(R)}}{\mathrm{dt}}$ and – after transformation of $\underline{\psi}_{m(R)}$ to the stator fixed reference frame – the term $\frac{\mathrm{d}\underline{\psi}_{m(S)}}{\mathrm{dt}}$.
Additionally, both air gap models calculate the electromagnetic torque from (21).

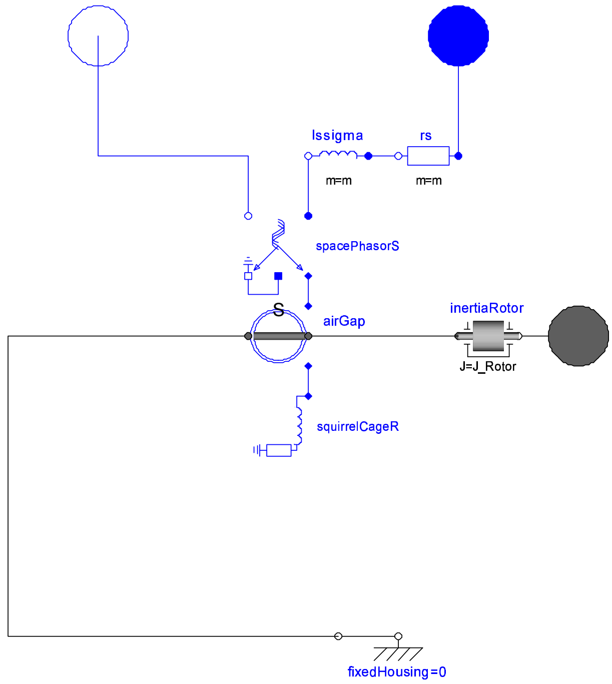

Figure 1: Asynchronous induction machine with squirrel cage; basic *Machines* library

The angular displacement between the rotor and the stator reference frame is:

$$\gamma = \int \omega_m dt \quad (22)$$

The transformation of a space phasor from a rotor fixed coordinate system to a stator fixed reference frame is performed by:

$$\underline{\psi}_{m(S)} = \underline{\psi}_{m(R)} \mathrm{e}^{\mathrm{j}\gamma} \quad (23)$$

The inverse transformation therefore is:

$$\underline{\psi}_{m(R)} = \underline{\psi}_{m(S)} \mathrm{e}^{-\mathrm{j}\gamma} \quad (24)$$

Although the zero system quantities do not contribute to the fundamental of the main field, they may give rise to additional leakage flux linkage components, though. Therefore, zero sequence connector `zero` is also provided in the `SpacePhasor` transformation model. If the zero sequence component connector is grounded, which is the regular case, no additional leakage flux linkages are taken into account [3].
Standard machine parameters are stator and rotor resistance R_s and R_r, stator and rotor leakage inductance $L_{s\sigma}$ and $L_{r\sigma}$, the main inductance L_m as well as the number of pole pairs p and rotor

inertia J. The following models of asynchronous induction machines are provided in the *Machines* library:

- `AIM_SquirrelCage` (asynchronous induction machine with squirrel cage): The squirrel cage is modelled as equivalent two axis winding model in the rotor circuit; the rotor is not accessible.

- `AIM_SlipRing` (asynchronous induction machine with wound rotor winding and slip rings): The rotor is equipped with a symmetrical rotor winding; this winding topology requires an additional parameter `TurnsRatio` which represents the effective ratio of stator to rotor turns of the respective three phase windings.

2.3 Permanent Magnet Synchronous Machine

The permanent magnet synchronous machine has the same stator winding topology as an asynchronous induction machine. Since the developed models are equipped with a damper winding, rotor winding topology is comparable with a squirrel cage induction machine. Synchronous machines without damper cage have to have control in order to work stable; they are therefore not provided in the current basic *Machines* library.
Saliencies of the rotor are considered through different main field inductances in the d- and q-axis (direct and quadrature axis) L_{md} and L_{mq}. We have to use the rotor fixed reference frame to consider these saliencies correctly.
Currently there are only two models provided:

- `SM_PermanentMagnetDamperCage`: The permanent magnet is modelled by means of a superimposed constant current source in the direct axis.

- `SM_ReluctanceRotorDamperCage` (synchronous induction machine with reluctance rotor): The rotor has a squirrel cage; electromagnetic torque in synchronism is generated due to saliencies of the rotor only.

3 Extended Machines Library

The *ExtendedMachines* library models are not restricted to three phases and symmetrical windings.

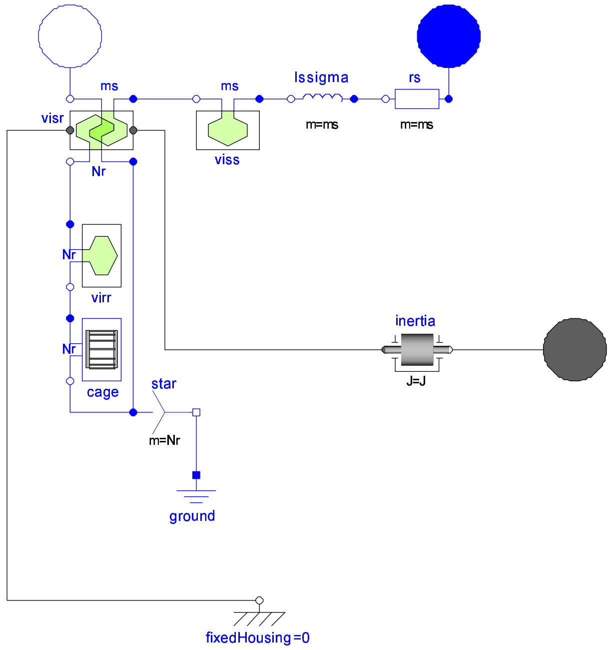

Figure 2: Extended model of a squirrel cage induction machine

The focus of this library is polyphase asynchronous and synchronous induction machines. The provided types of machines are squirrel cage and slip ring asynchronous induction machines as well as permanent magnet synchronous machines. For each of these models two implementations are provided. The *symmetrical* implementation assumes symmetrical windings in the stator and rotor of the polyphase induction machines. The *winding topology* implementation models the topology of each stator and rotor winding including possible asymmetries and winding faults. For these reasons, space phasor theory is not applicable to the *ExtendedMachines* library models any more.

3.1 Voltage Equations

It is assumed that neither the number of phases of the stator m_s nor the number of phases of the rotor m_r is restricted to three.

The voltage equations of the machines are modelled graphically. The used models which represent the partial voltage drops are based on equations, though. Stator voltage equation for each of the $i \in [1, 2, ..., m_s]$ stator phases is:

$$v_{Si} = R_{Si} i_{Si} + L_{S\sigma i} \frac{\mathrm{d}i_{Si}}{\mathrm{d}t} + \sum_{j=1}^{m_S} L_{Si,Sj} \frac{\mathrm{d}i_{Sj}}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}t} \sum_{j=1}^{m_R} L_{Si,Rj} i_{Rj} \qquad (25)$$

In this equation $L_{Si,Sj}$ represents the mutual inductance between the stator phases i and j. For $i = j$ this term equals the self inductance of stator phase i. The voltage drops across the inductances $L_{Si,Sj}$ are modeled through `VoltageEquations.SelfInductance`. The syllable `Self` was chosen due to the fact the linkage refers to only one machine side (either stator or rotor), although mutual linkages are taken into account. The instance `viss` of such model is implemented in the graphical model of the squirrel cage induction machine, which shown in fig. 2.

The mutual inductance $L_{Si,Rj}$ between a stator phase i and a rotor phase j is dependent of the rotor angle (22). The voltage drops across this inductances with respect to the stator and rotor side (linkage) are processed in the instant `visr` (fig. 2) of `VoltageEquation.MutualInductance`. This model computes torque and is connected with the mechanical shaft (flange) and the support which is currently fixed. Once the basic *Machines* library provides a support connector of the machine, the *ExtendedMachines* library will provide such a connector, too.

Rotor voltage equation has basically the same structure as (25):

$$v_{Ri} = R_{Ri} i_{Ri} + L_{R\sigma i} \frac{\mathrm{d}i_{Ri}}{\mathrm{d}t} + \sum_{j=1}^{m_R} L_{Ri,Rj} \frac{\mathrm{d}i_{Rj}}{\mathrm{d}t} + \frac{\mathrm{d}}{\mathrm{d}t} \sum_{j=1}^{m_S} L_{Ri,Sj} i_{Sj} \qquad (26)$$

This equations have to be applied to each phase of the rotor winding. The voltage drop across mutual inductances is processed in instant `visr`, the voltage drops across the mutual and self inductances $L_{Ri,Rj}$ of the rotor side are processed in `virr`, which is also an instant of `VoltageEquations.SelfInductance`.

The air gap model of the basic *Machines* library is equivalent to the models `viss`, `visr` and `virr` in fig. 2.

For a slip ring induction machine the voltage drop across the rotor resistances R_{Ri} and the rotor leakage inductances $L_{R\sigma i}$ can be modeled in accordance with the stator model. For the squirrel cage asynchronous induction machine of fig. 2 these voltage drops are replaced by a sophisticated model of the cage with $m_r = N_r$ rotor bars. This model takes the connection of the bars and end rings of the real squirrel cage into account.

The effort of the *ExtendedMachines* models is the determination of parameters. In accordance to [4] each inductance of the stator side is designed in the fashion of:

$$L_{Si,Sj} = L w_{Si} w_{Sj} \xi_{pSi} \xi_{pSj} \,\mathrm{Re}(\xi_{zSi} \xi_{zSj}^*) \qquad (27)$$

In this equation L represents a base inductance, w_{Si} is the number of turns of phase i, ξ_{pSi} is the pitch factor of phase i and ξ_{zSi} is a complex winding factor which considers the topology of phase winding i with respect the stator reference frame. The inductances of the rotor side are based on equivalent equations. The mutual inductances of the stator and rotor inductances have to take the rotor angle (22) into account:

$$L_{Si,Rj} = L w_{Si} w_{Rj} \xi_{pSi} \xi_{pRj} \,\mathrm{Re}(\xi_{zSi} \xi_{zRj}^* \mathrm{e}^{-\mathrm{j}\gamma}) \qquad (28)$$

The only difference between this equations and (27) is the rotational phasor $\mathrm{e}^{-\mathrm{j}\gamma}$. The inductances of (28) depend on the rotor angle (22) and are therefore time dependent. Rotor skewing is not considered. In (28) the rotor or stator skewing is not considered.

So far only the first order space harmonics waves (fundamental) are taken into account. The machine models are going to be extended for higher space harmonics; this will be implemented in the near future.

3.2 Symmetrical Winding Models

The pitch factors of the symmetrical winding models are set to one without having any restrictions. The symmetrical topology is considered by

$$\xi_{zSi} = \mathrm{e}^{-\mathrm{j}2\pi i/m_S}, \qquad (29)$$

the product of the number of turns and the base inductance is derived from the magnetizing inductance L_m which is a (symmetrical) machine parameter.

The implemented models with respect to a symmetric winding are:

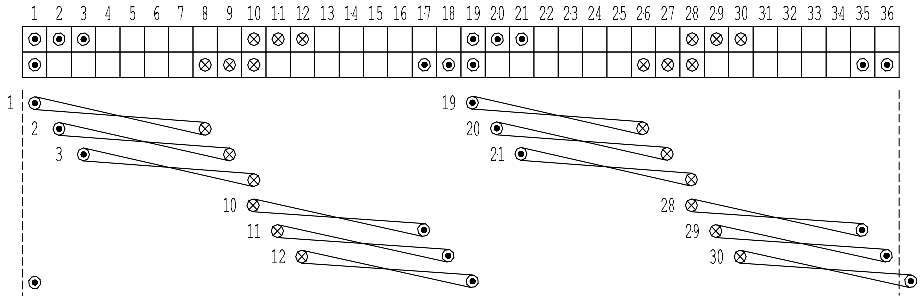

Figure 3: Topology of 7/9-pitch symmetrical three phase stator winding, phase 1

- `AIM_SlipRing`: Same parameters as basic *Machines* library; arbitrary numbers of stator and rotor phases are supported; symmetric winding

- `AIM_SquirrelCage`: Same parameters as basic *Machines* library; arbitrary number of stator phases and rotor bars is provided; symmetric stator winding; rotor may be modelled asymmetrically by overwriting rotor parameters

- `SM_PermanentMagnetDamperCage`: Same parameters as `SM_PermanentMagnetDamperCage` of the basic *Machines* library; arbitrary number of stator phases is supported; stator inductances are not constant due to the saliency of the rotor, which is considered; the rotor is equipped with a damper cage with an arbitrary number of bars; damper cage may be modelled asymmetrically by overwriting rotor parameters

- `SM_PermanentMagnet`: Same parameters as `SM_PermanentMagnetDamperCage`, without parameters of the damper cage, though

3.3 Winding Topology Models

The winding topology models can handle polyphase machines and even stator asymmetries and stator faults. For now, the only assumption with respect to winding topologies is, that the coil pitch of each winding has to be equal. Further developments will consider coils with unequal coil pitches, too. However, the coil pitches of stator and rotor windings do not have to be equal, though.

Structure wise there is no difference between the symmetrical implementation the topology implementation. Just the handling and pre-calculation of machine parameters is different. An example of the topology of one phase winding (phase 1) of a symmetrical three phase machine is shown in fig. 3. The location of each coil of the phases in terms of multiples of stator slots is indicated by matrix $y_S[i,j]$. The first index i indicates the phase, the second index j represents the of the number of the coil. The first row (phase 1) of this matrix with respect to the depicted winding in fig. 3 is:

$$y_S[1,:] = [1,2,3,19,20,21,10,\\ 11,12,28,29,30]$$

Since the orientations of the coils are not equal, matrix e is defined, which defines the orientation of each coil. In our example the first row (phase 1) of this matrix is:

$$e[1,:] = [+1,+1,+1,+1,+1,+1,\\ -1,-1,-1,-1,-1,-1]$$

The orientation $e[i,j]$ of a certain coil corresponds with the location $y_s[i,j]$ and the respective number of turns (each coil has 12 turns):

$$w_{cS}[1,:] = [12,12,12,12,12,12,\\ 12,12,12,12,12,12]$$

If the magnetic field caused by any coil is oriented up, the respective element in e equals $+1$, otherwise it equals -1. Parameter $y_{cs} = 7$ means that the coil pitch is seven slots. The total number of stator slots N_s is a model parameter, too.

For phase i the winding factors are:

$$\xi_{cSi} = \sin(p\frac{y_{cS}m_s}{N_s}) \quad (30)$$

$$\xi_{zSi} = \frac{1}{w_{Si}}\sum_j e[i,j]\mathrm{e}^{-\mathrm{j}py_S[i,j]\frac{2\pi}{N_s}} \quad (31)$$

The number of turns of $i \in [1, 2, ..., m_s]$ is:

$$w_{Si} = \sum_j w_{cS}[i,j] \quad (32)$$

Depending on the machine type, winding factors and the numbers of turns for the polyphase stator and rotor winding are derived in the initial sections of the machine models. These parameters are passed to the graphically modelled voltage equations as shown in fig. 2.
Currently the following machines with winding topology are modelled:

- `AIM_SlipRingWinding`: Same parameters as `AIM_SlipRing`; additionally, winding topology of stator and rotor winding has to be provided through data vectors which determine the exact orientation and arrangement of each coil.
- `AIM_SquirrelCageWinding`: Same parameters as `AIM_SquirrelCage`; additionally winding topology of stator has to be provided through data vectors which determine the exact orientation and arrangement of each coil; rotor topology has to be provided by the number of bars and the ratio of bar to end ring resistance as well as the ratio of bar to end ring leakage reactance; a symmetrical cage is predefined, certain parameters can be overwritten in the parameter window, though.
- `SM_PermanentMagnetWinding`: Same parameters as `SM_PermanentMagnet` of the basic *Machines* library; arbitrary numbers of stator phases are supported; stator inductances are not constant due to the saliency of the rotor, which is considered; additionally winding topology of stator has to be provided through data vectors which determine the exact orientation and arrangement of each coil; the machine has no damper cage.
- `SM_PermanentMagnetDamperCageWinding`: Same parameters as `SM_PermanentMagnetWinding`; arbitrary numbers of stator and rotor phases are supported; additionally winding topology of stator has to be provided through data vectors which determine the exact orientation and arrangement of each coil; the machine has a damper cage; a symmetrical cage is predefined, certain parameters can be overwritten in the parameter window, though, in order to simulate an asymmetrical damper cage.

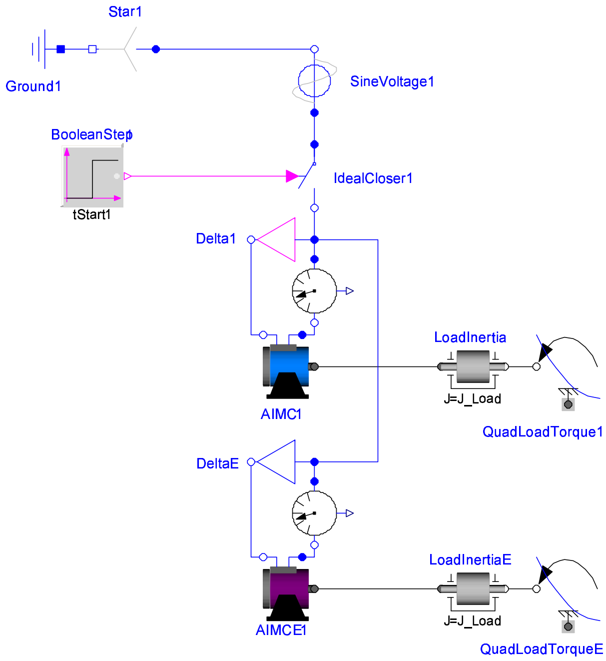

Figure 4: Direct start on line of squirrel cage induction machines; AIMC1 from basic *Machines* library, AIMCE1 from *ExtendedMachines* library

4 Example

To show the usage of the libraries, we will demonstrate simulation of starting an asynchronous induction machine with squirrel cage direct on line. Figure 4 presents the model using the basic *Machines* library as well as the *ExtendedMachines* library:
Each `AIM_SquirrelCage`-model connected in delta is electrically connected through one three phase switch to a three phase sinusoidal voltage source from the `MultiPhase` library. Mechanically each machine is connected to an individual load, consisting of an inertia and a load torque which is quadratic dependent on speed. Standard machine parameters are used. Load inertia is the same

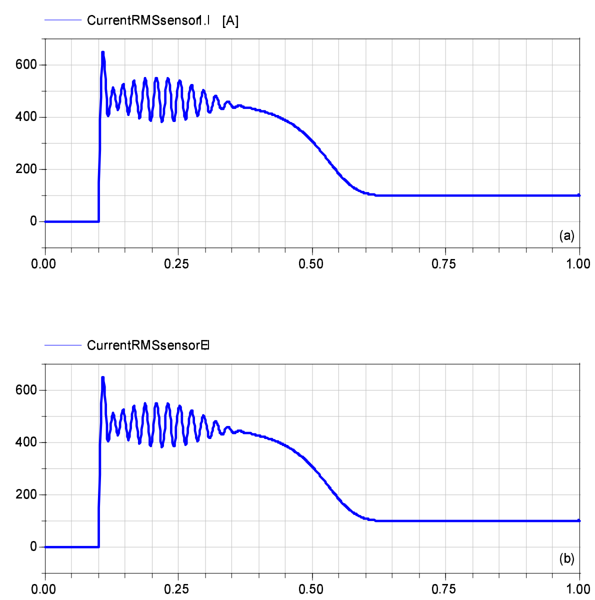

Figure 5: $\frac{1}{\sqrt{2}}$-fold of the magnitude of the current space phasor of the modelled squirrel cage machines (a) *Machines* library, (b) *ExtendedMachines* library

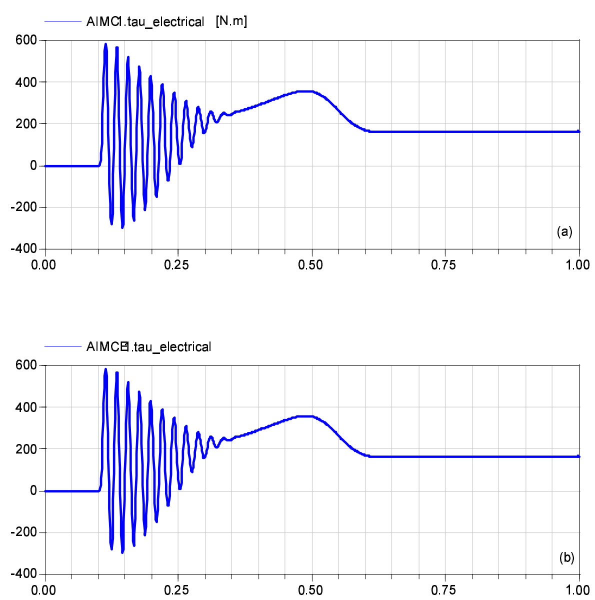

Figure 6: Electrical torque of the modelled squirrel cage machines (a) *Machines* library, (b) *ExtendedMachines* library

as the machine's inertia, and nominal load torque and speed are the same as the machine's rated values. After 0.1 seconds the switch is closed, high starting currents build up the magnetic field and each motor is able to develop starting torque, accelerating the inertias. The extended machines models was simulated with symmetrical stator windings and 28 rotor bars. The resulting currents of each machine are shown in fig. 5, the electrical torques are shown in fig. 6. These results demonstrate that both machine models have the same operational behavior.

5 Conclusions

The structure and basic equations of the basic *Machines* library using space phasors as well as the *ExtendedMachines* were presented. The *ExtendedMachines* library deals also with polyphase machines with arbitrary numbers of stator and rotor phases as well as asymmetrical or even faulty windings. The simulation results of both models were compared and match qualitatively and quantitatively.
Further developments will focus on:

- Implementation of a mechanical support connector representing the housing
- Additional machine types like electrically excited synchronous machines
- Modelling of iron, friction and stray losses
- Modelling of saturation effects of main and leakage inductances
- Modelling of skin effect in deep rotor bars
- Coupling of the electromagnetic models with thermal models [5]
- Modelling of higher field harmonics in space

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