M. Beuschel:

A Uniform Approach for Modeling Electrical Machines.

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A Uniform Approach for Modeling Electrical Machines

Michael Beuschel

Abstract

In this paper, an approach is presented that enables uniform modeling of different types of electrical machines using a novel Modelica library of magnetic components. Results of simulations with Dymola are presented. This approach is also applicable to education.

1 Introduction

Modelica provides a very general approach of modeling physical systems. Libraries for electrical and electronic as well as for mechanical components are already distributed on an open source code basis.

Based on this, a new library[1] for modeling rotational magnetic fields has been developed also including interfaces to electrical and mechanical components.

In this paper, rotary electro-magnetic motors are considered. Basically, different types of electrical machines employ the same physical principle: A magnetic field is produced that always tends towards a state of minimal energy. This is achieved by a change of the rotor position, which is the desired effect of a motor.

2 A Modelica Library of Magnetic Components

Calculation of magnetic circuits is often done using a notation similar to that of electrical circuits. Therefore, the *magnetic flux* ψ and the *magnetic potential difference* $\Delta\theta$ can be treated like current i and voltage v respectively. These are used in the following to model magnetic components.

2.1 Magnetic Connectors

As the focus of this paper is on modeling rotating electrical machines, both magnetic flux ψ_x, ψ_y and magnetic potential difference $\Delta\theta_x$, $\Delta\theta_y$ are used in 2-dimensional space vector representation including real and imaginary part (x- and y-axis respectively). This is reflected by the definition of *magnetic connectors* `MagP` and `MagN`, which only have different icons to identify more easily the pins of a component (see Fig. 1).

2.2 Basic Magnetic Components

Some basic magnetic components have been implemented (see Fig. 1).

- As in electrical circuits, a *magnetic ground* (`MagGround`) is mandatory in every magnetic circuit model to define the "magnetic potential" for simulation.[2]

$$\begin{aligned} \theta_x &= 0 \\ \theta_y &= 0 \end{aligned} \tag{1}$$

- A permanent magnet is a *magnetic source* (`MagSource`), that generates a magnetic potential difference $\Delta\theta$ with angular orientation β.

$$\begin{aligned} \Delta\theta_x &= \Delta\theta \cos(\beta) \\ \Delta\theta_y &= \Delta\theta \sin(\beta) \end{aligned} \tag{2}$$

- A *linear magnetic resistance* (`MagResistance`) connects the magnetic potential difference with the magnetic flux by

$$\begin{aligned} \psi_x R_m &= \Delta\theta_x \\ \psi_y R_m &= \Delta\theta_y \\ \text{with} \quad R_m &= N^2/M \end{aligned} \tag{3}$$

  The magnetic resistance R_m is determined by the number N of turns and the corresponding (electrical) inductance M. For 2-dimensional simulation, the above operation is calculated for the real and imaginary part of the magnetic field separately.

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[1] For details on the Modelica implementation, please see the appendix.

Figure 1: Basic magnetic components

Employing basic magnetic components, interfaces to electrical and mechanical components are discussed in the next section (see Fig. 2).

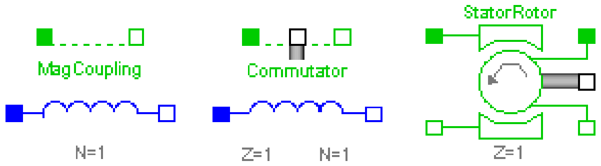

Figure 2: Magnetic interface components

2.3 Magnetic Coupling

A *linear magnetic coupling* (`MagCoupling`) is based on the electrical `OnePort` class. It relates electrical voltage v and current i to magnetic potential difference and flux due to the induction law. An additional scaling factor k adjusts magnetic to electrical values due to simplified modeling and field geometry.

$$\begin{aligned} v &= -\frac{N}{k}\left(\cos(\beta)\,\frac{d\psi_x}{dt} + \sin(\beta)\,\frac{d\psi_y}{dt}\right) \end{aligned} \tag{4}$$

$$\begin{aligned} \Delta\theta_x &= k\,N\,i\cos(\beta) \\ \Delta\theta_y &= k\,N\,i\sin(\beta) \end{aligned} \tag{5}$$

N is the number of turns; β gives the orientation of the winding. Combining a magnetic coupling with a magnetic resistance (3), the well known equation $v = -M\,di/dt$ of an inductance is obtained.

2.4 Commutator

A *commutator* block (`Commutator`) is based on the block magnetic coupling with additional rotation of the magnetic field orientation due to the function of a commutator in DC machines.

As the winding of a rotor moves forward the magnetic field rotates backwards in the rotor coordinate system. This is why the negative mechanical angle $-Z\varphi$ is used here instead of β. Z scales the mechanical angle to obtain the magnetic one, where Z is half the number of poles. The mechanical connector `flange_b` can be connected to components of the `Modelica.Mechanics.Rotational` library.

2.5 Stator and Rotor

To model the interaction between the stationary and rotational part of electrical machines, a *stator rotor* block (`StatorRotor`) is employed. It provides transformation between stator and rotor coordinates and calculates the mechanical torque τ from magnetic flux ψ_x, ψ_y and potential difference $\Delta\theta_x$, $\Delta\theta_y$.

$$\begin{aligned} 0 &= \psi_{1x} + \psi_{2x}\cos(Z\,\varphi) - \psi_{2y}\sin(Z\,\varphi) \\ 0 &= \psi_{1y} + \psi_{2x}\sin(Z\,\varphi) + \psi_{2y}\cos(Z\,\varphi) \end{aligned} \tag{6}$$

$$\begin{aligned} \Delta\theta_{1x} &= \Delta\theta_{2x}\cos(Z\,\varphi) - \Delta\theta_{2y}\sin(Z\,\varphi) \\ \Delta\theta_{1y} &= \Delta\theta_{2x}\sin(Z\,\varphi) + \Delta\theta_{2y}\cos(Z\,\varphi) \end{aligned} \tag{7}$$

$$\tau = -Z\,\psi_{2x}\,\Delta\theta_{2y} + Z\,\psi_{2y}\,\Delta\theta_{2x} \tag{8}$$

3 Modeling Electrical Machines Using the Magnetics Library

The components of the magnetics library have been tested implementing common electrical machines in the Dymola simulation environment. In Figure 3 the corresponding icons of a DC machine, a permanent magnet DC machine, an induction AC machine and a permanent magnet synchronous AC machine are displayed.

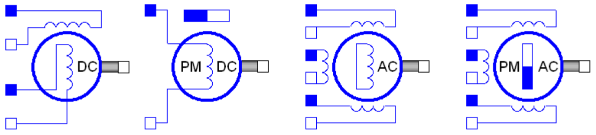

Figure 3: Electrical machine models (icons)

3.1 DC machine

Figure 4 shows the implementation of the DC machine. The stator winding provides the flux due to the stator current I_S through *PositivePin1* and *NegativePin1*. The related magnetic field is applied to the

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[2] In physics no magnetic monopole is known. Thus, the "magnetic potential" θ ist only used in the magnetic ground and the magnetic connector classes to distinguish from the magnetic potential difference $\Delta\theta$ that always needs two reference points.

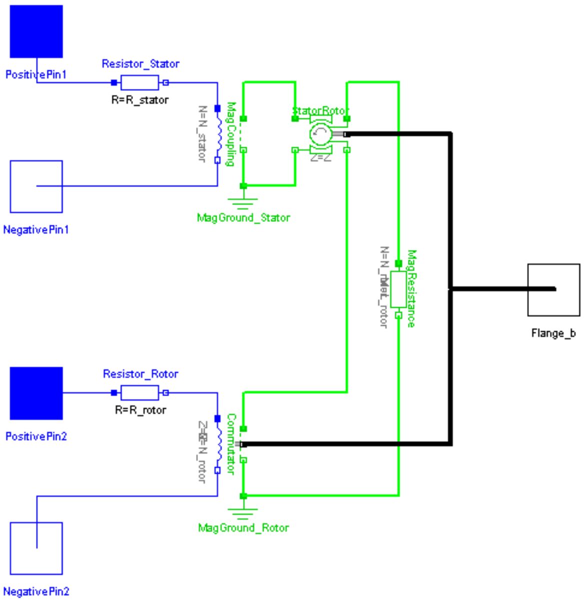

Figure 4: DC machine implementation

stator rotor block at an angle of 90° using a magnetic coupling block.

The magnetic resistance R_m is determined by the inductance L_R and the number N_R of turns of the rotor winding, which also has to match the corresponding commutator block.

The induced voltage (back emf) is calculated employing (4). Whereas the orientation of the flux is constant in stator coordinates, from the view point of the rotor coordinate system it rotates. This is achieved by introducing a commutator block. The number of poles ($2Z$) has to be identical for the stator rotor block as well as for the commutator, of course.

Employing the flux $\psi_S = \Delta\theta_S / R_m = L_S I_S / N_S$ of the stator winding and the magnetic potential difference $\Delta\theta_R = I_R N_R$ caused by the rotor current I_R through *PositivePin2* and *NegativePin2*, the torque τ the and induced voltage v_i of the DC machine can be calculated employing the machine constant $k_m = 2ZN_R/\pi$.

$$\tau = \frac{2}{\pi} \cdot Z \psi_S N_R I_R = k_m \psi_S \cdot \frac{\Delta\theta_R}{N_R} \tag{9}$$

$$v_i = \frac{2}{\pi} \cdot Z \psi_S N_R \omega = k_m \psi_S \omega \tag{10}$$

Assuming an ideal DC machine, the flux ψ_S is almost equally spread over $180°/Z$ of the airgap. In the same way, also the rotor current I_R is the same for alle turns (depending on the type of the rotor winding).

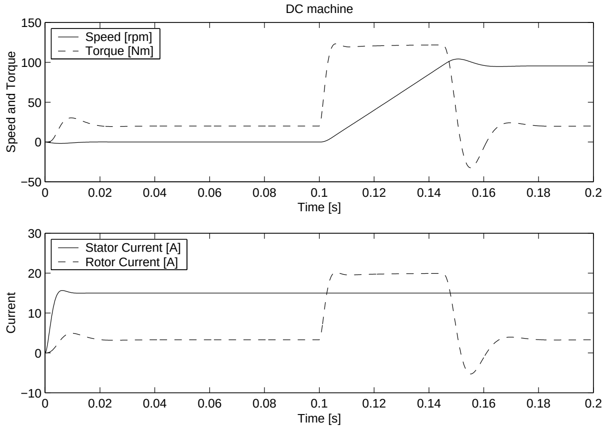

Figure 5: DC machine simulation results

However, as the magnetics library employs a space vector representation of the flux, a scaling factor $k = 2/\pi$ for the flux has to be introduced in the magnetic coupling block in order to model (9) and (10) correctly. Hence, the magnetic potential difference $\Delta\theta_y$ and, applying the magnetic ressistance R_m, the magnetic flux ψ_y are:

$$\Delta\theta_y = \frac{2}{\pi} \Delta\theta_S$$

$$\psi_y = \frac{2}{\pi} \psi_S$$

An acceleration procedure of this machine using another current controller for the rotor current I_R as well as a speed controller and applying a load torque of $20\,Nm$ has been simulated, see Fig. 5.

The data of the implemented DC machine are as follows:

Inductance Stator	L_S	=	6.4	H
Inductance Rotor	L_R	=	4.0	mH
Turns Stator Winding	N_S	=	2400	
Turns Rotor Winding	N_R	=	60	
Resistance Stator	R_S	=	1.0	Ω
Resistance Rotor	R_R	=	0.25	Ω
Number of Poles / 2	Z	=	4	
Mass Inertia	J	=	0.43	$kg\,m^2$

3.2 Permanent Magnet DC Machine

The DC machine has then been modified using a permanent magnet to provide the flux at an angle of 90° (see Fig. 6). The magnetic potential difference $\Delta\theta_y$ of the magnetic source is set to get the same flux ψ_y as above. The scaling factor k is included, too.

$$\Delta\theta_y = \frac{2}{\pi} \cdot I_S N_S \tag{11}$$

The same acceleration procedure as in Fig. 5 has been simulated, see Fig. 7.

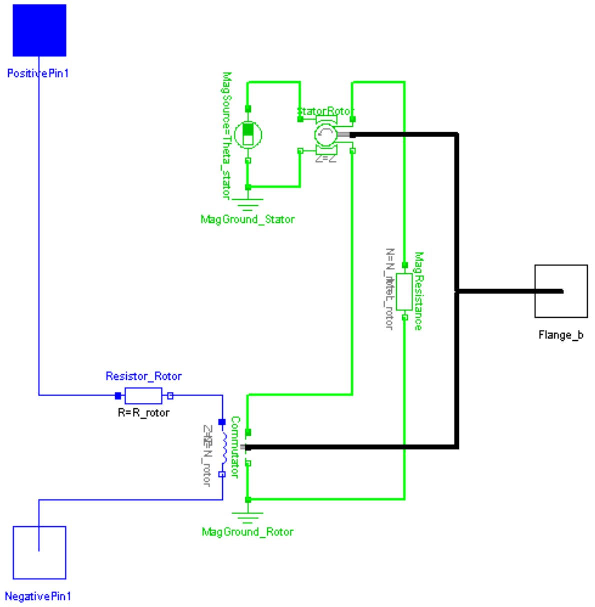

Figure 6: Permanent magnet DC machine implementation

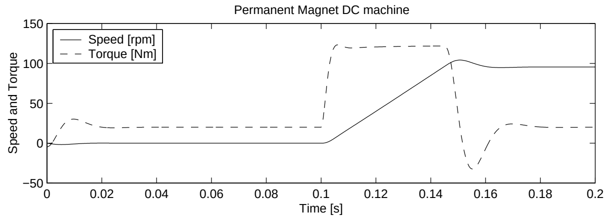

Figure 7: Permanent magnet DC machine simulation results

3.3 Simulation of an Induction AC Machine

Employing components of the magnetics library, also an induction AC machine has been implemented (see Fig. 8). The three stator windings are modeled separately, including resistance R_S and leakage inductance $L_{S\sigma}$ each. They are coupled to the magnetic circuit using magnetic coupling blocks at angular orientation of 0°, 120° and 240°.

The magnetic resistance R_m may either be applied to the stator or to the rotor side of the magnetic circuit (the first one is chosen here). The magnetic resistance is determined by the mutual inductance M and the number N_S of turns in each stator winding, which has to match the number of turns in the corresponding magnetic coupling blocks.

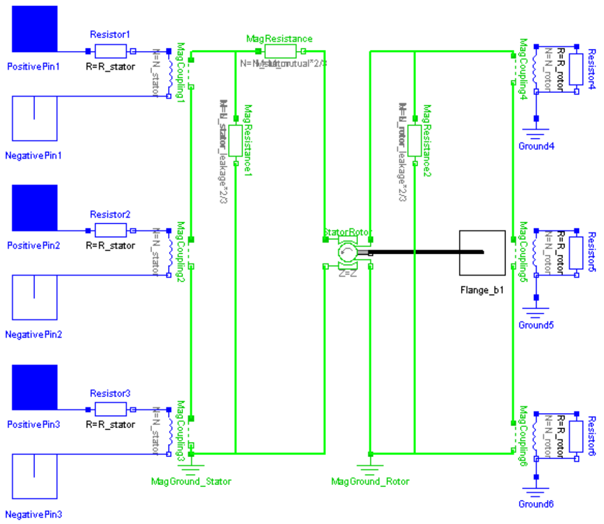

Figure 8: Induction AC machine implementation

Commonly, the mutual inductance M is referred to a single phase and is defined using the amplitude of the flux vector $|\vec{\psi}|$ and the peak phase current $\widehat{I}_S$.

$$M = N_S \frac{|\vec{\psi}|}{\widehat{I}_S} \tag{12}$$

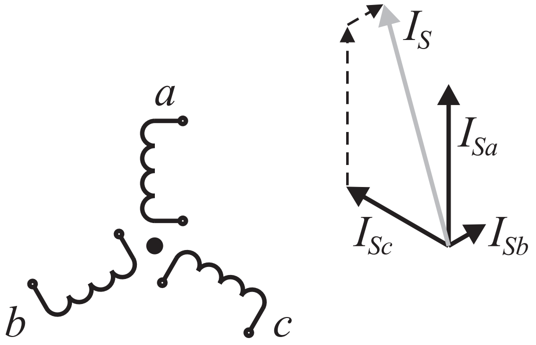

Figure 9: Space vector representation of stator current I_S

The amplitude of the magnetic potential difference vector $|\Delta\vec{\theta}|$ is (see also Fig. 9)

$$\begin{aligned} |\Delta\vec{\theta}| &= N_S \left| I_{Sa}(t) + I_{Sb}(t)\, e^{j120^\circ} + I_{Sc}(t)\, e^{j240^\circ} \right| \\ &= N \frac{3}{2} \widehat{I}_S \end{aligned} \tag{13}$$

which determines the actual magnetic resistance R_m using $|\vec{\psi}|$ and $|\Delta\vec{\theta}|$ as

$$R_m = \frac{|\Delta\vec{\theta}|}{|\vec{\psi}|} = \frac{N_S \frac{3}{2} \widehat{I}_S}{\frac{M}{N_S} \widehat{I}_S} = \frac{3}{2} \cdot \frac{N_S^2}{M} \tag{14}$$

The same calculation is applied to the leakage inductances $L_{S\sigma}$ and $L_{R\sigma}$.[3]

The rotor has to employ at least two windings at equally spaced angle. In the example in Fig. 8, a 3-phase rotor winding is modeled.

A start-up of this machine connected to symmetric 3-phase mains ($v_{eff} = 230V$, $f = 50Hz$) and applying a load torque of $20Nm$ has been simulated, see Fig. 10. The data of the implemented induction AC machine are as follows (all numbers of turns equal 1):

Leakage Inductance Stator	$L_{S\sigma}$	=	2.1	mH
Leakage Inductance Rotor	$L_{R\sigma}$	=	1.9	mH
Mutual Inductance	M	=	32.2	mH
Resistance Stator	R_S	=	324	$m\Omega$
Resistance Rotor	R_R	=	203	$m\Omega$
Number of Poles / 2	Z	=	3	
Mass Inertia	J	=	0.8	kgm^2

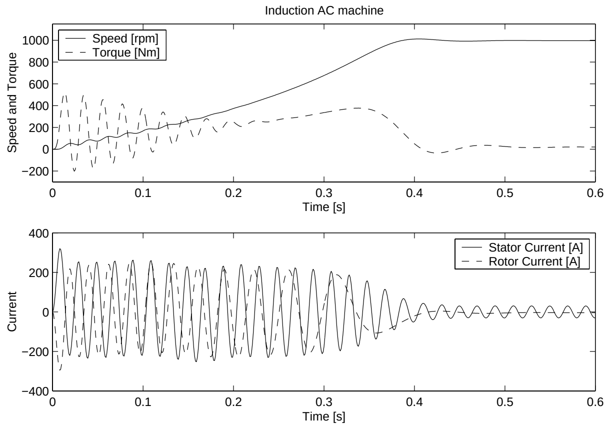

Figure 10: Induction AC machine simulation results

3.4 Permanent Magnet Synchronous AC Machine

Based on the above induction machine, a synchronous AC machine has been simulated, where the rotor flux is provided by a permanent magnet (see Fig. 11). The stator is identical to the induction machine. At the rotor, a 2-pole damping winding has been introduced to obtain a smooth torque output without vector control.

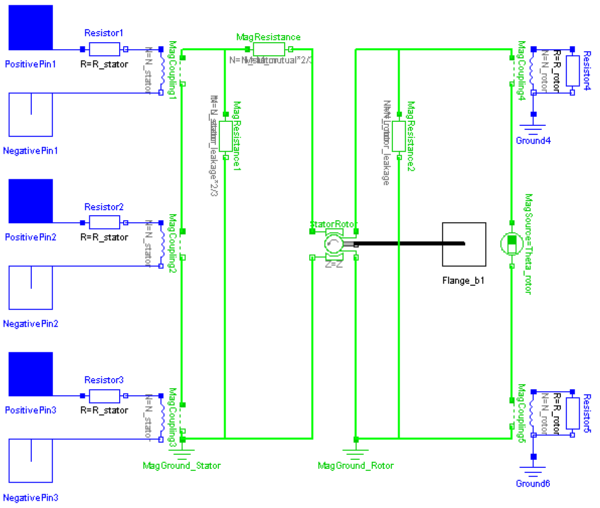

Figure 11: Synchronous AC machine implementation

Figure 12 shows simulation results of the synchronous AC machine. The stator windings have been connected to a frequency and amplitude sweep 3-phase supply. The magnetic source applies a magnetic potential difference $\Delta\theta = N_S I_S = 5A$ that corresponds to a flux of $\psi = \Delta\theta / R_m = 1.71Vs$. The data of the damping windings of the implemented machine are as follows:

Leakage Inductance Rotor	$L_{R\sigma}$	=	1.0	mH
Resistance Rotor	R_R	=	40	$m\Omega$

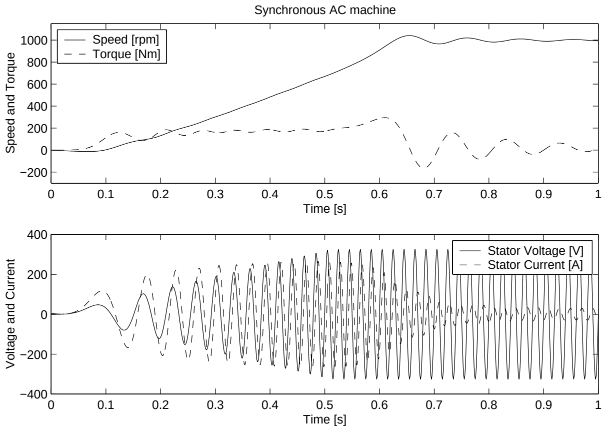

Figure 12: Synchronous AC machine simulation results

4 Conclusion

A new Modelica library of magnetic components has been implemented and tested simulating DC and AC

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[3] For an improved version of the magnetics library, 3 magnetic resistances related to the 3 windings should be employed rather than a single inductance. However, this would require angle sensitive magnetic resistances that are not yet implemented. Alternatively, the leakage inductances can also be implemented in the electrical circuits.

machines. Simulation results have been validated using conventional motor models.

The presented approach enables a uniform and intuitive modeling of different types of electrical machines. It also shows that different types of electrical machines employ the same basic principles. Therefore, this approach might be attractive especially for education purposes.

However, due to redundant model variables compared to conventional models, the presented approach is not optimized in terms of simulation efficiency. It also appears to be numerically more sensitive. Therefore, the quality of simulation results significantly depends on the integration algorithm and its tolerance setting.

5 Outlook

Further investigations should be done regarding the magnetics library itself as well as its application.

A variable magnetic resistance, a nonlinear magnetic resistance $R_m(\Delta\theta)$ and a magnetic resistance $R_m(\beta)$ with angular orientation should be introduced to enable modeling of e.g. saturation, variable air gap and reluctance effects (e.g. switched reluctance motors). Furthermore, the existing components can be improved employing a vector implementation. This would extend the library to 3-dimensional modeling (e.g. of magnetic bearings).

The presented models of electrical machines can then be refined and extended, e.g. by modeling leakage effects by individual magnetic components. In addition, also other magnetic devices such as 1-phase and 3-phase transformers can be modeled employing the magnetics library.

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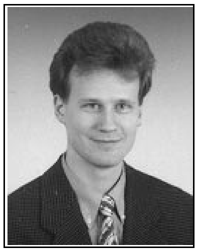

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Since 1996 he has been with the Power Electronics and Electrical Drives Department of the Technical University of Munich as a research assistant. His research interests include signal analysis as well as nonlinear control applications of electrical drives.

Appendix:
Modelica Package ”Magnetics”

This package will become available on the Modelica homepage http://www.Modelica.org/library/library.html.

```
package Magnetics

  connector MagP "Positive magnetic pin"
    SIunits.MagneticPotentialDifference theta_x;
    SIunits.MagneticPotentialDifference theta_y;
    flow SIunits.MagneticFlux psi_x;
    flow SIunits.MagneticFlux psi_y;
  end MagP;

  connector MagN "Negative magnetic pin"
    SIunits.MagneticPotentialDifference theta_x;
    SIunits.MagneticPotentialDifference theta_y;
    flow SIunits.MagneticFlux psi_x;
    flow SIunits.MagneticFlux psi_y;
  end MagN;

  class MagGround "Magnetic ground"
    Modelica.Electrical.Analog.Magnetics.MagP mag_p;
  equation
    mag_p.theta_x = 0;
    mag_p.theta_y = 0;
  end MagGround;

  class MagSource "Magnetic potential difference source"
    parameter SIunits.Angle beta=1e-8;
    parameter SIunits.MagneticPotentialDifference theta=1;
    SIunits.MagneticPotentialDifference theta_x;
    SIunits.MagneticPotentialDifference theta_y;
    Modelica.Electrical.Analog.Magnetics.MagP mag_p;
    Modelica.Electrical.Analog.Magnetics.MagN mag_n;
  equation
    theta_x = mag_p.theta_x - mag_n.theta_x;
    theta_y = mag_p.theta_y - mag_n.theta_y;
    0 = mag_p.psi_x + mag_n.psi_x;
    0 = mag_p.psi_y + mag_n.psi_y;
    theta_x = theta*cos(beta);
    theta_y = theta*sin(beta);
  end MagSource;

  class MagResistance "Magnetic resistance"
    parameter Real N(final min=0) = 1;
    parameter SIunits.Inductance M = 1;
    SIunits.MagneticPotentialDifference theta_x;
    SIunits.MagneticPotentialDifference theta_y;
    SIunits.MagneticFlux psi_x;
    SIunits.MagneticFlux psi_y;
```

```
  Modelica.Electrical.Analog.Magnetics.MagP mag_p;
  Modelica.Electrical.Analog.Magnetics.MagN mag_n;
equation
  theta_x = mag_p.theta_x - mag_n.theta_x;
  theta_y = mag_p.theta_y - mag_n.theta_y;
  0 = mag_p.psi_x + mag_n.psi_x;
  0 = mag_p.psi_y + mag_n.psi_y;
  psi_x = mag_p.psi_x;
  psi_y = mag_p.psi_y;
  N*N*psi_x = M*theta_x;
  N*N*psi_y = M*theta_y;
end MagResistance;


class MagCoupling "Linear magnetic coupling"
  extends Modelica.Electrical.Analog.Interfaces.OnePort;
  parameter SIunits.Angle beta = 1e-8 "Mag. Field Orient.";
  parameter Real N(final min=0) = 1 "Number of Turns";
  parameter Real k(final min=0) = 1 "Scaling Factor";
  SIunits.MagneticPotentialDifference theta_x;
  SIunits.MagneticPotentialDifference theta_y;
  SIunits.MagneticFlux psi_x;
  SIunits.MagneticFlux psi_y;
  Modelica.Electrical.Analog.Magnetics.MagP mag_p;
  Modelica.Electrical.Analog.Magnetics.MagN mag_n;
equation
  theta_x = mag_p.theta_x - mag_n.theta_x;
  theta_y = mag_p.theta_y - mag_n.theta_y;
  0 = mag_p.psi_x + mag_n.psi_x;
  0 = mag_p.psi_y + mag_n.psi_y;
  psi_x = mag_p.psi_x;
  psi_y = mag_p.psi_y;
  v = -N/k*cos(beta)*der(psi_x) - N/k*sin(beta)*der(psi_y);
  theta_x = N*k*i*cos(beta);
  theta_y = N*k*i*sin(beta);
end MagCoupling;


class Commutator "Commutator with magnetic coupling"
  extends Modelica.Electrical.Analog.Interfaces.OnePort;
  parameter Real Z(final min=0) = 1 "Number of Poles / 2";
  parameter Real N(final min=0) = 1 "Number of Turns";
  parameter Real k(final min=0) = 1 "Scaling Factor";
  SIunits.Angle phi "Rotational Magnetic Angle";
  SIunits.MagneticPotentialDifference theta_x;
  SIunits.MagneticPotentialDifference theta_y;
  SIunits.MagneticFlux psi_x;
  SIunits.MagneticFlux psi_y;
  Modelica.Electrical.Analog.Magnetics.MagP mag_p;
  Modelica.Electrical.Analog.Magnetics.MagN mag_n;
  Modelica.Mechanics.Rotational.Interfaces.Flange_b flange_b;
equation
  theta_x = mag_p.theta_x - mag_n.theta_x;
  theta_y = mag_p.theta_y - mag_n.theta_y;
  0 = mag_p.psi_x + mag_n.psi_x;
  0 = mag_p.psi_y + mag_n.psi_y;
  psi_x = mag_p.psi_x;
  psi_y = mag_p.psi_y;
  0 = flange_b.tau;
  phi = -flange_b.phi*Z;
  v = -N/k*cos(phi)*der(psi_x) - N/k*sin(phi)*der(psi_y);
  theta_x = N*k*i*cos(phi);
  theta_y = N*k*i*sin(phi);
end Commutator;


class StatorRotor "Stator and rotor of electric machines"
  parameter Real Z(final min=0) = 1 "Number of Poles / 2";
  SIunits.Angle phi(final start=1e-8) "Rotational Angle";
  SIunits.MagneticPotentialDifference theta_1x "port 1";
  SIunits.MagneticPotentialDifference theta_1y "port 1";
  SIunits.MagneticPotentialDifference theta_2x "port 2";
  SIunits.MagneticPotentialDifference theta_2y "port 2";
  SIunits.MagneticFlux psi_1x "port 1";
  SIunits.MagneticFlux psi_1y "port 1";
  SIunits.MagneticFlux psi_2x "port 2";
  SIunits.MagneticFlux psi_2y "port 2";
equation
  theta_1x = mag_1p.theta_x - mag_1n.theta_x;
  theta_1y = mag_1p.theta_y - mag_1n.theta_y;
  theta_2x = mag_2p.theta_x - mag_2n.theta_x;
  theta_2y = mag_2p.theta_y - mag_2n.theta_y;
  0 = mag_1p.psi_x + mag_1n.psi_x;
  0 = mag_1p.psi_y + mag_1n.psi_y;
  0 = mag_2p.psi_x + mag_2n.psi_x;
  0 = mag_2p.psi_y + mag_2n.psi_y;
  psi_1x = mag_1p.psi_x;
  psi_1y = mag_1p.psi_y;
  psi_2x = mag_2p.psi_x;
  psi_2y = mag_2p.psi_y;
  flange_b.tau = Z*psi_2x*theta_2y - Z*psi_2y*theta_2x;
  phi = flange_b.phi*Z;
  0 = psi_1x + psi_2x*cos(phi) - psi_2y*sin(phi);
  0 = psi_1y + psi_2x*sin(phi) + psi_2y*cos(phi);
  theta_1x = theta_2x*cos(phi) - theta_2y*sin(phi);
  theta_1y = theta_2x*sin(phi) + theta_2y*cos(phi);
end StatorRotor;


class DC_machine "DC machine using magnetic elements"
  parameter Real Z(final min=0) = 4 "Number of Poles / 2";
  parameter Real L_rotor(final min=0) = 0.004;
  parameter Real N_stator(final min=0) = 2400;
  parameter Real N_rotor(final min=0) = 60;
  parameter Real R_stator(final min=0) = 1;
  parameter Real R_rotor(final min=0) = 0.25;

  Modelica.Electrical.Analog.Interfaces.PositivePin
      PositivePin1;
  Modelica.Electrical.Analog.Interfaces.NegativePin
      NegativePin1;
  Modelica.Electrical.Analog.Interfaces.PositivePin
      PositivePin2;
  Modelica.Electrical.Analog.Interfaces.NegativePin
      NegativePin2;
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor_Stator(R=R_stator);
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor_Rotor(R=R_rotor);
  Modelica.Electrical.Analog.Magnetics.MagCoupling
      MagCoupling(beta=3.14159/2, N=N_stator, k=2/3.14159);
  Modelica.Electrical.Analog.Magnetics.Commutator
      Commutator(Z=Z, N=N_rotor);
  Modelica.Electrical.Analog.Magnetics.MagGround
      MagGround_Stator;
  Modelica.Electrical.Analog.Magnetics.MagGround
      MagGround_Rotor;
  Modelica.Electrical.Analog.Magnetics.StatorRotor
      StatorRotor(Z=Z);
  Modelica.Electrical.Analog.Magnetics.MagResistance
      MagResistance(N=N_rotor, M=L_rotor);
  Modelica.Mechanics.Rotational.Interfaces.Flange_b
      Flange_b;
equation
  connect(PositivePin1, Resistor_Stator.p);
  connect(PositivePin2, Resistor_Rotor.p);
  connect(NegativePin2, Commutator.n);
  connect(NegativePin1, MagCoupling.n);
  connect(Resistor_Stator.n, MagCoupling.p);
  connect(Resistor_Rotor.n, Commutator.p);
  connect(MagCoupling.mag_p, StatorRotor.mag_1p);
  connect(MagCoupling.mag_n, StatorRotor.mag_1n);
  connect(MagGround_Stator.mag_p, MagCoupling.mag_n);
  connect(MagGround_Rotor.mag_p, Commutator.mag_n);
  connect(StatorRotor.mag_2p, MagResistance.mag_p);
  connect(MagResistance.mag_n, Commutator.mag_n);
  connect(Commutator.mag_p, StatorRotor.mag_2n);
  connect(StatorRotor.flange_b, Flange_b);
  connect(Commutator.flange_b, Flange_b);
end DC_machine;


class DC_PM_machine "Permanent magnet DC machine"
  parameter Real Z(final min=0) = 4 "Number of Poles / 2";
  parameter Real Theta_stator(final min=0) = 36000*2/3.14159
      "Stator mag. Pot. Diff.";
  parameter Real L_rotor(final min=0) = 0.004;
  parameter Real R_rotor(final min=0) = 0.25;
  parameter Real N_rotor(final min=0) = 60;

  Modelica.Electrical.Analog.Interfaces.PositivePin
      PositivePin1;
  Modelica.Electrical.Analog.Interfaces.NegativePin
      NegativePin1;
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor_Rotor(R=R_rotor);
  Modelica.Electrical.Analog.Magnetics.MagSource
      MagSource(beta=3.14159/2, theta=Theta_stator);
  Modelica.Electrical.Analog.Magnetics.StatorRotor
      StatorRotor(Z=Z);
  Modelica.Electrical.Analog.Magnetics.MagGround
      MagGround_Stator;
  Modelica.Electrical.Analog.Magnetics.MagGround
      MagGround_Rotor;
  Modelica.Electrical.Analog.Magnetics.MagResistance
      MagResistance(N=N_rotor, M=L_rotor);
  Modelica.Electrical.Analog.Magnetics.Commutator
      Commutator(Z=Z, N=N_rotor,
      psi_y(start=-Theta_stator*L_rotor/N_rotorˆ2));
  Modelica.Mechanics.Rotational.Interfaces.Flange_b
      Flange_b;
equation
  connect(StatorRotor.mag_2p, MagResistance.mag_p);
  connect(Resistor_Rotor.n, Commutator.p);
  connect(PositivePin1, Resistor_Rotor.p);
  connect(Commutator.n, NegativePin1);
  connect(MagResistance.mag_n, Commutator.mag_n);
  connect(MagGround_Stator.mag_p, StatorRotor.mag_1n);
  connect(MagGround_Rotor.mag_p, Commutator.mag_n);
  connect(Commutator.mag_p, StatorRotor.mag_2n);
  connect(StatorRotor.flange_b, Flange_b);
  connect(Commutator.flange_b, Flange_b);
  connect(MagSource.mag_p, StatorRotor.mag_1p);
  connect(MagSource.mag_n, MagGround_Stator.mag_p);
end DC_PM_machine;


class AC_machine ÄC induction machine"
  parameter Real Z(final min=0) = 3 "Number of Poles / 2";
  parameter Real M_mutual(final min=0) = 0.0322;
  parameter Real L_stator_leakage(final min=0) = 0.0021;
```

```
  parameter Real L_rotor_leakage(final min=0) = 0.0019;
  parameter Real N_stator(final min=0) = 1 "Stator turns";
  parameter Real N_rotor(final min=0) = 1 "Rotor turns";
  parameter Real R_stator(final min=0) = 0.324;
  parameter Real R_rotor(final min=0) = 0.203;

  Modelica.Electrical.Analog.Interfaces.PositivePin
      PositivePin1;
  Modelica.Electrical.Analog.Interfaces.NegativePin
      NegativePin1;
  Modelica.Electrical.Analog.Interfaces.NegativePin
      NegativePin2;
  Modelica.Electrical.Analog.Interfaces.PositivePin
      PositivePin2;
  Modelica.Electrical.Analog.Interfaces.NegativePin
      NegativePin3;
  Modelica.Electrical.Analog.Interfaces.PositivePin
      PositivePin3;
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor1(R=R_stator);
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor2(R=R_stator);
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor3(R=R_stator);
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor4(R=R_rotor);
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor5(R=R_rotor);
  Modelica.Electrical.Analog.Basic.Resistor
      Resistor6(R=R_rotor);
  Modelica.Electrical.Analog.Basic.Ground Ground4;
  Modelica.Electrical.Analog.Basic.Ground Ground5;
  Modelica.Electrical.Analog.Basic.Ground Ground6;
  Modelica.Electrical.Analog.Magnetics.MagCoupling
      MagCoupling1(beta=0, N=N_stator);
  Modelica.Electrical.Analog.Magnetics.MagCoupling
      MagCoupling2(beta=2*3.14159265/3, N=N_stator);
  Modelica.Electrical.Analog.Magnetics.MagCoupling
      MagCoupling3(beta=4*3.14159265/3, N=N_stator);
  Modelica.Electrical.Analog.Magnetics.MagGround
      MagGround_Stator;
  Modelica.Electrical.Analog.Magnetics.MagCoupling
      MagCoupling4(beta=0, N=N_rotor);
  Modelica.Electrical.Analog.Magnetics.MagCoupling
      MagCoupling5(beta=2*3.14159265/3, N=N_rotor);
  Modelica.Electrical.Analog.Magnetics.MagCoupling
      MagCoupling6(beta=4*3.14159265/3, N=N_rotor);
  Modelica.Electrical.Analog.Magnetics.MagGround
      MagGround_Rotor;
  Modelica.Electrical.Analog.Magnetics.MagResistance
      MagResistance(N=N_stator, M=M_mutual*2/3);
  Modelica.Electrical.Analog.Magnetics.MagResistance
      MagResistance1(N=N_stator, M=L_stator_leakage*2/3);
  Modelica.Electrical.Analog.Magnetics.MagResistance
      MagResistance2(N=N_rotor, M=L_rotor_leakage*2/3);
  Modelica.Electrical.Analog.Magnetics.StatorRotor
      StatorRotor(Z=Z);
  Modelica.Mechanics.Rotational.Interfaces.Flange_b
      Flange_b1;
equation
  connect(PositivePin1, Resistor1.p);
  connect(NegativePin1, MagCoupling1.n);
  connect(PositivePin2, Resistor2.p);
  connect(NegativePin2, MagCoupling2.n);
  connect(PositivePin3, Resistor3.p);
  connect(NegativePin3, MagCoupling3.n);
  connect(MagCoupling2.mag_n, MagCoupling3.mag_p);
  connect(MagCoupling3.mag_n, MagGround_Stator.mag_p);
  connect(MagCoupling4.n, Resistor4.n);
  connect(MagCoupling6.n, Resistor6.n);
  connect(MagCoupling5.n, Resistor5.n);
  connect(MagCoupling4.mag_n, MagCoupling5.mag_p);
  connect(MagCoupling5.mag_n, MagCoupling6.mag_p);
  connect(MagCoupling6.n, Ground6.p);
  connect(MagCoupling5.n, Ground5.p);
  connect(MagCoupling4.n, Ground4.p);
  connect(MagGround_Rotor.mag_p, MagCoupling6.mag_n);
  connect(MagCoupling1.mag_p, MagResistance.mag_p);
  connect(MagGround_Stator.mag_p, StatorRotor.mag_1n);
  connect(StatorRotor.mag_2p, MagCoupling4.mag_p);
  connect(MagGround_Rotor.mag_p, StatorRotor.mag_2n);
  connect(MagCoupling1.mag_n, MagCoupling2.mag_p);
  connect(MagResistance.mag_n, StatorRotor.mag_1p);
  connect(MagCoupling4.p, Resistor4.p);
  connect(MagCoupling5.p, Resistor5.p);
  connect(MagCoupling6.p, Resistor6.p);
  connect(StatorRotor.flange_b, Flange_b1);
  connect(MagResistance1.mag_p, MagResistance.mag_p);
  connect(MagResistance1.mag_n, MagGround_Stator.mag_p);
  connect(Resistor3.n, MagCoupling3.p);
  connect(Resistor2.n, MagCoupling2.p);
  connect(Resistor1.n, MagCoupling1.p);
  connect(MagResistance2.mag_p, StatorRotor.mag_2p);
  connect(MagResistance2.mag_n, MagGround_Rotor.mag_p);
end AC_machine;


class AC_PM_machine ÄC PM machine using magnetic elements"
  parameter Real Z(final min=0) = 3 "Number of Poles / 2";
  parameter Real Theta_rotor(final min=0) = 0.172*2/3.14159;
```

```
    parameter Real M_mutual(final min=0) = 0.0322;
    parameter Real L_stator_leakage(final min=0) = 0.0021;
    parameter Real L_rotor_leakage(final min=0) = 0.001;
    parameter Real N_stator(final min=0) = 1 "Stator turns";
    parameter Real N_rotor(final min=0) = 1 "Rotor turns";
    parameter Real R_stator(final min=0) = 0.324;
    parameter Real R_rotor(final min=0) = 0.04;

    Modelica.Electrical.Analog.Interfaces.PositivePin
        PositivePin1;
    Modelica.Electrical.Analog.Interfaces.NegativePin
        NegativePin1;
    Modelica.Electrical.Analog.Interfaces.NegativePin
        NegativePin2;
    Modelica.Electrical.Analog.Interfaces.PositivePin
        PositivePin2;
    Modelica.Electrical.Analog.Interfaces.NegativePin
        NegativePin3;
    Modelica.Electrical.Analog.Interfaces.PositivePin
        PositivePin3;
    Modelica.Electrical.Analog.Basic.Resistor
        Resistor1(R=R_stator);
    Modelica.Electrical.Analog.Basic.Resistor
        Resistor2(R=R_stator);
    Modelica.Electrical.Analog.Basic.Resistor
        Resistor3(R=R_stator);
    Modelica.Electrical.Analog.Basic.Resistor
        Resistor4(R=R_rotor);
    Modelica.Electrical.Analog.Basic.Resistor
        Resistor5(R=R_rotor);
    Modelica.Electrical.Analog.Basic.Ground Ground4;
    Modelica.Electrical.Analog.Basic.Ground Ground6;
    Modelica.Electrical.Analog.Magnetics.MagSource
        MagSource(beta=0, theta=Theta_rotor);
    Modelica.Electrical.Analog.Magnetics.MagCoupling
        MagCoupling1(beta=0, N=N_stator);
    Modelica.Electrical.Analog.Magnetics.MagCoupling
        MagCoupling2(beta=2*3.14159265/3, N=N_stator);
    Modelica.Electrical.Analog.Magnetics.MagCoupling
        MagCoupling3(beta=4*3.14159265/3, N=N_stator);
    Modelica.Electrical.Analog.Magnetics.MagCoupling
        MagCoupling4(beta=0, N=N_rotor,
        psi_x(start=Theta_rotor*M_mutual/N_rotorˆ2*2/3));
    Modelica.Electrical.Analog.Magnetics.MagCoupling
        MagCoupling5(beta=3.14159265/2, N=N_rotor);
    Modelica.Electrical.Analog.Magnetics.MagGround
        MagGround_Stator;
    Modelica.Electrical.Analog.Magnetics.MagGround
        MagGround_Rotor;
    Modelica.Electrical.Analog.Magnetics.MagResistance
        MagResistance(N=N_stator, M=M_mutual*2/3);
    Modelica.Electrical.Analog.Magnetics.MagResistance
        MagResistance1(N=N_stator, M=L_stator_leakage*2/3);
    Modelica.Electrical.Analog.Magnetics.MagResistance
        MagResistance2(N=N_rotor, M=L_rotor_leakage);
    Modelica.Electrical.Analog.Magnetics.StatorRotor
        StatorRotor(Z=Z);
    Modelica.Mechanics.Rotational.Interfaces.Flange_b
        Flange_b1;
  equation
    connect(PositivePin1, Resistor1.p);
    connect(NegativePin1, MagCoupling1.n);
    connect(PositivePin2, Resistor2.p);
    connect(NegativePin2, MagCoupling2.n);
    connect(PositivePin3, Resistor3.p);
    connect(NegativePin3, MagCoupling3.n);
    connect(MagCoupling2.mag_n, MagCoupling3.mag_p);
    connect(MagCoupling3.mag_n, MagGround_Stator.mag_p);
    connect(MagCoupling4.n, Resistor4.n);
    connect(MagCoupling5.n, Resistor5.n);
    connect(MagCoupling5.n, Ground6.p);
    connect(MagCoupling4.n, Ground4.p);
    connect(MagGround_Rotor.mag_p, MagCoupling5.mag_n);
    connect(MagCoupling1.mag_p, MagResistance.mag_p);
    connect(MagGround_Stator.mag_p, StatorRotor.mag_1n);
    connect(StatorRotor.mag_2p, MagCoupling4.mag_p);
    connect(MagGround_Rotor.mag_p, StatorRotor.mag_2n);
    connect(MagCoupling1.mag_n, MagCoupling2.mag_p);
    connect(MagResistance.mag_n, StatorRotor.mag_1p);
    connect(MagCoupling4.p, Resistor4.p);
    connect(MagCoupling5.p, Resistor5.p);
    connect(StatorRotor.flange_b, Flange_b1);
    connect(MagResistance1.mag_p, MagResistance.mag_p);
    connect(MagResistance1.mag_n, MagGround_Stator.mag_p);
    connect(Resistor3.n, MagCoupling3.p);
    connect(Resistor2.n, MagCoupling2.p);
    connect(Resistor1.n, MagCoupling1.p);
    connect(MagResistance2.mag_p, StatorRotor.mag_2p);
    connect(MagResistance2.mag_n, MagGround_Rotor.mag_p);
    connect(MagCoupling4.mag_n, MagSource.mag_p);
    connect(MagSource.mag_n, MagCoupling5.mag_p);
  end AC_PM_machine;


end Magnetics;
```