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Physical Modeling of Switched Reluctance Motors using Modelica

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***Abstract*—This paper presents a novel Modelica library for physical modeling of switched reluctance machines. In order to deal with the nonlinear characteristics of switched reluctance drives, an analytical approximation function is applied when building a motor model. Furthermore, the look-up table based approach derived by the finite element method for computing the nonlinear model is also considered. Compared with other modeling approaches, physical modeling using the object-oriented modeling language-Modelica often exhibits a significant progress regarding model reusability, flexibility and range of modeling. One application example with a 16 stator 12 rotor poles 4 phase witched reluctance machine is presented to illustrate the use of the developed Modelica switched reluctance machine library.**

***Index Terms*—switched reluctance machine, modeling and simulation, motion control.**

I. Introduction

A Switched reluctance machine is a doubly salient pole machine fed by an unipolar power converter. Concerning its simplicity, robustness, low cost and high efficiency, the switched reluctance machine become a good competitor to conventional ac machines in aircraft and automobile industry [1]. Some new research works have presented the possibility to use the switched reluctance machine as generator in more electric aircraft [2] and as major actuator in the upcoming electric vehicle. Computer modeling and simulation can ease the whole product development process and controller design. Model based design is getting more and more attention in the last years. However, current modeling tools supporting switched reluctance machines e.g. Simpower by Mathworks does not provide users full flexibility to build models. In this work, a switched reluctance drive library has been made using Modelica- an object oriented modeling language to achieve the maximum flexibility, motor type converge and model reusability. In this library, all needed fundamental components for modeling switched reluctance machine are addressed. Modelica is a non-proprietary, object-oriented, equation based language to conveniently model complex physical systems containing, e.g., mechanical, electrical, electronic, hydraulic, thermal, control, electric power. Modelica Simulation Environments are available commercially and free of charge, such as CATIA Systems, Dymola, LMS AMESim, JModelica.org, MapleSim, MathModelica, OpenModelica, SCICOS, SimulationX. Modelica models can be imported conveniently into Simulink using export features of Dymola, MapleSim and SimulationX. or process-oriented subcomponents. Considering the good support of the newest Modelica standard, the Dymola system is selected to implement the switched reluctance machine library.

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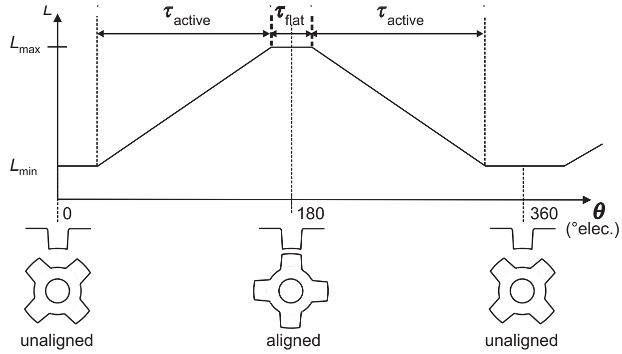

Fig. 1. Ideal inductance function of rotor position

II. Basic characteristics of SRM

A. Operation principle

In contrast to conventional DC-machine, synchronous and induction machine whose output torque can be presented by the vector product between current and magnetic field, switched reluctance machines work on the principle of reluctance force. The torque is developed from the physical nature of magnetic paths which always attempt to minize the magnetic resistance in the magnetic loop [3].

For the basic understanding, switched reluctance machines are often analyzed assuming linear operation without magnetic saturation in the iron lamination. This greatly simplifies the mathematical machine model since without the magnetic saturation the machine characteristic, i.e. phase inductance, can be considered as a function of rotor position only. In the linear consideration, the phase torque product of the switched reluctance machine is described as

$$T = \frac{1}{2} i^2 \frac{dL(\theta)}{d\theta} \tag{1}$$

Fig.1 shows the phase inductance curve as a function of rotor position for one electrical period. It starts at the rotor position with the minimum inductance defined as "unaligned position".

According to Eq. 1, torque can be produced in the position where the inductance gradient $dL(\theta)/d\theta$ is nonzero. Torque can be produced for both negative and positive directions. This also implies that switched reluctance machines are basically capable of breaking or generating operation. Note that the input current influences only the amplitude of the output torque due to the quadratic term i^2. Hence, the only possibility to command the direction of the output torque is controlling the phase excitation period according to the rotor position. The electrical characteristic of switched reluctance machines can be described by the generalized machine equation

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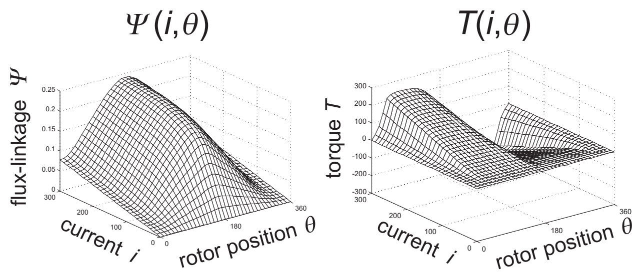

Fig. 2. Magnetic flux and torque functions of current and rotor position

$$v(t) = Ri(t) + \frac{d\Psi(t)}{dt} \qquad (2)$$

Substituting the $\Psi(t)$ by $L(\theta)i(t)$ Eq. 2 can be developed to

$$v(t) = Ri(t) + L(\theta)\frac{di(t)}{dt} + i\frac{dL(\theta)}{d\theta}\frac{d\theta}{dt} \qquad (3)$$

where $d\theta/dt = \omega$ The last term can be considered as induced back-emf. However, it should be noted that the product of the phase current and the induced back-emf in switched reluctance machines does not represent the mechanical power conversion in the same way like in the conventional machines, since only the half of the power flowing into the equivalent back-emf voltage source is converted into mechanical energy while the other half is stored in a form of magnetic energy. When the machine runs with high velocity, back-emf will be dominant in the Eq. 3. As result, the maximum speed of a switched reluctance machine can be approximately considered as proportional to the phase voltage. The description in Eq. 2 is generally valid for both linear and nonlinear operations of switched reluctance machines.

B. Modeling approaches

To model switched reluctance machines in practical working conditions, the magnetic saturation has to be treated. Some main factors, which affect the performance of a switched reluctance machine, are machine structure, rotor and stator poles, magnetization characteristic of the laminations and control strategy. The highly complex characteristic is presented by two nonlinear relations. As first one, the machine flux linkage is dependent on the stator current and rotor angular position such as

$$\psi = \psi(i, \theta) \qquad (4)$$

The second nonlinear functions reveals that the electromagnetic torque produced by each phase of the switched reluctance machine is determined by

$$\tau = \tau(i, \theta) \qquad (5)$$

The motor performance is fixed once these two nonlinear relationships are known. Such kind of state variable dependencies can be presented by Fig.2. These characteristics can be typically determined by analytical calculations, finite element methods [4], [5] or experimental measurements [6], [7], [8]. The Modelica switched reluctance machine library

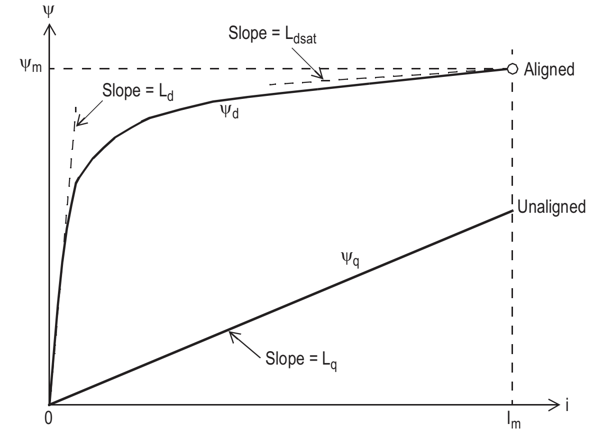

Fig. 3. Aligned and unaligned magnetization curves for building SRM analytical model

presented in this paper can deal with all three modeling methods. For fast prototyping the converter and control strategy, analytical approximation of the magnetization curves and torque characteristic is very convenient and desirable. By the analytical approximation approach [9], the magnetization flux performance can be presented by

$$\begin{aligned} \psi_q &= L_q i \\ \psi_d &= L_{dsat} i + A(1 - e^{-Bi}) \\ f(\theta) &= (2N_r^3/\psi^3)\theta^3 - (3N_r^2/\psi^2)\theta^2 + 1 \\ \psi &= L_q i + [L_{dsat} i + A(1 - e^{-Bi}) - L_q i] f(\theta) \end{aligned} \qquad (6)$$

where

$$\begin{aligned} A &= \psi_m - L_{dsat} I_m \\ B &= (L_d - L_{dsat})/(\psi_m - L_{dsat} I_m) \end{aligned} \qquad (7)$$

Furthermore, the electromagnetic torque results from the sum of the individual torques developed in each phase. The analytical expression for the torque of each phase can be written as

$$\begin{aligned} \tau_e(i, \theta) &= [0.5(L_{dsat} - L_q)i^2 + Ai + A(1 - e^{-Bi}] f'(\theta) \\ f'(\theta) &= (6N_r^3/\phi^3)\theta^2 - (6N_r^2/\phi^2)\theta \end{aligned} \qquad (8)$$

The parameters used in Eq. 6-Eq. 8 are explained in Tab. I and graphically interpreted in Fig. 3.

TABLE I
SYMBOLS USED FOR ANALYTICAL EXPRESSION OF THE MAGNETIZATION CURVES

Parameter	Description
L_q	Non-saturated inductance at unaligned position
L_d	Non-saturated inductance at aligned position
L_{dsat}	Saturated inductance at aligned position
I_m	Maximum current in stator windings
ψ_q	Magnetization curve at aligned position
ψ_d	Magnetization curve at unaligned position
ψ_m	Flux linkage with i_m
N_r	Rotor pole number

III. IMPLEMENTATION OF MODELICA SWITCHED RELUCTANCE DRIVE LIBRARY

The components needed for modeling a switched reluctance drive mainly contain power converter, air gap, mechanical parts, control unit, communication bus system, human

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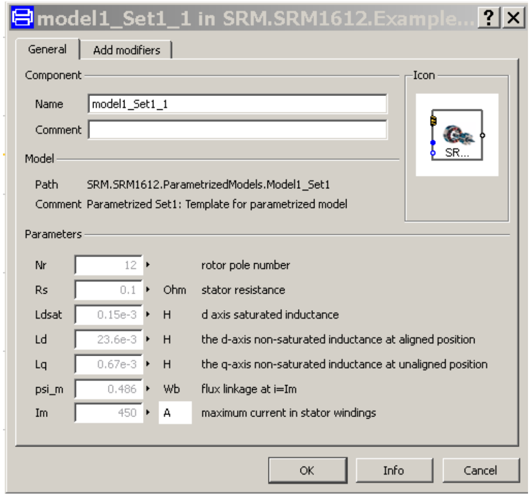

Fig. 4. Graphical interface to model an air gap

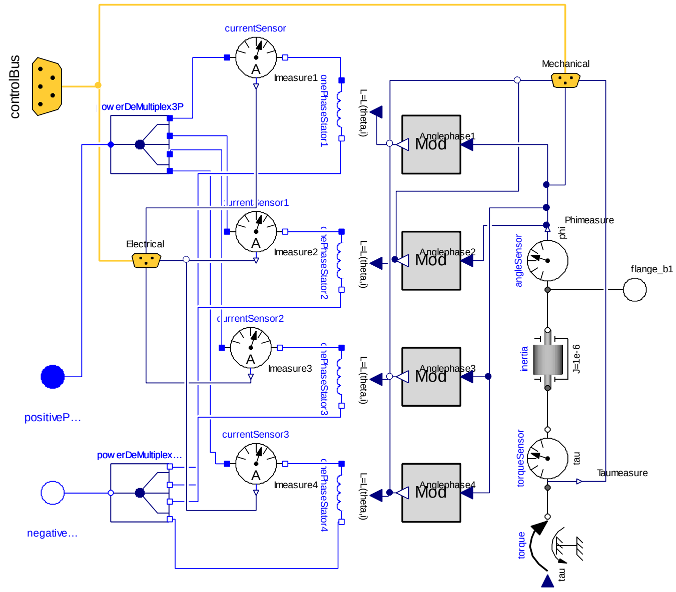

Fig. 5. Rotor model from a 12 rotor poles switched reluctance machine

machine interface and power supply. Using the Modelica standard library, which covers a wide range of infrastructural model in numerous physical domains, the major parts of switched reluctance machine library can be easily modularly established.

A. Model of rotor

The rotor of switched reluctance machine primarily comprises a number of air gaps. To model the air gap of a switched reluctance machine, the analytical representation described in the last section is applied. Typically, the aligned and unaligned magnetization curves in Fig. 3 are derived by finite element method or measurement. The result tables can be imported directly into the Modelica library. Afterwards all the parameters needed in the analytical model are automatically computed and put into the machine model. The rotor of a switched reluctance machine is modeled by object oriented approach, which allows to easily build a desired rotor model by putting air gap models together. The setup window to model an air gap is depicted in Fig. 4. A rotor model with 12 rotor poles is depicted in Fig. 5. The rotor model in Fig. 5 primarily consists of 4 air gaps besides some current sensor, data bus system and machine inertial. Additionally, some test blocks for verifying the analytical representation of magnetization curves are offered in the library. For example, the magnetization performance by analytical modeling approach is depicted in Fig. 6, where the phase current $i = 200A$ and the rotor position varies from 0 to 30 degree.

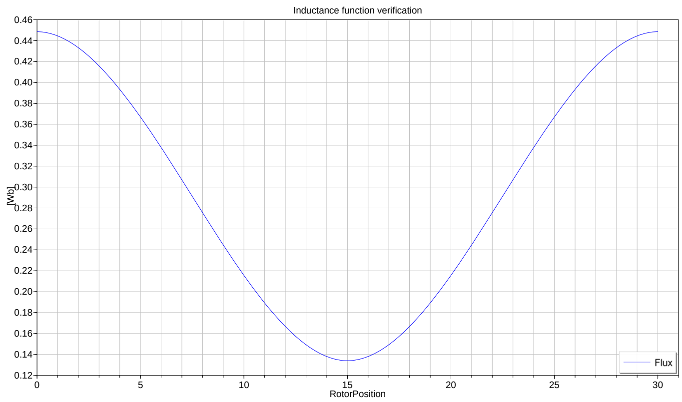

Fig. 6. Testing of magnetization curve

B. Model of control unit

Output torque of switched reluctance machines is commanded by two variables, i.e. excitation level represented by current or flux-linkage and rotor position. Therefore, a high-grade torque controller must possess two feedback signals, for either current or flux-linkage and for rotor position, to obtain a full access on output torque. There are two major control strategies e.g current based torque control and direct torque control [10], [12]. The major difference between two control strategies is that output torque is directly managed as a control variable and there is no inner current control

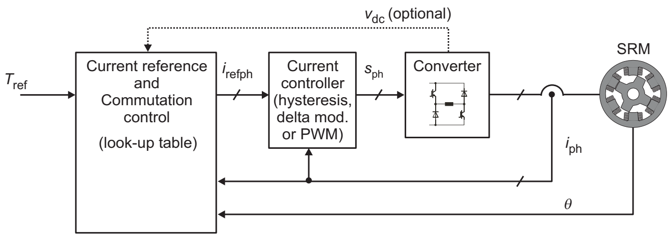

Fig. 7. Schematic current based torque control

loop any more. In this paper, only the current based torque control unit is considered. The schematic diagram of current based torque control is depicted in Fig. 7. Besides analytical modeling approach, the result of the finite element method for modeling the magnetic and mechanic characteristics in Eq. 4 and 5 can also be imported into the library by lookup tables. Based on those lookup tables, the model of a switched reluctance machine can also be done. However, those kinds of models are not quite suitable for control design due to high computation cost. The major components in a current based torque control unit are power converter, current controller and some signal sensors for current and rotor angle.

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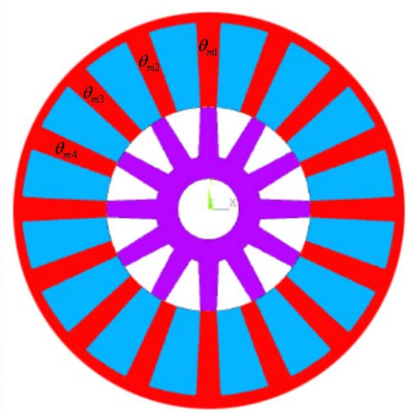

Fig. 8. Determination of phase related angle

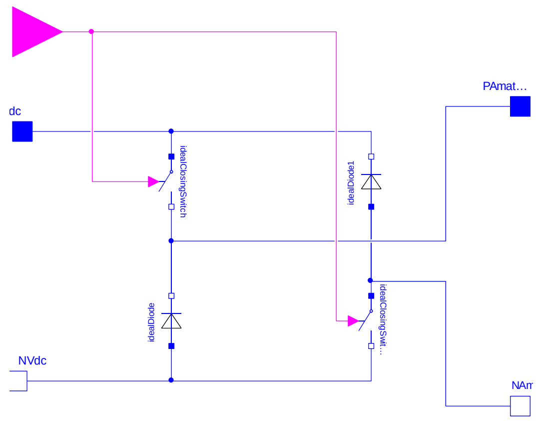

Fig. 9. Asymmetric bridge power converter

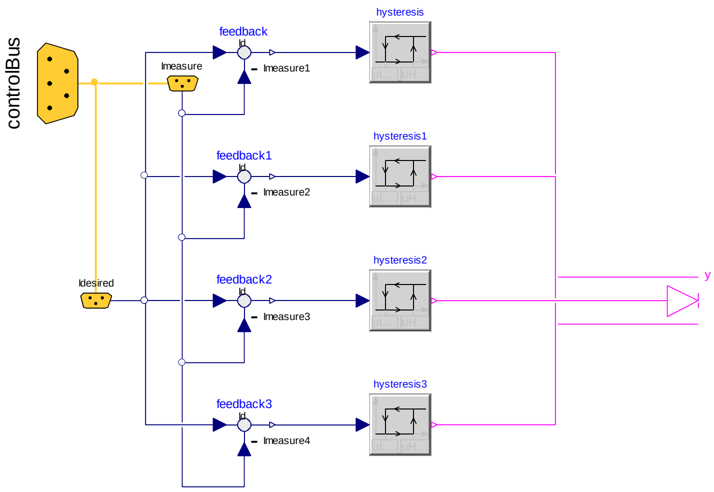

Fig. 10. Implementation of current controller

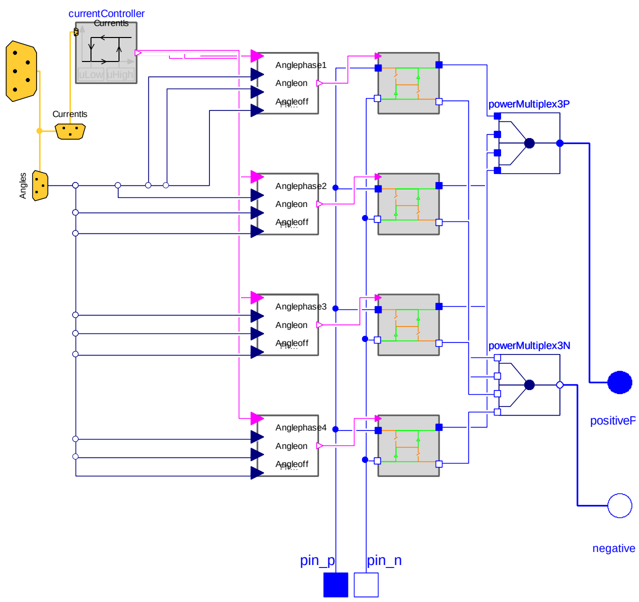

Fig. 11. Control unit for a 4 phase switched reluctance machine

Asymmetric bridge type power converter is addressed in the Modelica switched reluctance machine library. Using Modelica standard library, a power converter depicted in Fig. 9 can be easily modeled. Even more detail model converging thermal effects and power loss could also be treated. Since the turn on/off angles of each phase in rotor play a crucial role for torque control. The current angle in relation to each phase/rotor pair has to be conducted by the measured rotor rotation angle. Taking the example of a 16 stators 12 rotor poles switched reluctance machine, the angle between rotor and phase i , θ_{mi} with the assumption that the rotor at the starting point shown in Fig. 8 can be described as

$$\theta_{mi} = \Theta \bmod 30 - (i-1) \times 7.5 \tag{9}$$

where Θ is the measured rotor rotation angle.

Besides major components to build a switched reluctance machine, the infrastructure models of current controller provide user a convenient way to implement own control unit. The hysteresis current regulator offers a very fast dynamic response by keeping the output current in a given hysteresis band. Its switching frequency varies considerably with torque speed operation points and rotor position [11]. The hysteresis based approach for current control is incorporated in the Modelica library. The hysteresis band of current control is made by the Hysteresis block from Modelica standard library. Furthermore, some algorithms of direct torque control will also be included in the library.

In order present the physical model in reality, all data of control commands and sensor measurements are collected in a special bus system, which is implemented by the expandable connector in Modelica. A structural overview of the Modelica switched reluctance machine library is shown in Fig. 12. Additionally, the Modeling templates for three mostly used motor types (6/4, 8/6 16/12) are already included in the Modelica switched reluctance machine library.

IV. Application Example: Modeling of a 16/12 4 Phases Switched Reluctance Machine

As demonstration, the Modelica switched reluctance machine library has been applied to build a test rig of 16 stators/12 rotors 4 phases switched reluctance machine. The test rig in Fig. 13 comprises a human machine interface for defining desired current and turn on/off angle, a power supply, a motor control unit including current controller

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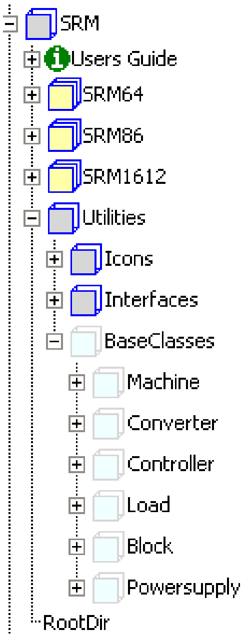

Fig. 12. Overview of the switched reluctance machine library

and the 16/12 switched reluctance machine as well as a mechanical load. The test rig is depicted in the Fig. 13. The parameters used for the test rig are listed in Tab. II. Two test cases have been performed. With the first test case, the switched reluctance machine is simulated without any load to indicate the idealized operation boundary. Simulation results of phase current, output torque and motor velocity are depicted in Fig. 14. With the second test case, a negative torque has been placed as load at 0.1s. The performance of the motor is shown by the phase current, output torque and velocity simulation results in Fig.15.

TABLE II
PARAMETERS IN THE DEMONSTRATION

Parameter	Value
L_q	0.9e-3 Henry
L_d	40e-3 Henry
L_{dsat}	0.2e-3 Henry
I_m	450 Ampere
ψ_m	0.5 Weber
N_r	12
R_s	0.02 Ohm
`Current Command`	200 A
`Turnon angle`	18 Deg
`Turnoff angle`	25 Deg
`Load`	-1000 Nm

V. CONCLUSION

In this paper, a novel Modelica library for modeling switched reluctance machines are presented. The basic components to build a arbitrary type of switched reluctance machine have been implemented using object oriented physical modeling approach. Additionally, control units for switched reluctance machines are also partly incorporated e.g. hysteresis current based torque controller. The work addressed here is a part from an ongoing project of a Modelica Power Drive library, which will contain mostly up-to-date machine types

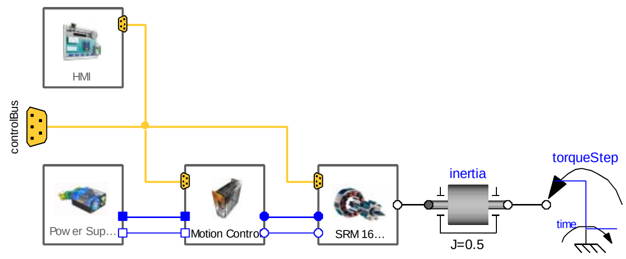

Fig. 13. Testrig of a 16/12 switched reluctance machine

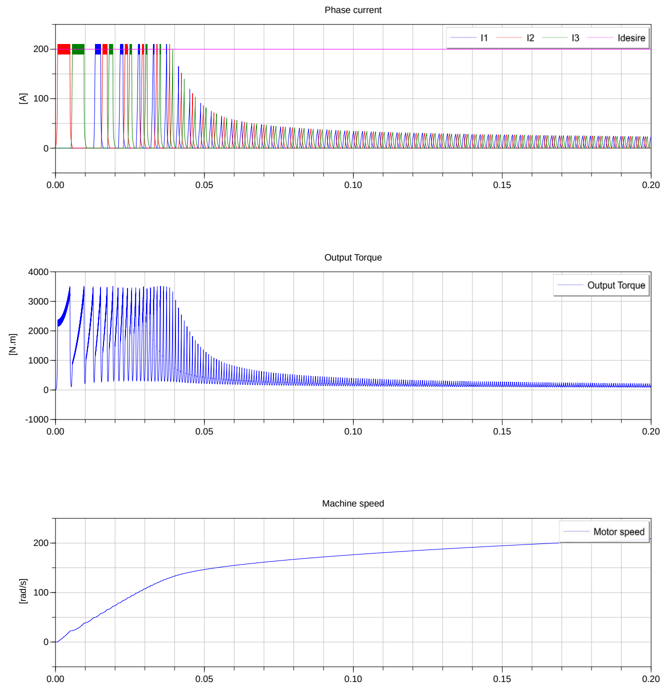

Fig. 14. Simulation result without load

and their corresponding intelligent controllers. In the near future, the direct torque control unit will also be implemented in the Modelica switched reluctance machine library.

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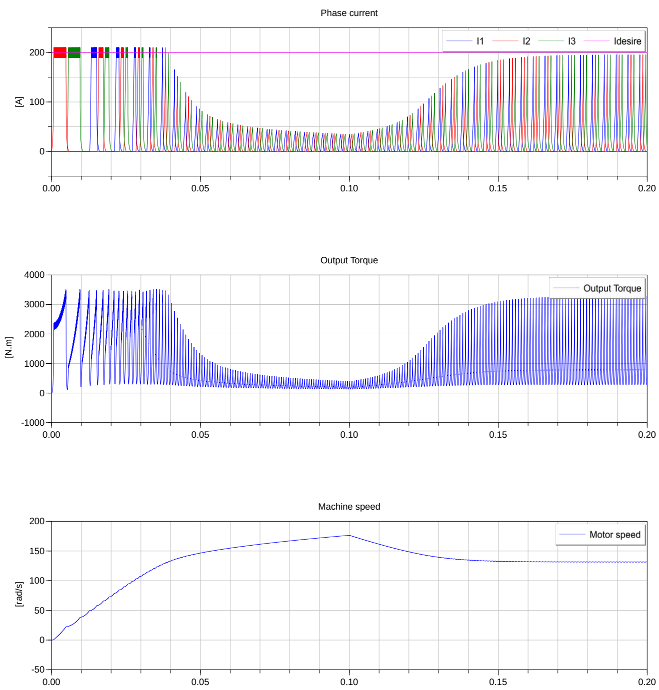

Fig. 15. Simulation result with predefined load profile

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