Bond graph models of electromechanical systems. The AC generator case

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***Abstract*— A systematic exposition of modeling of electromechanical systems in the bond graph formalism is presented. After reviewing electromechanical energy conversion and torque generation, the core element present in any electromechanical system is introduced, and the corresponding electrical and mechanical ports are attached to it. No modulated elements are necessary, since the energy representation of the electromechanical system takes care of the detailed, lumped parameter, dynamics. The general framework is applied to an AC generator, and the case of permanent magnets is also considered. The corresponding bond graphs are implemented in 20sim and simulations are then performed.**

I. Introduction

The bond graph formalism is a graphical approach to modeling, based on the concept of power and incorporating ideas from network theory in a general setting [1][2]. The systems are modeled as a set of elements which exchange energy in a power-conserving way. Generally, the models obtained in this framework, besides being noncausal, are inherently modular and correspond to the physical system more closely than in the more prevalent, signal-based modeling paradigm.

Given a bond graph model, causality can be assigned and algebraic-differential equations can then be obtained in an algorithmic way.

Bond graph modeling is a multi-domain approach that has been applied in a variety of disciplines, covering all areas of engineering but also many others such as biological systems[3]. To name just a few applications, bond graphs have been used to model electrical systems [4], mechanical systems [5][6][7], nonlinear magnetic systems [8], water rocket systems [9], hydraulic systems (trochoidal-gear pump [10], lubricated bearings [11]) or thermofluidic systems [12], and also variable structure systems as power converters [13][14]. Bond graph models, being intrinsically modular, have also been used to describe large and complex systems, such as four-wheel vehicles with electrically controlled brakes and steering [15], hybrid electric vehicles [16] or hybrid railway traction system [17].

Electrical machines are a natural area of application for bonds graphs, as they connect the electrical and mechanical domains. Examples include DC machines [18], three-phase machines, both induction ones [4][19] and synchronous [20], or some other more exotic systems as the Jeffcott rotor [21]. The electromagnetic coupling between the electrical and the mechanical domains has been also studied in detail in this formalism. In [22] saturation effects and nonlinearities has been included in a bond graph model of a claw-pole alternator. Finite elements can also be treated with the bond graph formulation [23].

This paper is organized as follows. In Section II, the electromechanical energy conversion core element for bond graph modeling is introduced. The generalized model of a DC machine, the elementary AC generator, is described and simulated in Section III, and Section IV discusses the permanent magnet case. Finally, Section V, states the conclusions of this work.

II. Electromechanical energy conversion and torque generation

Electrical domain systems with constitutive relations depending on geometric parameters develop additional mechanical ports through which power can flow and be exchanged with the electrical ports. Here we will cast the expressions for the constitutive laws of the ports into the bond graph form.

Consider the system displayed in Figure 1, which represents the sometimes called *coupling field* [24] in an electromechanical system. The IC element is the standard way of representing in bond graph theory a system where some of the state variables are driven by efforts (the I part), and some by flows (the C part). There are n_E generalized electrical ports (e_E, f_E) and n_M generalized mechanical ones (e_M, f_M), and the state variables are denoted by $p_E \in \mathbb{R}^{n_E}$ and $q_M \in \mathbb{R}^{n_M}$. Along these lines we will also use a magnetic and translation mechanics notation (which corresponds to $p_E = \lambda$ and $q_M = x$), although the ports can be of any nature. The purely electrical part, including any electrical resistors contained in the electromechanical device, are attached to the electrical ports, while any inertias, be it masses or rotating parts, and mechanical dissipations, are connected to the mechanical ones.

The dynamics of the state variables are driven by the

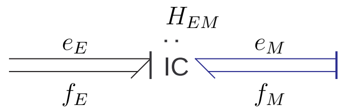

Fig. 1. Bond graph of a generalized electromechanical system.

corresponding power variables:

$$\begin{aligned} \dot{p}_E &= e_E \\ \dot{q}_M &= f_M, \end{aligned}$$

while the dual power variables at each port can be obtained from the energy function, or Hamiltonian, $H_{EM} = H_{EM}(p_E, q_M)$, yielding the constitutive relationships of the system[1]:

$$f_E = (\partial_{p_E} H_{EM})^T \tag{1}$$

$$e_M = (\partial_{q_M} H_{EM})^T \tag{2}$$

Here $(\cdot)^T$ denotes the transpose of a matrix $(\cdot)$. We use the standard mathematical notation where the derivative of an scalar function of several variables is a row vector, and hence the transpose in (1) and (2).

Notice that the existence of an energy function H_{EM} depends on the fulfilling of Maxwell's reciprocity relations. Indeed, from (1) and (2), and assuming sufficiently smooth functions,

$$\partial_{q_M} f_E = \partial_{p_E} e_M.$$

Thus, given $f_E(p_E, q_M)$ one can compute $e_M(p_E, q_M)$, or the other way around; this is frequently exploited when computing forces or torques in electromechanical systems, as will be explained below in more detail.

In Figure 1 we use an all-input power convention, meaning that power flows into the coupling field when it is positive. Indeed, one has that the time derivative of the coupling field energy is

$$\dot{H}_{EM} = \partial_{p_E} H_{EM} \dot{p}_E + \partial_{q_M} H_{EM} \dot{q}_M = f_E^T e_E + e_M^T f_M, \tag{3}$$

which represents the power flowing into the system. Notice that an output power convention for the mechanical ports is usual in the electrical machinery literature,

$$\dot{H}_{EM} = f_E^T e_E - e_M^T f_M,$$

for which $e_M = -(\partial_{q_M} H_{EM})^T$, instead of (2).

Let us rewrite (3) using a magnetic notation for the electric port and a rotation one for a single mechanical port:

$$\dot{H}_{EM} = v^T i + \tau_e \omega, \tag{4}$$

where $-\tau_e$ is the electrical torque generated by the system, $\omega = \dot{\theta}$ is the angular velocity at the mechanical port, and $v, i \in \mathbb{R}^{n_E}$ are the voltages and currents at the electrical ports. The evolution of the electrical state variable is given by

$$\dot{\lambda} = v, \tag{5}$$

[1]In this paper, to simplify the notation, the $\frac{\partial f}{\partial x}(x)$ operations has been also defined as $\partial_x f(x)$.

and the constitutive equation is

$$i = i(\lambda, \theta). \tag{6}$$

Then (4) becomes

$$v^T i + \tau_e \dot{\theta} = \dot{H}_{EM} \tag{7}$$

or, taking into account that (7) is an scalar equation and using (5) and (6),

$$i(\lambda, \theta)\dot{\lambda} + \tau_e(\lambda, \theta)\dot{\theta} = \dot{H}_{EM}. \tag{8}$$

In general, τ_e depends on λ and θ, with the only restriction that no torque is generated at zero magnetic flux:

$$\tau_e(\lambda = 0, \theta) = 0 \quad \forall\ \theta. \tag{9}$$

Thinking of H_{EM} as a function of λ and θ, equation (8) implies that the differentials are related by

$$\mathrm{d}H_{EM}(\lambda, \theta) = i^T(\lambda, \theta)\ \mathrm{d}\lambda + \tau_e(\lambda, \theta)\ \mathrm{d}\theta, \tag{10}$$

from which one obtains the two constitutive equations

$$i^T(\lambda, \theta) = \frac{\partial H_{EM}}{\partial \lambda}(\lambda, \theta), \tag{11}$$

$$\tau_e(\lambda, \theta) = \frac{\partial H_{EM}}{\partial \theta}(\lambda, \theta). \tag{12}$$

Assuming continuity of the second order partial derivatives, we get Maxwell's reciprocity relations for this case:

$$\frac{\partial i^T}{\partial \theta}(\lambda, \theta) = \frac{\partial \tau_e}{\partial \lambda}(\lambda, \theta). \tag{13}$$

In fact, if $n_E > 1$, there are also Maxwell reciprocity relations internal to the electric part, given by

$$\frac{\partial i_j}{\partial \lambda_k}(\lambda, \theta) = \frac{\partial i_k}{\partial \lambda_j}(\lambda, \theta) \quad \forall\ j, k = 1, \ldots, n_E, \tag{14}$$

which follow from the continuity assumption on the second order partial derivatives of H_{EM} with respect to λ.

Actually, it can be shown that, given arbitrary constitutive equations $i(\lambda, \theta)$, $\tau_e(\lambda, \theta)$, Maxwell's relations are sufficient and necessary conditions for the existence of the energy function $H_{EM}(\lambda, \theta)$ from which i and τ_e can be derived using (11) and (12). Alternatively, if $i(\lambda, \theta)$ is given and the existence of H_{EM}, *i.e.* the conservation of energy in the electromechanical system, is assumed, imposition of (13) and (9) allows to determine $\tau_e(\lambda, \theta)$. In fact, this provides also a way to compute directly H_{EM}. Defining $H_{EM}(0, 0) = 0$, $H_{EM}(\lambda, \theta)$ can be obtained by integrating (10) from $(0, 0)$ to its final value (λ, θ) along an arbitrary path in state space:

$$H_{EM}(\lambda, \theta) = \int_{(0,0)}^{(\lambda,\theta)} \left(i^T(\tilde{\lambda}, \tilde{\theta})\ \mathrm{d}\tilde{\lambda} + \tau_e(\tilde{\lambda}, \tilde{\theta})\ \mathrm{d}\tilde{\theta} \right). \tag{15}$$

The fact that this is a well-defined function, *i.e.* that the system is energy conserving, allows computing the integral using any convenient path. In particular, we can consider a first leg with $\tilde{\lambda} = 0$ and $\tilde{\theta}$ going from 0 to θ. This yields a zero contribution to the line integral (15), since the first term does not contribute because $\mathrm{d}\tilde{\lambda} = 0$, while the second does not either because of

(9). On a second leg, we reach the final point in state space with $\tilde{\theta} = \theta$, and hence $\mathrm{d}\tilde{\theta} = 0$. Thus (15) boils down to

$$H_{EM}(\lambda, \theta) = \int_0^\lambda i^T(\tilde{\lambda}, \theta)\, \mathrm{d}\tilde{\lambda}.$$

The result does not depend on the particular path through λ state space, due to (14). Once H_{EM} is obtained, τ_e can be computed as well using (12), although if only τ_e is needed a different, although of the same computational complexity, way through (13) can be followed.

III. Bond graph model of an elementary AC generator

Figure 2 shows an elementary AC generator, or alternator. The system consists in a magnetic field generated by the so-called field winding (or by a permanent magnet, see Section IV), and a rotating coil.

We illustrate the physical operation of the system and develop the associated IC-element.

A. AC machine description

The elementary AC generator (see Figure 2) contains two electric circuits, one of them stationary and the other one rotating, and can act both as a generator or as a motor. In generator mode, given a mechanical speed ω and a voltage v_s in the stationary windings, an AC voltage v_r is induced in the rotating circuit. Conversely, in motor mode, feeding the circuits with voltages v_s constant and a controlled, with a stationary, $v_r = A \sin \omega_r t$, the machine revolves with an averaged speed equal to ω_r.

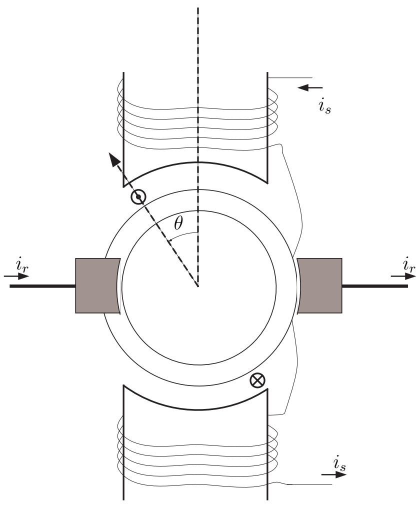

Fig. 2. An elementary AC generator.

We write down the electrical equations of the rotating and stationary circuits [24]

$$\begin{aligned} v_r &= r_r i_r + \dot{\lambda}_r \\ v_s &= r_s i_s + \dot{\lambda}_s \end{aligned}$$

or in a compact form, with $V^T = [v_r, v_s]$, $i^T = [i_r, i_s]$, $\lambda^T = [\lambda_r, \lambda_s]$ and $R = \mathrm{diag}\{r_r, r_s\}$,

$$V = Ri + \dot{\lambda}$$

where v are voltages, i currents, λ fluxes and subindexes r and s refer to rotating and stationary, respectively. The relationship between the fluxes and currents is given by

$$\lambda = \mathcal{L}(\theta) i$$

with[2]

$$\mathcal{L} = \begin{bmatrix} L_r & L_m(\theta) \\ L_m(\theta) & L_s \end{bmatrix}, \tag{16}$$

where the mutual inductance is given by

$$L_m = l_m \cos(\theta),$$

and L_r, L_s are the rotating and stationary inductances, respectively. Furthermore, the mechanical equation is

$$\tau = J_m \dot{\omega} + b\omega + \tau_e \tag{17}$$

where ω is the mechanical speed, τ is an external torque, τ_e is the electrical torque, J_m is the rotor inertia and b represents the viscous damping. The electrical torque, τ_e, induced (or produced) by the interaction of the magnetic fields, see [24][3],is

$$\tau_e = -l_m i_r i_s \sin(\theta). \tag{18}$$

B. Bond graph model

Following the energy based description of the electromechanical coupling detailed in Section II, the bond graph model of the system is depicted in Figure 3.

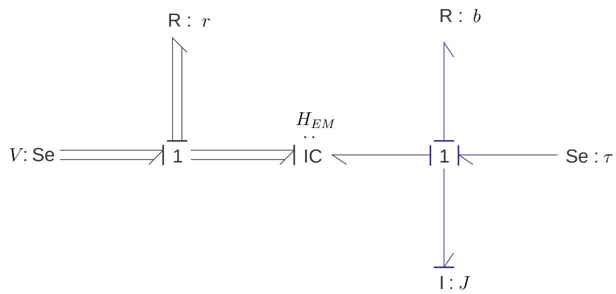

Fig. 3. Bond graph of an alternator.

The elements are: effort sources, Se, which contains the rotating and stationary voltages ($V^T = [v_r, v_s]$), and the external torque (τ), dissipative elements, R, with the resistance of the coils ($R = \mathrm{diag}\{r_r, r_s\}$) and the viscous damping, b, the I-element which contains the rotor inertia (J) and, finally, the IC-element introduced in Section II. Notice that the electrical subsystem is described by multi-power bonds (which in this case are two-dimensional).

This bond graph describes any operation mode, since power can flow to or into the ports of the IC element.

[2]Note that, since $L_r, L_s > L_m$ the matrix $\mathcal{L}$ is always positive definite, $\mathcal{L} > 0$.

[3]The minus sign comes from the input power convention for the IC element.

The state variables for the IC-elements are

$$p_E = \begin{bmatrix} p_{Er} \\ p_{Es} \end{bmatrix} = \begin{bmatrix} \lambda_r \\ \lambda_s \end{bmatrix} = \lambda \in \mathbb{R}^2$$
$$q_M = \theta,$$

and their dynamics are described by the energy function. The magnetic energy is given by

$$H_{EM} = \frac{1}{2} p_E^T \mathcal{L}^{-1} p_E. \qquad (19)$$

where $\mathcal{L}$, which depends on q_M, is defined in (16). Now, the constitutive relationships of the system, (1) and (2), allow to compute the fluxes and efforts from the energy function (19), yielding

$$f_E = \begin{bmatrix} f_{Er} \\ f_{Es} \end{bmatrix} = \partial_{p_E} H_{EM} = \mathcal{L}^{-1} p_E$$
$$e_M = \partial_{q_M} H_{EM} = -\frac{1}{2} f_E^T (\partial_{q_M} \mathcal{L}) f_E$$

where, from (16)

$$\partial_{q_M} \mathcal{L} = \begin{bmatrix} 0 & \partial_{q_M} L_m \\ \partial_{q_M} L_m & 0 \end{bmatrix},$$

and consequently, taking into account that $\partial_{q_M} L_m = -l_m \sin(q_M)$, the effort of the mechanical port is given by

$$e_M = -l_m f_{Er} f_{Es} \sin(q_M),$$

which corresponds to the equation (18). Finally the state variables can be obtained from

$$\dot{p}_E = \begin{bmatrix} e_{Er} \\ e_{Es} \end{bmatrix}$$
$$\dot{q}_M = f_M.$$

The relationship between the port variables (fluxes and efforts) of the IC-element with the variables of the system is as follows: f_E are the inductor currents (i_r and i_s), e_E are the rotating and stationary voltages (v_r and v_s), f_M is the mechanical speed (ω) and e_M is the electrical torque (τ_e).

An important fact of this approach is that no modulated elements are used: the dynamics is described completely by the energy function and the constitutive relationship of the ports.

The bond graph presented in Fig. 3 can be also split into the rotating and the stationary electrical circuits, and then the model can also be drawn as in Fig. 4.

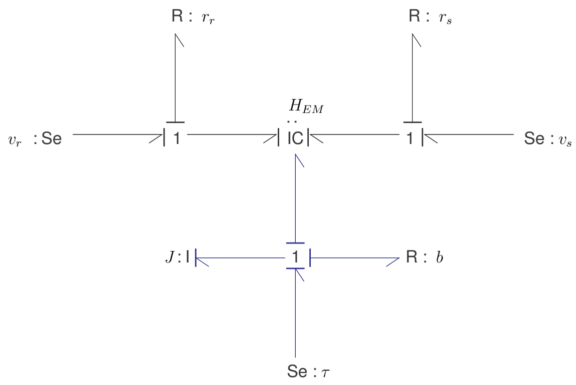

Fig. 4. Bond graph of an alternator.

C. Simulations

The bond graph described in the previous subsection has been simulated using the 20sim software. The elements are obtained from the standard library, except the IC-element, which is constructed from the standard IC-element by adding the appropriate ports and writing the following code, where `PE.e`=e_E, `PM.e`=e_M, `PE.f`=f_E, `PM.f`=f_M,

```
Lm=lm*cos(qM);
dLm=-lm*sin(qM);
L=[Lr,lm;lm,Ls];
dL=[0,dLm;dLm,0];
pE = int (PE.e);
reset = if qM > 2*pi then true else false end;
qM = resint(PM.f,0,reset);
PM.f=inverse(L)*pE;
PE.e=-1/2*transpose(PE.f)*dL*PE.f;
```

The machine parameters are set to $L_r = 40$mH, $L_s = 40$H, $l_m = 1$H, $r_r = 0.5\Omega$, $r_s = 4\Omega$, $J = 1 \cdot 10^{-4}$kg·m^2, $b = 0.005$N·m·s^{-1} and $v_s = 5$V.

Only the generator mode is simulated, but the motor one can also be easily simulated with an appropriate rotating voltage ($v_r = A \sin(\theta)$). In this case a resistance of $R_L = 500\Omega$ is connected in series with the rotating circuit. To simulate this effect the value of r_r is increased. Notice that this load resistance can also be explicitly introduced in the bond graph of Fig. 4, substituting the Se-element with the v_r voltage by a R-element with the R_L value. In this simulation $\tau = 2$Nm, and the initial condition for λ_s is set to $\lambda(0) = 49.9922$Wb.

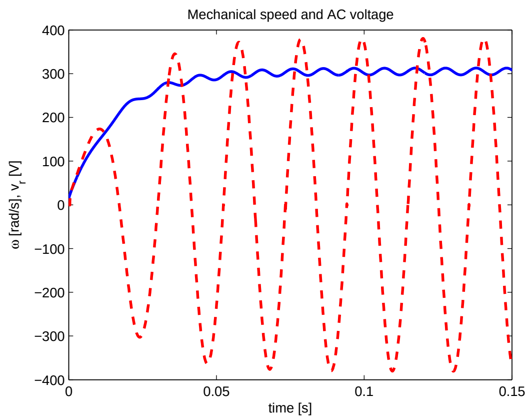

Fig. 5. Mechanical speed and AC voltage.

Figures 5 and 6 show the dynamical response of the system. Notice that the rotating voltage is close to be a sinusoidal function. In fact due to the fact that the stationary flux and current are not constant (see Fig. 6) some small oscillations appear in the mechanical speed (see Fig. 5), and consequently

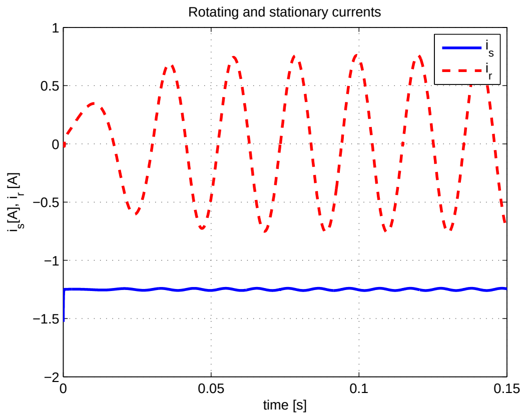

Fig. 6. Simulation results: rotating and stationary currents for an alternator.

the v_r waveform is not a pure sine.

IV. The permanent magnet case

A. System description

In this system the field winding is replaced with a permanent magnet. In the general case the magnetic flux, λ, is a function of the geometric distribution of the coils and the permanent magnets, and can be given by (see [25] or [26] for a Hamiltonian formalism example)

$$\lambda = \mathcal{L}(\theta)i + \mu(\theta)$$

where $\mathcal{L}(\theta)$ is the inductance matrix, i are currents and $\mu(\theta)$ is the flux linkage due to the permanent magnets. The energy function of the magnetic field is

$$H_{EM} = \frac{1}{2}(\lambda - \mu(\theta))^T \mathcal{L}^{-1}(\lambda - \mu(\theta)). \tag{20}$$

In this simple one dimensional case, where the stationary electric circuit is replaced with a permanent magnet, the only electrical dynamics is due to the rotating part and then $i = i_r \in \mathbb{R}$, $\mathcal{L} = L_r$, $\lambda = \lambda_r \in \mathbb{R}$ and

$$\mu(\theta) = \Phi \cos(\theta)$$

where Φ is the field flux.

The dynamics of this system is described by the electrical equation

$$v_r = r_r i_r + \dot{\lambda}_r,$$

while the mechanical part remains the same as in (17), with the following electrical torque

$$\tau_e = -i_r \Phi \sin(\theta).$$

B. The bond graph model

Similarly to the previous Section, the bond graph can be built using an IC-element, see Figure 7. It contains the same elements for the mechanical part of the previous example while, in the electrical domain, the stationary elements are removed and the permanent magnet is included in the IC-element.

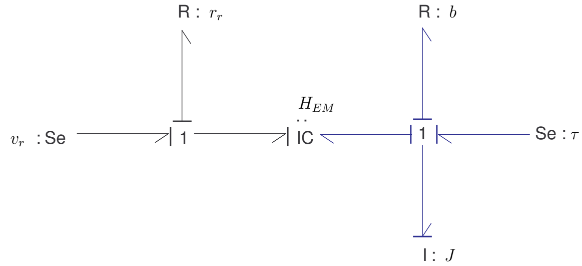

Fig. 7. BG of a rotating electrical AC machine with permanent magnets.

The state variables of the IC-element are

$$\begin{aligned} p_E &= \lambda_r \\ q_M &= \theta. \end{aligned}$$

As mentioned before, the magnetic energy is given by (20), and for one coil we get

$$H_{EM} = \frac{1}{2L_r}(p_E - \mu(q_M))^2.$$

From the constitutive relationship of this element (1) and (2),

$$\begin{aligned} f_E &= \partial_{p_E} H_{EM} = \frac{1}{L_r}(p_E - \mu(q_M)) \\ e_M &= \partial_{q_M} H_{EM} = -f_E \partial_{q_M} \mu \end{aligned}$$

where

$$\partial_{q_M} \mu = -\Phi \sin(\theta).$$

Finally, the state variables can be computed as

$$\begin{aligned} \dot{p}_E &= \dot{p_{E_r}} = e_E \\ \dot{q}_M &= f_M. \end{aligned}$$

Note that, again, the relationship between the port variables (fluxes and efforts) of the IC-element with the variables of the system is f_E is the inductor current, e_E is the electromotive force, f_M is the mechanical speed and e_M is the electrical torque.

C. Simulations

The bond graph of the permanent magnet AC alternator has been also simulated using the 20sim software. The parameters are the same as in the previous simulations, with the field flux of the permanent magnet set to $\Phi = 0.8$Wb.

Fig. 8 shows the mechanical speed and the produced AC voltage. Notice that the behavior is similar to the results obtained in the previous subsection for an AC machine with a field winding.

V. Conclusions

In this paper the electromechanical energy conversion using bond graph approach is presented. The IC-element is introduced and one example is presented: an elementary AC machine. The AC machine study includes the field winding and the permanent magnet cases. Simulations results verify the presented bond graph models.

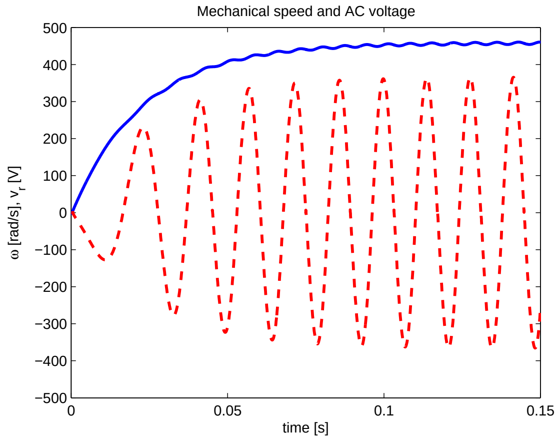

Fig. 8. Mechanical speed and AC voltage for an alternator with PM.

This general philosophy for modeling electromechanical systems, namely using a core IC-element to model the electromechanical energy conversion, can be extended to more complex machines, such as DC machines (considering the commutation effects), or three-phase (or poly-phase) electrical machines, such as induction motors or synchronous generators. The only difference when dealing with different systems consists in replacing the energy function and, if necessary, adding some modulated transformers to represent any commuting effects. Simplifying transformations, such as the dq transformation, can be represented inside the IC-element.

Putting the electromechanical conversion inside the IC-element allows for greater modularity and flexibility in the level of detail of the description of the system. For instance, the interface of the IC-element does not change if the internal dynamics of the electrical machine is described with more detail, adding magnetic saturation or distributed parameter effects. Besides, the bond graph description does not select *a priori* a given mode of operation, and the same model can be reused in different contexts by changing the external sources.

Acknowledgments

CB and AD-C were partially supported by the Spanish government research projects MTM2007-62480 and DPI2007-62582, respectively.

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