Different energetic techniques for modelling traction drives

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***Abstract*— In this paper the traction system of an automatic subway is described using four different energetic graphical techniques: Bond-Graph (BG), Energetic Macroscopic Representation (EMR), Power-Oriented Graphs (POG) and Vectorial Bond-Graph (VBG). The aim of this paper is to highlight the analogies and the differences between these modelling techniques in the analysis and simulation of the considered system.**

I. Introduction

A lot of modelling methods are available for describing electromechanical systems, from the physical relationships to state space models or the classical transfer function schemes. More recently, new graphical tools have been used to suggest other views of these systems. The Bond Graph methodology [1], [2] is used for modelling dynamic systems in many different physical areas, and more particularly electromechanical ones [3]. The Causal Ordering Graph has been developed 10 years ago to build control of electrical systems using inversion rules [4]. Power flow diagram has been more recently developed for control purpose of electromechanical systems [5]. Energetic Macroscopic Representation has been developed in 2000 to analyse and control systems with several electrical machines [6], [7]. All these descriptions have been compared in [8]. In this paper, this comparison is extended to Vectorial Bond Graph and Power-Oriented-Graph [9], [10].

II. The studied traction system

The traction system of an automatic subway [6] is taken as example in Fig. 1. The supply rail delivers a DC voltage to an embedded filter. The DC voltage is then distributed to 3 choppers. Two of them supply the field windings of two DC machines. The armature windings of both machines are connected in series and are supplied by the middle chopper. Each machine is associated with a bogie. The car of the subway is moved by two bogies. The dashed lines present in Fig. 1 represent physical power sections. Each section is numbered in order to easily identify it in the following description. The state space equations of the considered system are now listed, see [8].

- *The input filter*, from section ① to section ④, is characterized by the inductor L_f with internal resistance R_f and the capacitor C_f:

$$\begin{cases} L_f \frac{d}{dt} i_f &= V_{DC} - R_f\, i_f - u_f \\ C_f \frac{d}{dt} u_f &= i_f - i_{cp} \end{cases} \tag{1}$$

- *The three choppers*, from ④ to ⑤, distribute the filter voltage u_f to the windings of the two DC machines:

$$\begin{cases} u_1 = u_2 = u_3 = u_f \\ i_{cp} = i_{cp1} + i_{cp2} + i_{cp3} \end{cases} \tag{2}$$

The switching functions $m_{cp(i)}$, for $i \in \{1, 2, 3\}$ define the connections of the filter with the motor windings:

$$\begin{cases} u_{cp(i)} = m_{cp(i)}\, u_f \\ i_{cp(i)} = m_{cp(i)}\, i_{load(i)} \end{cases} \tag{3}$$

where $m_{cp(i)} \in \{0, 1\}$, $i \in \{1, 2, 3\}$, $i_{load1} = i_{fd1}$, $i_{load2} = i_{arm}$ and $i_{load3} = i_{fd2}$.

- *The field and armature windings* of the two DC motors, from ⑤ to ⑦, are described by two field equations:

$$L_{fd(k)} \frac{d}{dt} i_{fd(k)} + R_{fd(k)} i_{fd(k)} = u_{chop(k)} - e_{fd(k)} \tag{4}$$

where $k \in \{1, 2\}$, $u_{chop1} = u_{cp1}$, $u_{chop2} = u_{cp3}$ and only one equation for the series of the two armature windings:

$$L_{arm} \frac{d}{dt} i_{arm} + R_{arm} i_{arm} = u_{cp2} - e_{arm} \tag{5}$$

where $R_{arm} = R_{arm1} + R_{arm2}$ and $L_{arm} = L_{arm1} + L_{arm2}$, see [6]. Note: for the considered system the e.m.f e_{fd1} and e_{fd2} of the field windings are null.

- *The power links between the DC motors and bogies*, from ⑦ to ⑧, are described by equations:

$$\begin{cases} T_{m(k)} = k_{dcm(k)}\, i_{fd(k)}\, i_{arm} = k_{fd(k)}\, i_{arm} \\ e_{arm(k)} = k_{dcm(k)}\, i_{fd(k)}\, \Omega_{b(k)} = k_{fd(k)}\, \Omega_{b(k)} \\ e_{arm} = e_{arm1} + e_{arm2} \end{cases} \tag{6}$$

where $k \in \{1, 2\}$, $i_{fd(k)}$ and i_{arm} are the field and armature currents, $T_{m(k)}$ are the motor torques, $k_{fd(k)} = k_{dcm(k)}\, i_{fd(k)}$ are the torque constants, $\Omega_{b(k)}$ are the bogie rotation speeds and $e_{arm(k)}$ are the induced back

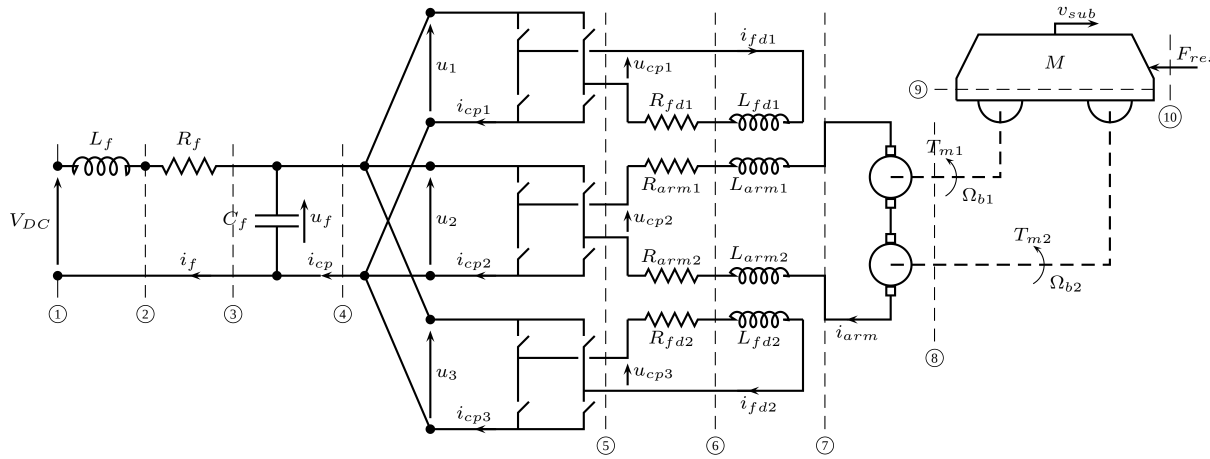

Fig. 1. Power structure of the subway traction system.

electromotive voltages. A simple mechanical transmission links the subway velocity v_{sub} to the bogie speed $\Omega_{b(k)}$ and the bogie traction force $F_{b(k)}$ to the machine torque $T_{m(k)}$:

$$\begin{cases} \Omega_{b(k)} = m_{b(k)}\, v_{sub} \\ F_{b(k)} = m_{b(k)}\, T_{m(k)} \end{cases} \tag{7}$$

where $m_{b(k)}$ is the bogie ratio. Both traction forces are coupled through the chassis to give the total force F_{tot}:

$$\begin{cases} v_{b1} = v_{b2} = v_{sub} \\ F_{tot} = F_{b1} + F_{b2} \end{cases} \tag{8}$$

The subway velocity v_{sub} is obtained directly from the traction and resistive forces:

$$M \frac{d}{dt} v_{sub} = F_{tot} - F_{res} \tag{9}$$

where M is the mass of the subway. The subway environment produces a resistive force to the motion F_{res}, which depends on the velocity square and on the slope α:

$$F_{res} = F_0 + a_r\, v_{sub} + b_r\, v_{sub}^2 + M\, g \sin\alpha \tag{10}$$

III. Description using Bond-Graph

The bond graph (BG) modelling tool [2], based on energy and information flow, uses a uniform notation for all types of physical system. Power exchanges are represented with half arrows (“bonds”) bringing a pair of conjugated variables called effort and flow whose product is the instantaneous power exchanged between elements or subsystems. Three “passive” elements represent energy dissipation (R) and energy storage (I, C) phenomena, two “active” elements (Se, Sf) model power supply, and four power conserving “junction” elements (0, 1, TF, GY) constitute the structure of the model. Causality information is shown up on each half arrow by means of the causal stroke drawn perpendicularly to the bond. If the parameter of the BG element is not a constant one, a letter M (modulate) is used as a prefix for the name of the element and an additional unidirectional powerless control input is added: GY –> MGY. Fig. 2 shows the BG model of the subway traction system.

IV. Description using Energetic Macroscopic Representation

The Energetic Macroscopic Representation (EMR) is a graphical tool based on the action-reaction principle [7],[11]. Specific pictograms are associated to each power component depending on their power function: energy accumulation (rectangle with an oblique bar), conversion without energy accumulation (square for electrical conversion, circle for electromechanical conversion, triangle for mechanical conversion), interleaved forms for energy distribution. The EMR of the studied system is given in Fig. 3. This description points out the coupling devices, which distribute energy. It has been shown that these components are the key of energy management in such systems [12].

V. Description using Power-Oriented Graphs

The Power-Oriented Graphs (POG), see [9], [10], are normal block diagrams combined with a particular “modular” structure essentially based on the use of only two blocks: an *elaboration block* which can store and dissipate energy (i.e. capacitors, inductances, resistances, springs, masses, dampers, etc.), and a *connection block* which can only “transform” the energy, that is, transform the system variables from one type of energy-field to another (i.e. any type of transformers and gyrators). The POG scheme of the considered system is shown in Fig. 4. This scheme is characterized by the following matrices and vectors:

$$\mathbf{m}_{cp} = \begin{bmatrix} m_{cp1} \\ m_{cp2} \\ m_{cp3} \end{bmatrix}, \qquad \mathbf{R}_m = \begin{bmatrix} R_{fd1} & 0 & 0 \\ 0 & R_{arm} & 0 \\ 0 & 0 & R_{fd1} \end{bmatrix}$$

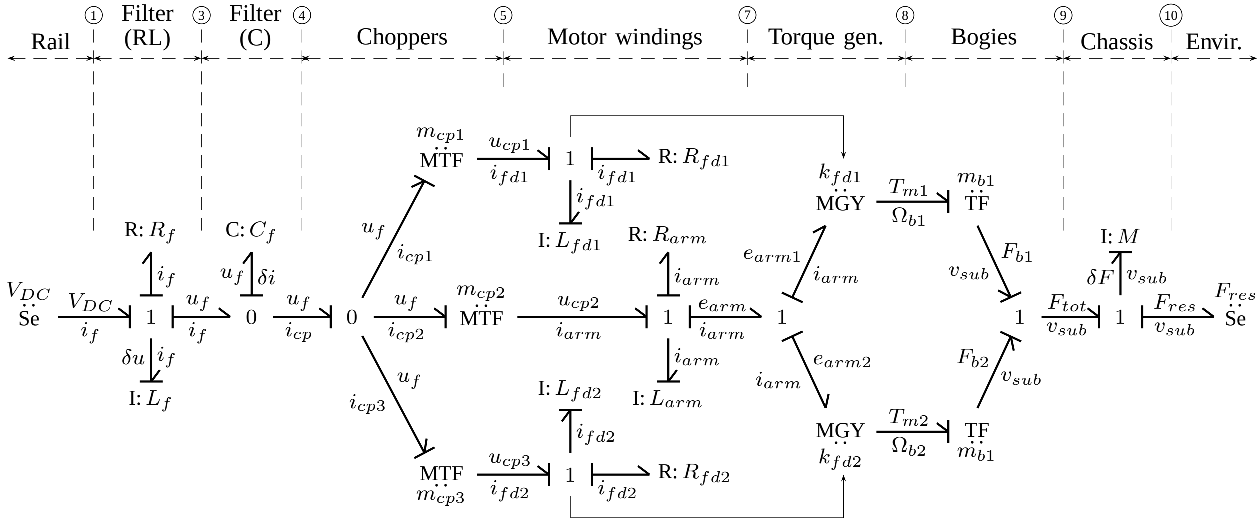

Fig. 2. Bond-Graph description of the subway traction system.

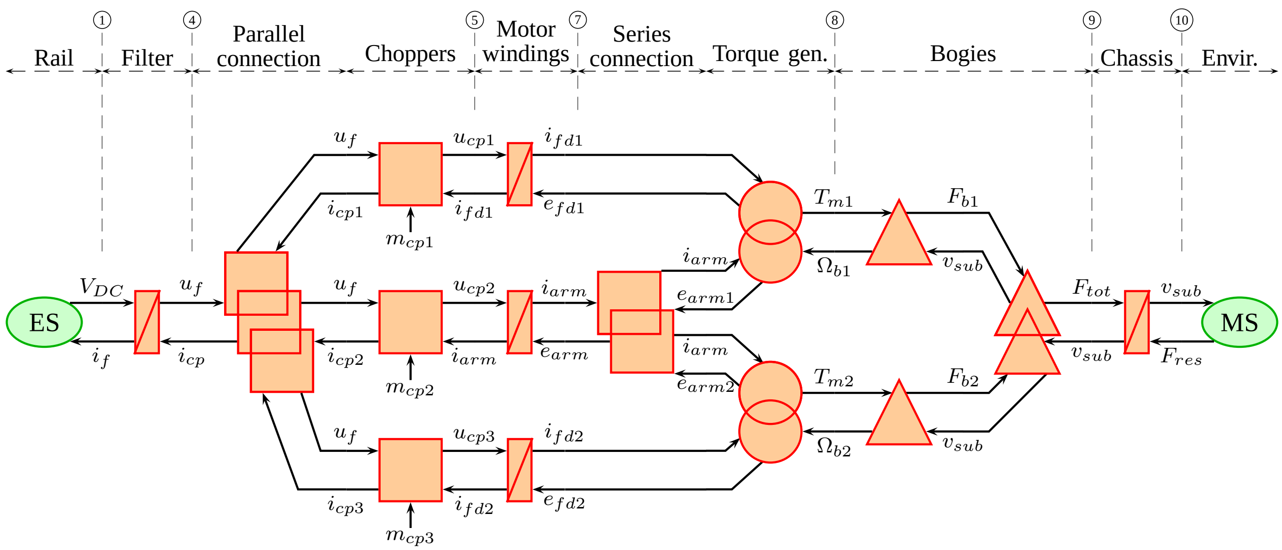

Fig. 3. EMR description of the subway traction system.

$$\mathbf{L}_m = \begin{bmatrix} L_{fd1} & 0 & 0 \\ 0 & L_{arm} & 0 \\ 0 & 0 & L_{fd1} \end{bmatrix}, \qquad \mathbf{M}_b = \begin{bmatrix} m_{b1} & m_{b2} \end{bmatrix},$$

$$\mathbf{M}_e = \begin{bmatrix} 0 & k_{dcm1}\, i_{fd1} & 0 \\ 0 & k_{dcm2}\, i_{fd2} & 0 \end{bmatrix}, \quad \mathbf{u}_{cp} = \begin{bmatrix} u_{cp1} \\ u_{cp2} \\ u_{cp3} \end{bmatrix}, \quad \mathbf{i}_m = \begin{bmatrix} i_{fd1} \\ i_{arm} \\ i_{fd2} \end{bmatrix},$$

$$\mathbf{e}_m = \begin{bmatrix} e_{fd1} \\ e_{arm} \\ e_{fd2} \end{bmatrix}, \quad \mathbf{\Omega}_b = \begin{bmatrix} \Omega_{b1} \\ \Omega_{b2} \end{bmatrix}, \quad \mathbf{T}_m = \begin{bmatrix} T_{m1} \\ T_{m2} \end{bmatrix}$$

The blocks present in Fig. 4 between sections ④ - ⑤ and sections ⑦ - ⑨ are *connection blocks*, all the other blocks of the scheme are *elaboration blocks*. The POG schemes always show a direct correspondence between pairs of system variables and real power flows: the product of the two variables involved in each dashed line of the scheme has the physical meaning of "power flowing through the section". A POG scheme always satisfies the following two rules: 1) *along all the loops of the scheme must be present an "odd" number of signs "−"* (the black spots in the summation blocks); 2) *the direction of the power flowing through a section is positive if an "even" number of signs "−" is present along all the paths which link the input to the output*. These rules allows the POG schemes to be converted into BG schemes, and vice versa.

VI. Description using Vectorial Bond Graph

Fig. 5 shows the vectorial Bond Graph of the examined system. All parameters, scalar ones as well as matrices, are the same as defined for EMR and POG. The parameter

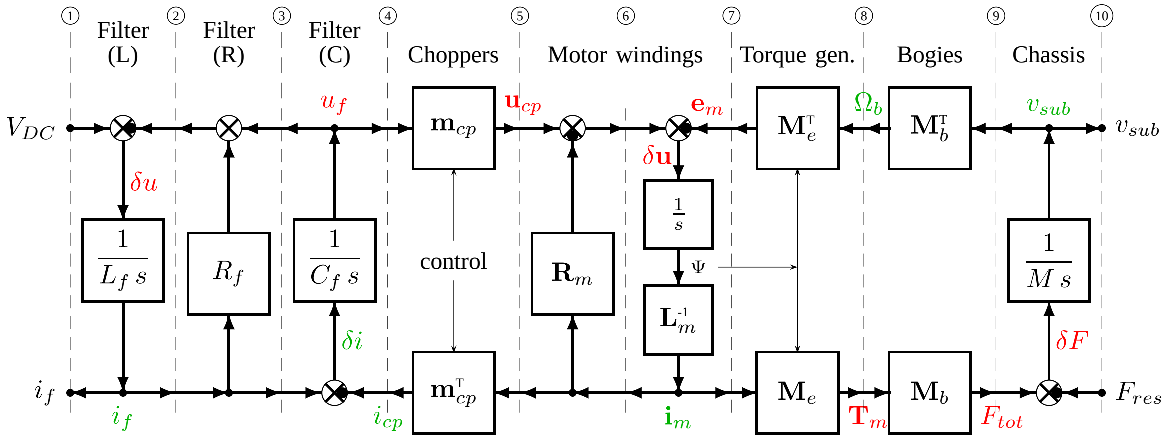

Fig. 4. The POG scheme of the subway traction system.

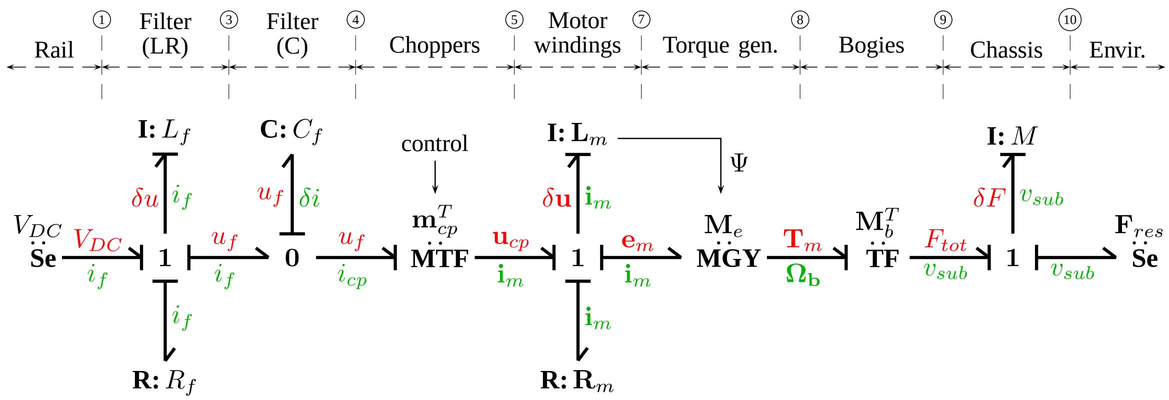

Fig. 5. Vectorial Bond Graph of the subway traction system.

input for each element, i.e. transposed or not, inverse or not, is prepared regarding the use of the Simulink Bond Graph library BG V.2.0 [13] to simulate the system. In this case the desired integral causality is system inherent.

If the physical scheme of the considered system is clearly enough and the system is not too complicated the BG may be constructed directly based on this scheme. This means that a good enough physical scheme (step 1) enables the direct construction of a BG (step 2) and this results in direct a graphical programming of the simulation structure of the BG (step 3), for instance via Simulink [13], [14]. In that case the system equations may be derived from the BG (step 4). Therefore, some experiences provided, the BG method offers the possibility of system analysis without explicit equation generation. If the mentioned condition is not fulfilled the second step consists of the generation of the equation system via usual methods. Each node computes one power variable. Without any causality error a 1-node computes an effort power variable by summation of the effort variables of all other bonds of this 1-node. The summation sign results from a direction comparison between preferred power transmission, i.e. the bond direction, and the transmission direction of the considered variable to this node. Opposite directions imply a negative sign. This rule has to be applied to 0 nodes and flow power variables by analogy. All other elements are clearly described by the respective definition equations if the given causality is taken into account. This objective fact explains the easy derivation of Signal Flow Diagrams based on Bond Graphs as well as the close relationship to the POG. As mentioned above POG and BG may define and use the same parameter matrices. In fact there are two major differences in evidence. On the one hand more then three bond connections will be split and on the other hand the forward and the backward direction of a TF resp. a GY element is explicitly visible.

VII. Comparison

A detailed comparison of EMR, POG and BG graphical techniques is given in Tab. I. In most cases the generation of a BG based on a given POG is easily practicable and vice versa. Regarding the teaching and initial training

Mnemonic	EMR	POG	BG
Title	Energetic Macroscopic Representation	Power Oriented Graph	Bond Graph
Author	A. Bouscayrol	R. Zanasi	H. M. Paynter
Year	2000	1991	1959
Symbolism	dependent of the energy domain	independent of the energy domain	independent of the energy domain
Energy domain	electrically / mechanically; extensible in principle	all known	all known
Connections	unidirectional	unidirectional	bidirectional
Power variables	scalar or vectorial (but not obvious in this example)	scalar or vectorial	scalar or vectorial
Causality	exclusive integral	integral preferably; differential possible	integral (preferably) or differential
Basic elements	9 (electrical / mechanical)	4 = 2 (basic elements) + 2 (I/O, mixing point)	9 = 8 (Simulink blocks) + 1 (activated bond)
Visibility of both directions	graphically visible	graphically visible	not graphically visible
Assistance for the control	inversion rules, see [4]	none	none
Reference direction for power flow	no	it is not explicit, but it is present in the graph	yes
Displacement / momentum explicitly	no	yes	yes
Special measure element	no	no	yes
Mathematical model from graphical description	partially obtainable	directly obtainable (explicit in the graph)	directly obtainable (implicit in the graph)
Simulink library	icon library	none (not necessary)	add-on library BG V.2.1
Usage hints	user defined subsystems	standard blocks	blocks and editor as usual
Main objective	simulation and control	simulation and analysis	simulation and design

TABLE I
DETAILED COMPARISON OF EMR, POG AND BG.

of power flow based modelling, the POG profits by its minimal set of defined elements and the possibility of a quick implementation into a simulation structure. As for BGs valid the physical structure remains conserved and the transformation of the power variables is clearly recognizable. In contrast to that, the BG may represent a more compact model because of the definition of bidirectional connections - please compare Fig. 4 with Fig. 5. Furthermore BGs offer implicit information of the performed use of the power. Moreover some familiarity with BG modelling and certain mechanical resp. electrical schemes provided it may be easier and more effective to generate directly a BG model without definition of any equation systems in a first step. According to the aim of modelling power flow based both methods guarantee power data at each point of the model of course.

Comparing EMR and scalar BG, it is apparent that EMR coupling devices (distribution/addition of energy) correspond with BG nodes and EMR energy accumulation elements subsume BG C/I-storages and R-elements (losses), i.e. they are more compact, but offer less external information and thus contain time constants like signal flow diagrams - please compare Fig. 2 with Fig. 3. Furthermore in principle there is a clear correspondence between EMR converter elements and TF resp. GY of BG's - this is also valid for modulated parameters. EMR is restricted to integral causality and typically scalar connections, but provides a better base for the derivation of control structures because of the graphical definition of the coupling devices. Although the previous remarks show an implicitly close relationship between POG and EMR, this may not be seen clearly apparent via the diagrams and results from the graphical representations on the one hand as well as on the other hand from the reduced set of elements for the POG. A possible scalar POG representation does not influences this statement essentially. Nevertheless it may be recognized that pairs of POG connection blocks correspond to EMR converter elements, one or several POG elaboration sections correspond to energy accumulation elements and POG mixing points as a part of the elaboration sections serve as EMR coupling devices.

VIII. SIMULATION

The EMR, POG and VBG schemes of Fig. 3, Fig. 4 and Fig. 5 can be easily converted in three different Simulink block diagrams, see [15]. The simulation results shown in Fig. 6-9 have been obtained using the following parameters: input voltage $V_{DC} = 750$ V, filter parameters $C_f = 6$ $\mathbf{m}$F, $R_f = 0.01$ Ohm and $L_f = 0.9$ mH, DC motor parameters $L_{fd1} = L_{fd2} = 0.5$ H, $R_{fd1} = R_{fd2} = 2$ Ohm, $L_{arm1} = L_{arm2} = 0.54$ mH and $R_{arm1} = R_{arm2} = 0.025$ Ohm, torque coefficients $k_{dcm1} = k_{dcm2} = 0.077$, bogie ratios $m_{b1} = m_{b2} =$

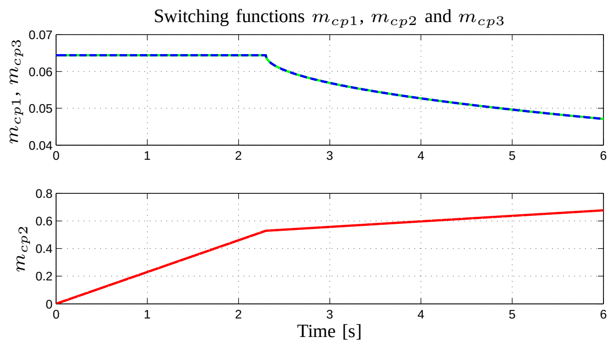

Fig. 6. The switching functions m_{cp1} (blue-dashed), m_{cp2} (red) and m_{cp3} (green).

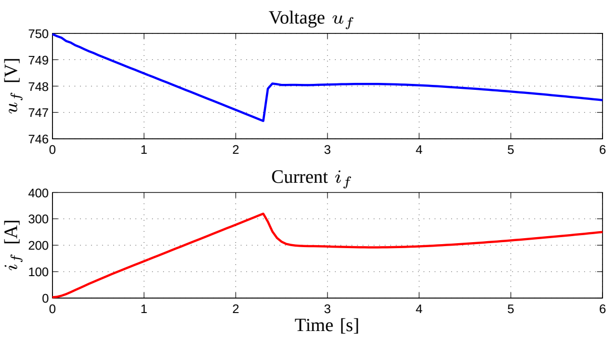

Fig. 7. Input filter: voltage u_f and current i_f.

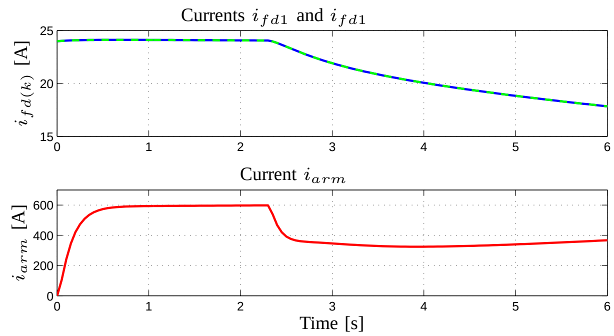

Fig. 8. Field and armature windings: currents i_{fd1} (blue-dashed), i_{arm} (red) and i_{fd2} (green-dashed).

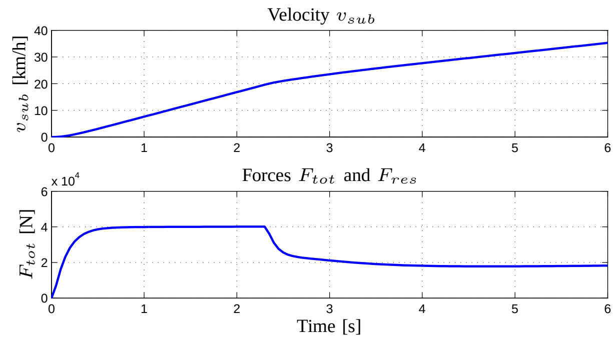

Fig. 9. Subway velocity v_{sub} and traction force F_{tot}.

18.12, chassis mass $M = 15000$ kg, resistance force parameters $F_0 = 1550$ Nm, $a_r = 30$, $b_r = 4$ and $\alpha = 0$. Initial conditions: $v_{sub}(0) = 750$ V, $i_{fd1}(0) = i_{fd2}(0) = 24$ A. The average values of the modulation functions m_{cp1}, m_{cp2} and m_{cp3} are shown in Fig. 6. The voltage u_f and the current i_f of the filter are shown in Fig. 7. The field and armature currents i_{fd1}, i_{fd2} and i_{arm} are shown in Fig. 8. Finally, the subway velocity v_{sub} and the traction force F_{tot} are shown in Fig. 9. Because they are based on the same relationhsips, all the presented descriptions lead to the same simulation results.

IX. Conclusion

The same traction system has been modelled using four different modelling techniques, all based on energetic considerations. The main common points and differences of these techniques have been discussed. They just suggest different graphical descriptions of the same modelling relationships, in order to graphically point out one or several characteristics of the system. For these reasons, they give another global view of system in comparison with classical tools as transfer functions or state space models. Simulation results have been provided.

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