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Reverse engineering of a railcar prototype via energetic macroscopic representation approach

Kréhi Serge Agbli [a,*], Daniel Hissel [a], Marco Sorrentino [b], Frédéric Chauvet [c], Julien Pouget [d]

[a] FCLAB Research Federation, FR CNRS 3539, FEMTO-ST/Energy Department, UMR CNRS 6174, University of France-Comté, 90010 Belfort Cedex, France
[b] Department of Industrial Engineering, University of Salerno, via Giovanni Paolo II, 132, Fisciano, SA 84084, Italy
[c] SNCF/Rolling Stock Engineering Centre, 4 Allée des Gémeaux, 72100 Le Mans, France
[d] SNCF/Innovation and Research/Optimization and Network Services/Group of Energetic and Technique for the Maintenance, 40 avenue des Terroirs de France, Immeuble Lumière, Aile Nord, 4ème étage, 75611 Paris Cedex 12, France

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ABSTRACT

Energetic Macroscopic Representation (EMR) modelling approach is proposed to perform model-based reverse-engineering of a new railcar range, having six propulsion units, each consisting of a diesel engine and a traction motor. Particularly, EMR intrinsic features were exploited to perform phenomenological structuration of power flows, thus allowing proper and comprehensive modelling of complex systems, such as the under-study railcar. Based on some prospective real trips, selected in such a way as to enable realistic evaluation of effective railcar effort, EMR-based prediction of railcar energy consumption is performed. Furthermore, physical consistency of each powertrain component operation was carefully verified. The suitability of EMR approach was thus proven effective to perform reverse-engineering of known specifications and available experimental data, with the final aim of reconstructing a high fidelity computational tool that meets computational burden requirements for subsequent model-based tasks deployment. Finally, specific simulation analyses were performed to evaluate the potential benefits attainable through electric hybridization of the original powertrain.

1. Introduction

The recent worldwide awareness of increasingly challenging environmental and energy savings issues, associated to transportation, pushes the French Railway Society (SNCF) to become more and more committed to develop and implement innovative, yet practical, solutions to reduce greenhouse gas emissions and pollutants. This accordingly implies the reduction of the fuel consumption of the company's rolling stock. By tackling the greenhouse gas emissions and pollutants, the SNCF deals at the same time with the environmental issues and its spending reduction policy.

Therefore, many efforts are made to comply with the environmental standards. By means of engineering processes, the SNCF intends to deal with the above issues on the trains of its rolling stock. That is to say, reduce the fuel consumption without compromising on rail network service. To fulfil this objective, the company engaged some researches around three key items, namely efficient powertrains sizing, proper hybridization and reliable and suitable energy management [1–6]. Several works exist, in the literature, on the same topics involving electrical and hybrid electrical vehicles [7–25]. On the other hand, current literature denotes a substantial lack of contribution in the field of model-based energetic analysis of railcars.

More in detail, railcar powertrains differ from each other in terms of power flow topologies. Therefore, several energetic models were developed for hybridization, sizing and energy management purposes for a given topology. Nevertheless, such models often fail in terms of generalisation and versatility capabilities, thus requiring substantial adaptation work prior to transfer associated model-based procedures to a different powertrain topology. Many locomotives models are available [4–14] but cannot be directly used on another hybrid system. As it is for models, it is also for the related energy management.

In fact, even if the hybrid system is pertinently designed, to make use of its beneficial features the power flows should properly be managed along the mission of the train. Energy management is, therefore, a key-point for a suitable and efficient behaviour of the drivetrain.

* Corresponding author.
E-mail addresses: serge.agbli@femto-st.fr (K.S. Agbli), daniel.hissel@univ-fcomte.fr (D. Hissel), msorrentino@unisa.it (M. Sorrentino), frederic.chauvet@sncf.fr (F. Chauvet), julien.pouget@sncf.fr (J. Pouget).

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Nomenclature

A	resistance force's coefficient (da N/t)
B	resistance force's coefficient (da N/t/(km/h))
C	resistance force's coefficient (da N/t/(km/h)^2)
T_{de}	engine torque (N m)
T_{de_res}	total load torque (N m)
Ω_{de}	engine speed (rad s^{-1})
T_{hf}	hydraulic circuits torque (N m)
T_{ab}	24 V alternator torque (N m)
T_{altp}	mean alternator torque (N m)
P_f	fuel chemical power (W)
$\dot{m}_f$	fuel mass flow (kg s^{-1})
$\dot{m}_{th}$	thermal losses equivalent fuel mass flow (kg s^{-1})
K_p	IP controller proportional coefficient
K_i	IP controller proportional integral coefficient
C_i	capacitor i (F)
L_i	inductance (H)
v_i	voltage i (V)
i_i	current i (A)
R_i	resistance i (Ω)
m_i	modulation function
T_{mtr}	traction machine torque (N m)
I_{dq}	current in dq frame (A)
E_{dq}	the electromotrice force in the dq frame (V)
i	the line' corrected profile (‰)

Greek

φ_{rd}	the rotor flux induced by the permanent magnets (Wb)
ξ	damping coefficient
ω_n	undamped natural frequency (rad s^{-1})
α	the line' corrected angle (rad)

Acronyms

LHV	Low Heating value
PMSM	permanent magnet synchronous machine
PWP	power pack
EMR	Energetic Macroscopic Representation
MCS	maximum control structure
DMU	diesel multiple units

Subscripts

ref	reference value
rd	rotor's d axle

Before tackling a particular energy management strategy in the hybridization framework, the related model should be developed. It can afterwards be exploited to perform model-based development of a convenient energy management strategy emphasising on causal strategies. These are real-time application propitious [26–31]. Instead, non-causal strategies are time-consuming and are only used off-line [32–35].

Furthermore, all the foregoing approaches are, most of the time, dealt with assuming driving cycles to be known in advance. For trains such an approach could in principle be successful and well posed. Nevertheless, in real-world railway service operation there are many contingencies for which it is impossible to predict with certainty the driving cycles. Moreover, the specific railcar powertrain topology, to be destined to a given path, could often be difficult to determine. This happens especially because of the above mentioned need of tackling energy and environmental issues by introducing advanced powertrain technologies, such as hybrid railcars. In this purpose, SNCF, in close cooperation with Alstom (the new railcar manufacturer), has developed the specific railcar range, on which this work focuses on, in a hybridization purpose. The challenges will accordingly be, on one hand, to be able to handle the enormous amount of information and specification provided by Alstom and SNCF, and, on the other, to develop a modelling framework generic enough to account for a number of railcar powertrain topologies. Consequently, a realistic model-based hybridization and efficiency analysis will be fulfilled. This goal is pursued using a physical modelling process.

In fact, the expected modelling tool should cover complex systems, implying subsystems interaction based on systemic approach. Therefore, this tool will lead to obtaining best performance. Moreover, energy management purpose requires the respect of the physical causality; hence the causal principle need. However, the energy management is achieved through the control, thus implying the inversion of a causal model of the system in order to respect its energy properties. In fact, a complex system requires organised modelling approach, useful for intermediary steps. The graphical modelling tool complying with the earlier modelling criteria described is EMR. It is characterised by the power flow phenomenological structuration, thanks to a causal relationship based on action–reaction and physical causality principles. Furthermore, EMR is based on control feature. This allows deducing a control structure from the EMR model leading to a real application-based behaviour. This graphical modelling tool is particularly suitable for developing control tasks destined to multi-physics systems [36,40].

Several energetic systems models aiming for control purpose and using EMR were already developed in different engineering applications [5,6,18,37–48].

EMR is a very strong graphical modelling tool for the particular engineering process presented here. This process is based on an accredited railcar prototype (passengers' transportation ability to operate on suburban main-lines) already on service. By the help of EMR, the pursued objectives were reached, as deeply described and accordingly commented in the current article.

The novelty in the modelling methodology presented and discussed throughout the paper relies on the enabled "reverse engineering" process. In fact, for standard engineering process, first is performed the feasibility study and afterwards the modelling and analytical simulation. Once the previous steps have been achieved, a fine-tuning step-based validation tests on the prototype is needed before the large-scale production. It is here used large scale produced devices result from this standard process. Based on these devices, further analyses are made in order to deal with the energy issues above mentioned. By reverse engineering, we mean the phenomenological description and modelling of an existing system. It could be of help to improve the system behaviour and its efficiency. The greenhouse reduction policy is increasingly strengthening. Therefore, the countries and the companies need to apply more and more the "reverse engineering". Moreover, this approach is helpful to make their energetic devices comply with the environmental standards.

The energetic model should then be developed aiming at accurately describing the existing prototype railcar power flows behaviour. Such a reverse engineering modelling approach is pursued disregarding depth knowledge of the train energetic devices and sub-systems. This considerable lack of knowledge is due to either