IEEE VTS Motor Vehicles Challenge 2019 – Energy Management of a dual-mode locomotive

Walter Lhomme[1,2*], Tony Letrouvé[2,3], Loïc Boulon[4], Samir Jemeï[2,5,6], Alain Bouscayrol[1,2], Frédéric Chauvet[2,3]
[1] Univ. Lille, Centrale Lille, Arts et Métiers Paris Tech, HEI, EA 2697 –
L2EP - Laboratoire d'Électrotechnique et d'Électronique de Puissance, F-59000 Lille, France
[2] French network on HEV, MEGEVH, France
[3] Innovation & Research Dept., SNCF, Paris, France
[4] Université du Québec à Trois-Rivières, Hydrogen Research Institute, Trois-Rivières, Canada
[5] FEMTO-ST Institute, Univ. Bourgogne Franche-Comté, CNRS, F-90010 Belfort, France
[6] FCLAB, Univ. Bourgogne Franche-Comté, CNRS, F-90010 Belfort, France

*Corresponding author: Walter.Lhomme@univ-lille.fr

***Abstract* — After the success of the first two international IEEE VTS Motor Vehicles Challenges launched in 2016 at Hangzhou, China, and in 2017 at Belfort, France during the IEEE Vehicle Power and Propulsion Conference (VPPC), this paper proposes the technical framework of the third challenge. For the edition of 2019 the challenge is focused on a dual-mode locomotive. The locomotive is powered either from a DC overhead line through a pantograph or using an on-board fuel cell with battery and supercapacitors. By taking into account the operational costs the challenge issue is to propose an Energy Management Strategy (EMS) to minimize the consumption of the electricity network and hydrogen; and to increase the lifetime of the fuel cell and energy storage system. The locomotive model will be provided to the participants using Matlab-Simulink software. Both industrial and academic teams are welcomed to propose their own EMS. The participants with top scoring will be invited to present their results in a special session at the 2019 IEEE VPPC.**

Keywords — Railway traction, fuel cell, battery, supercapacitor, overhead line, bi-mode, Energetic Macroscopic Representation

I. INTRODUCTION

Since 2016, the IEEE Vehicular Technology Society (VTS) proposes to participate each year, during the annual conference IEEE-VPPC, at an international challenge devoted to the Energy Management Strategy (EMS) of a studied vehicle. The two best participant teams that propose the best EMS receive an award with a grant to attend the next IEEE-VPPC conference and to present their results in a special session. The first edition, launched in October 2016 at Hangzhou in China, dealt with a fuel cell vehicle with battery [1]. The second edition, launched in December 2017 at Belfort in France, was dedicated to a range extender vehicle [2]. For these first two editions 48 and 92 industrial and academic participants from 14 and 16 countries proposed their EMS. On the strength of this success, the IEEE VTS, the University of Lille, SNCF, the French railway company, UQTR, the University of Bourgogne Franche-Comté and MEGEVH, the French scientific network on electric and hybrid vehicles, launch the third IEEE VTS Motor Vehicles Challenge. This challenge focuses on the energy management of a dual-mode locomotive. Both industrial and academic, from college and university, teams are welcomed to participate. The participants with top scoring will be invited to present their results in a special session at the 2019 IEEE-VPPC.

Transportation systems are a key issue in the challenge of global warming and petroleum resource depletion. New electrified vehicles are then developed to face this challenge [3]. If the production of electric locomotives is increasing [4], diesel-electric locomotives are still and often used, specifically due to electrification cost of the infrastructure [5]. To reduce the impact of the diesel engine on the environment, a compromise consists to use dual-mode locomotives to operate on non- and electrified tracks [6]. Dual-mode locomotive is classically powered by an on-board diesel-electric set or using a catenary connected to a DC or AC overhead line. The main advantage is to be local environment friendly and economically profitable when the route is electrified. The pollution and CO_2 emissions can then be reduced. With its Mitrac Hybrid, Bombardier has chosen this technology to operate on non- and electrified tracks [7]. Diesel-electric set generates electrical power from fuel, with an internal combustion engine, to supply the electric traction subsystem. For this kind of architecture, no energy recovery during braking is possible. Moreover, the diesel engine power has to be sized to provide the maximum traction power, and its best efficient operation point is not often reached. The use of an Energy Storage System (ESS) is a valuable way to reduce the energy consumption of diesel-electric locomotives, but also of electric locomotives [8], [9]. Different hybridizations of diesel-electric locomotive have been developed using battery [10]-[12], supercapacitors [13], [14] and flywheels [15]. An alternative solution consists to replace the engine by a fuel cell [16], [17].

Hydrogen mobility is rapidly scaling up in many countries. France launched, in June 2018, its national hydrogen roadmap which sets ambitious targets in terms of mobility.

The roadmap aims, for instance, to increase the hydrogen vehicles deployment, i.e. 5000 light vehicles and 200 heavy vehicles, and 100 hydrogen stations by 2023. The railway sector is also targeted in this roadmap. Following the 2015 United Nations Climate Change Conference COP21 engagement, SNCF has set strong ecological targets: cut greenhouse gases emissions by 20% and decrease energy consumption by 25% by 2025 [18]. SNCF is actively working toward the replacement of diesel propulsion with low carbon alternative systems. Hydrogen is seen as an interesting candidate to address decarbonization of non-electrified rail lines. With its iLint, Alstom has recently developed a first hydrogen train prototype and has shown the technical feasibility of this technology. The emergence of hydrogen technology in the rail sector brings new questions on system architecture, on-board energy management and financial benefits. This is the main focus of this challenge.

A hybrid electric vehicle combines the advantages of different kind of sources to meet several objectives, such as reducing the fuel consumption or improving the battery lifetime [19]. To reach these objectives the EMS is the key factor [20]-[25]. Indeed, a smart EMS decides how the system has to operate according to specifications. For the third IEEE VTS Motor Vehicles challenge the EMS development for a dual-mode locomotive with a fuel cell, battery and supercapacitors is proposed. In the framework of this challenge, the locomotive model and its control is provided into a Matlab-Simulink environment using the Energetic Macroscopic Representation (EMR). By taking into account the operational costs, challenge participants will have to design and propose an EMS to:

- minimize the consumption of the electricity network,
- minimize the consumption of the hydrogen,
- increase the lifetime of the fuel cell,
- increase the lifetime of the ESS.

The remainder of the paper is organized as follows. Section II presents the studied locomotive. Section III describes the architecture of the locomotive model, control and strategy. Section IV is devoted to the EMS design specifications, the scoring procedure and the software.

II. STUDIED DUAL-MODE LOCOMOTIVE

The studied vehicle is a regional train with a dual-mode locomotive. The locomotive has a common drivetrain that operates on non- and electrified tracks. The traction subsystem is composed of four traction drives. The vehicle is limited at a maximum speed up to 140 km/h and the considered mass is 140 t. The locomotive can be powered by a non-reversible DC overhead line through a pantograph or using an on-board fuel cell (FC on Fig. 1) with battery (BAT) and supercapacitors (SC). All of the sources are connected to the DC bus, which has a voltage range between 1 kV to 1.9 kV. Reversible boost choppers and smoothing inductors are used to interface the DC bus to the battery and supercapacitors. A non-reversible boost chopper is used for the fuel cell subsystem. The main parameters of the studied locomotive are summed up in Table 1. A polymer electrolyte membrane fuel cell (PEMFC), a Li-ion battery and supercapacitors with organic electrolyte are used in this study. All the numerical values of the parameters will be provided into Matlab files, available on the IEEE VTS 2019 Challenge website [26].

III. LOCOMOTIVE MODELING

A Matlab-Simulink™ simulation of the studied locomotive model with all the numerical values of the parameters will be provided to the challenge participants. The model is organized using EMR, which is a graphical description of energetic systems [27], [28]. Pictograms are used to describe the system: 1) green oval pictograms describe the source of the system; 2) orange rectangle pictograms with diagonal line describe accumulation elements, which store energy and impose state variables; 3) orange square and circle pictograms describe respectively a mono and a multi-domain conversion of energy without accumulation of energy; 4) overlapped orange pictograms describe coupling elements, which distribute energy without accumulation of energy. According to the physical causality principle the accumulation elements impose inputs and outputs to other elements.

The electrical relationships of the structural scheme of Fig. 1 are synthetized in Table 2. All current nodes are described with coupling elements to distribute the energy (3)-(7). The braking resistor is considered as a controllable source (10). Its current is equal to its reference. The choppers, their smoothing inductors and their controls are described with static models, which are sufficient for an energetic study. Maps of efficiency describe then the losses (1)-(2). In Fig. 2, the choppers are described by mono-domain converters.

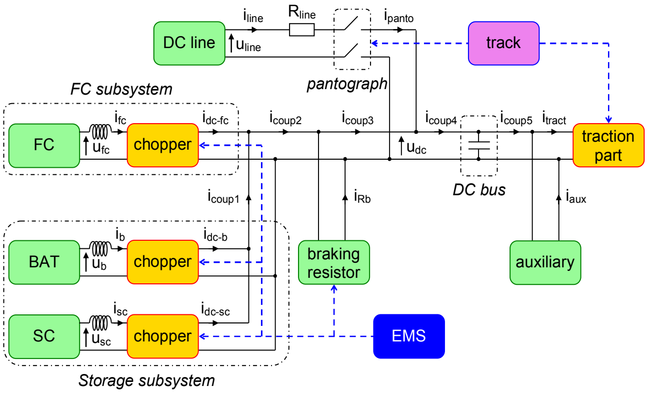


Fig. 1. Structural scheme of the studied locomotive

TAB. 1. MAIN PARAMETERS OF THE STUDIED LOCOMOTIVE

Locomotive	
Mass	140 t
Maximal speed	140 km/h
Number of traction drive	4
DC bus	
Voltage range of the DC bus	1000 – 1900 V
Capacity of the DC bus	40 mF
DC overhead line	
Voltage of the catenary	1500 V
Resistance per unit of length	0.1 Ω/km

TAB. 2. RELATIONSHIPS OF THE STUDIED LOCOMOTIVE

BAT and SC boost chopper	$i_X = \frac{u_{dc} i_{dc-X}}{\eta_{dc-X}^{\gamma} u_X}$ with $X \epsilon [b, sc]$; $\begin{cases} i_{dc-X} = i_{dc-X-ref} \\ u_{dc} > u_X \end{cases}$; $i_{X-min} \le i_X \le i_{X-max}$ and $\begin{cases} \gamma = 1 \; if \; u_{dc} i_{dc-X} \ge 0 \\ \gamma = -1 \; if \; u_{dc} i_{dc-X} < 0 \end{cases}$	(1)
FC boost chopper	$i_{fc} = \frac{u_{dc} i_{dc-fc}}{\eta_{dc-fc} u_{fc}}$ with $\begin{cases} i_{dc-fc} = i_{dc-fc-ref} \\ u_{dc} > u_{fc} \end{cases}$ and $\begin{cases} 0 \le i_{fc} \le i_{fc-max} \\ A_{min} \le \frac{d}{dt} i_{fc} \le A_{max} \end{cases}$	(2)
current nodes	$i_{coup1} = i_{dc-b} + i_{dc-sc}$	(3)
	$i_{coup2} = i_{coup1} + i_{dc-fc}$	(4)
	$i_{coup3} = i_{coup2} - i_{Rb}$	(5)
	$i_{coup4} = i_{coup3} + i_{panto}$	(6)
	$i_{coup5} = i_{tract} + i_{aux}$	(7)
DC line and pantograph	$\begin{cases} \text{pantograph connect. (ON)} \\ i_{line} = i_{panto} = \frac{u_{line} - u_{dc}}{R_{line}} \end{cases}$ with $i_{line} = i_{panto} \ge 0$	(8)
	$\begin{cases} \text{pantograph disconnect. (OFF)} \\ i_{line} = i_{panto} = 0 \end{cases}$	(9)
braking resistor	$i_{Rb} = i_{Rb-ref}$ with $i_{Rb} \ge 0$	(10)
DC bus	$i_{coup4} - i_{coup5} = C_{dc} \frac{d}{dt} u_{dc}$	(11)

The DC overhead line and pantograph are described with the source DC in Fig. 2. When the pantograph is connected to the DC line (ON) the currents of the DC line and pantograph are determined by the ratio between the voltages applied on the line resistor (8). As the electricity network is considered as irreversible the braking energy cannot be sent back to the electricity network. The currents can be only positive. When the pantograph is disconnected to the DC line (OFF) the currents of the DC line and pantograph are set to zero (9). The DC bus is a key element of the architecture. Every power flow passes through it. The dynamic relationship (11) is then required to describe it. As a DC bus stores energy an accumulation element is used to describe it in Fig. 2.

The traction subsystem is described by an electrical source (Tract. in Fig. 2), which delivers the traction current i_{tract} for a given speed profile $v_{loco-ref}$. The traction subsystem is based on four electric traction drives. Each of them are connected to a mechanical transmission, which contains a gearbox, wheels, and a mechanical brake. No slipping phenomena, no curve and no mass transfer are considered. Moreover, the electric drives are modeled by static relationships. A closed-control loop with an inversion-based control of the EMR is achieved to track the speed profile. More explanations and details can be found in [29]. The auxiliary subsystem is described by an electrical source (Aux. in Fig. 2), which delivers the auxiliary current i_{aux}. Main auxiliaries are considered in this paper, i.e. the heating system of the passenger cabins, the air compressor of the braking and the ventilation. The modelling part of the heating system can be found in [30]. A current profile will be given for each studied speed profile.

The core of the FC model is the polarisation curve $V_{fc-cell} = f(J_{fc-cell})$: the voltage of one cell as a function of the current density in A/cm^2. The current density and the total voltage are then calculated in an adaptation element from the total current and the voltage of one cell, respectively. The hydrogen consumption is a linear function of the current, including an overconsumption stoichiometry factor. Due to limitation to gas supply dynamics, the variation rate of the total current is limited (A_{min} and A_{max} in (2)). The battery model is based on an open-circuit voltage with a series resistor. Both parameters are indexed with the State of Charge (SoC) of the battery. The supercapacitors are modelled with RC branch model, which result from the Zubieta and Bonert model [31]. The Zubieta and Bonert model is an electrical circuit composed of several RC branches, whose time constants are different to take into account the internal physical phenomena.

IV. ENERGY MANAGEMENT STRATEGY DESIGN

A. Specification and Scoring

Depending on the speed profile of the locomotive $v_{loco-ref}$ the traction subsystem of Fig. 2 will impose to the DC bus the required current i_{coup5}, which is from the currents of the traction and auxiliary subsystems. The required current will have to be managed by the sources of the locomotive in the best way to minimize the consumptions of the electricity network and hydrogen; and to increase the lifetime of the fuel cell and ESS. To develop and test their own EMS three speed profiles will be available to the participants. All proposed participant EMS will be, however, scored with an unknown speed profile. The challenge issue is then to propose a real-time optimization based-EMS.

Because a fuel cell does not produce any pollutants the DC overhead line and the fuel cell could be used at the same time. If a track is electrified participants have then the choice to use the fuel cell and/or the DC line. The battery, supercapacitors and braking resistors could, therefore, be used with the DC line and/or the fuel cell.

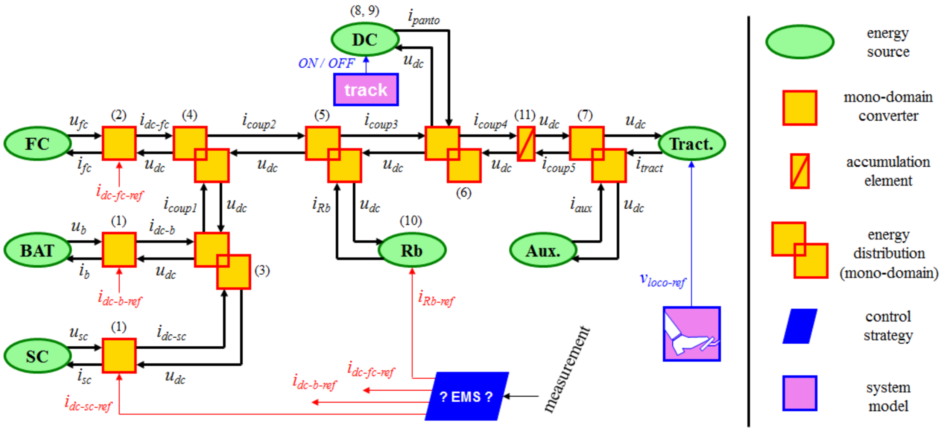


Fig. 2. Energetic macroscopic representation of the studied locomotive

1) Minimize the consumption of the electricity network – The operational cost of the electricity network is calculated by taking into account the total energy consumption of the DC overhead line:

$$€_{net}(t) = \frac{N_{cost}}{3600.1.10^6} \int_0^t p_{line}(t)\, dt \tag{12}$$

with $p_{line}(t)$ the instantaneous power (W) delivered by the DC line of the electricity network, and N_{cost} the cost of the electricity network per unit of energy (€/MWh), which takes into account the public electricity network tariffs (TURPE).

2) Minimize the consumption of the hydrogen – The hydrogen operational cost is calculated by taking into account the hydrogen consumption:

$$€_{H_2}(t) = \frac{H_{2-cost}}{1.10^3} \int_0^t \dot{m}_{H2}(t)\, dt \tag{13}$$

with $\dot{m}_{H2}(t)$ the hydrogen mass flow (g/s) and H_{2-cost} the hydrogen cost per unit of hydrogen mass (€/kg) based on the projection of 2020 [32].

The lifetime of the fuel cell and ESS is taken into account by a depreciation cost. Degradation functions $\Delta_X(t)$, with X the considered sources – fuel cell, battery or supercapacitors –, have then to be detailed. A value of 0 and 1 will respectively correspond to the beginning and end of the considered sources life.

3) Increase the lifetime of the fuel cell – The fuel cell degradation function $\Delta_{fc}(t)$ depends on the power operation $p_{fc}(t)$ and the start number N_{start} of the fuel cell [33], [34]:

$$\Delta_{fc}(t) = N_{start}\Delta_{start}(t) + \int_0^t \delta(t)\, dt \tag{14}$$

$$\delta(t) = \frac{\delta_0}{3600}\left(1 + \frac{\alpha}{P_{fc-rat}^2}\left(p_{fc}(t) - P_{fc-rat}\right)^2\right) \tag{15}$$

with $\Delta_{start}(t)$ the start-stop degradation coefficient, δ_0 and α load coefficients and P_{fc-rat} the rated power of the fuel cell (W). The fuel cell is considered as ON when its current $i_{fc}(t)$ will be greater than 0 A. The operational cost of the fuel cell can then be deduced from $\Delta_{fc}(t)$:

$$€_{fc}(t) = \frac{P_{fc-rat}}{1.10^3} FC_{cost}\Delta_{fc}(t) \tag{16}$$

with FC_{cost} the fuel cell cost per unit of power (€/kW), which is based on the target of the department of energy (DOE) of the USA [35].

4) Increase the lifetime of the supercapacitors – The lifetime of the supercapacitors is expected to be 15 years. A regional train travels 2000 h a year, i.e. an expected lifetime of 30000 h for 15 years. The degradation function of the supercapacitors $\Delta_{sc}(t)$ is calculated by the ratio between the use time t_{use} and the expected lifetime:

$$\Delta_{sc}(t) = \frac{t_{use}}{30.10^3} \tag{17}$$

The operational cost of the supercapacitors can then be deduced from $\Delta_{sc}(t)$:

$$€_{sc}(t) = E_{sc-rat}SC_{cost}\Delta_{sc}(t) \tag{18}$$

with E_{sc-rat} the rated energy of the supercapacitors (kWh) and SC_{cost} the supercapacitors cost per unit of energy (€/kWh).

5) Increase the lifetime of the battery – The lifetime of the battery is expected to be the half of the lifetime of the supercapacitors, i.e. 15000 h for 7.5 years. The battery degradation function $\Delta_b(t)$ depends of the state of charge with $f(SoC_b)$ and power dynamics with $g(i_b)$ [36]:

$$\Delta_b(t) = \frac{1}{3600.15.10^3.Q_{b-rat}} \int_0^t |f(SoC_b).g(i_b).i_b(t)|\, dt \tag{19}$$

with Q_{b-rat} and $i_b(t)$ respectively the rated capacity (Ah) and the current (A) of the battery. The operational cost of the battery can then be calculated from $\Delta_b(t)$:

$$€_b(t) = E_{b-rat}B_{cost}\Delta_b(t) \tag{20}$$

with E_{b-rat} the rated energy of the battery (kWh) and B_{cost} the battery cost per unit of energy (€/kWh).

To have a fair scoring of the EMS, the final SoC of the battery and supercapacitors should be the same for each participant. As real-time EMS is used, the SoC at the end of the cycles will be different. A charge sustaining process is then needed to sustain the SoC. It may be noted that the participants have not to be developed this charge sustaining mode. A positive or negative penalty $€_{sust}$ will be then used to sustain the ESS using the DC line:

$$€_{sust}(t) = \frac{N_{cost}}{1.10^3}\left(\eta_{dc-b-avg}.E_{b-end} + \eta_{dc-sc-avg}.E_{sc-end}\right) \qquad (21)$$

with $\eta_{dc-b-avg}$ and $\eta_{dc-sc-avg}$ the average value of the efficiency maps of the boost choppers; and E_{b-end} and E_{sc-end} the energy stored of the battery and supercapacitors at the end of the simulation (kWh). Negative and positive penalties mean respectively that the ESS has been too charged and discharged during the simulation. The ESS would be then charged by the DC line for a positive penalty and the ESS would help the DC line by giving power for a negative penalty during the propulsion of the locomotive. The total cost to minimize $€_{tot}$ can then be defined as:

$$€_{tot} = €_{net} + €_{H_2} + €_{fc} + €_{sc} + €_{b} + €_{sust} \qquad (22)$$

B. *Matlab-Simulink Simulation Program*

The EMR of the train has been implemented in Matlab-Simulink^{TM} using a library with basic EMR elements (Fig. 3) [37]. Three profiles of the speed, with different maximal speeds – 50, 100 and 140 km/h –, and electrified tracks are given to the participants to develop and test their own EMS (Fig. 4). The electrified tracks have been chosen to propel the train at interstation of the travel.

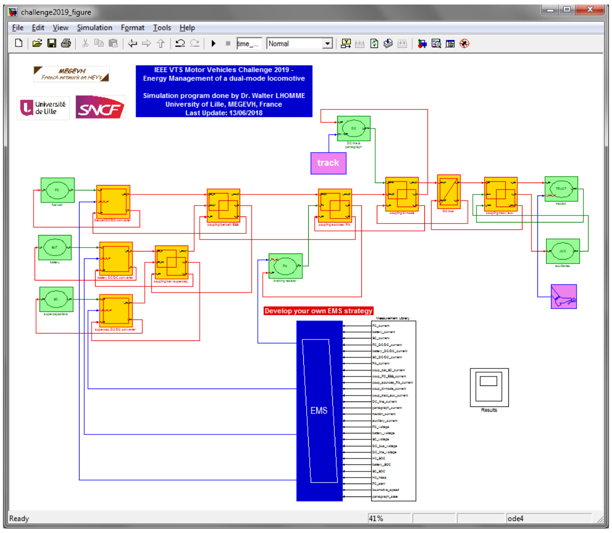
All available measurements are listed in the “Measurement library” subsystem, which is depicted with the white block in Fig. 3. It should be noted that even if the given program is an open source, participants have not the right to modify the system model and the “Measurement library” subsystem. The participants have to only develop their EMS, which is depicted with the dark blue block in Fig. 3. It should be noted that an example with a filtering-based EMS is given into this block. All the numerical values of the simulation parameters will be provided into Matlab files. The limitations of the system, e.g. DC bus voltage range, minimal and maximal voltage of the supercapacitors, maximal current of the battery, maximal variation rate of the fuel cell current, will be detailed and will have to be respected. Some simulation results are given in the block “Results”, which is depicted by the scope in Fig. 3. The simulation procedure is defined in a “read me” file from the downloadable Matlab-Simulink^{TM} file available on the IEEE VTS 2019 Challenge website [26].

C. *Participation procedure and award*

Participants are invited to join in with this challenge by following the participation procedure describes in the IEEE VTS 2019 Challenge website: http://www.uqtr.ca/VTSMotorVehiclesChallenge19. Teams that propose the best EMS will receive an award with a certificate, an invitation to write and present a paper in a special session for the VPPC conference in 2019, and a grant that will cover the expenses related to the attendance of 2019 IEEE VPPC.

V. CONCLUSION

In this paper, the technical framework of the third IEEE VTS Motor Challenge is proposed. The challenge participants shall design and propose an Energy Management Strategy (EMS) for a dual-mode locomotive using the pantograph or an on-board fuel cell with battery and supercapacitors. By taking into account the operational costs the aim of the strategy is to minimize the consumption of the electricity network and hydrogen; and to increase the lifetime of the fuel cell and energy storage system. Participants will be ranked on the basis of a cost function with an unknown scoring speed profile. This challenge can then promote the achievement of future innovative EMS for locomotive application.



IEEE VTS Motor Vehicles Challenge 2019 -
Energy Management of a dual-mode locomotive

Simulation program done by Dr. Walter LHOMME
University of Lille, MEGEVH, France
Last Update: 13/06/2018

Fig. 3. Matlab-Simulink^{TM} simulation program

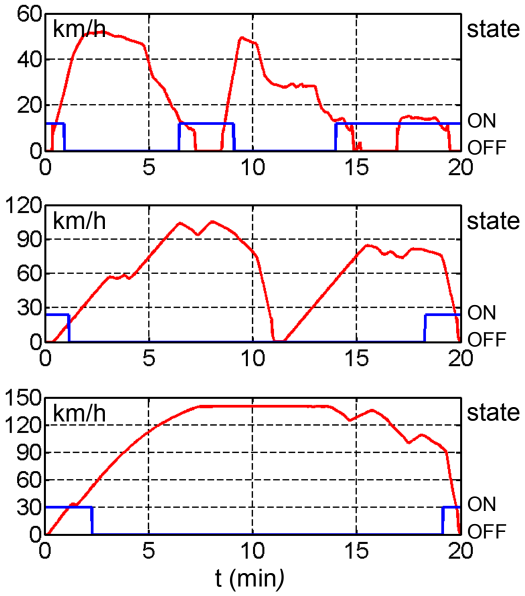


Fig. 4. Profiles of the locomotive speed (red) and the electrified tracks (blue) for the EMS development

REFERENCES

[1] C. Dépature, S. Jemei, L. Boulon, A. Bouscayrol, N. Marx, S. Morando, and A. Castaings, “IEEE VTS motor vehicles challenge 2017 – Energy management of a fuel cell/battery vehicle”, *IEEE-VPPC 2016*, Hangzhou, China, Oct. 2016.

[2] C. Dépature, S. Pagerit, L. Boulon, S. Jemei, A. Rousseau, A. Bouscayrol, “IEEE VTS motor vehicles challenge 2018 – Energy management of a range extender electric vehicle”, *IEEE-VPPC 2017*, Belfort, France, Dec. 2017.

[3] C.C. Chan, “The state of the art of electric, hybrid and fuel cell vehicles”, *Proc. of the IEEE*, vol. 95, no. 4, pp. 704-718, Apr. 2007.

[4] H. Kurz, “Rolling across Europe’s vanishing frontiers [electric railway technology]”, *IEEE Spectrum*, vol. 36, no. 2, pp. 44 – 49, Feb. 1999.

[5] T. R. Eastham, “Running off the rails”, *IEEE Spectrum*, vol. 40, no. 1, pp. 66-99, Jan. 2003.

[6] A. Della Valle, G. Pede, A. Coccia, E. Sciubba, “Thermo-economic analysis of dual-mode hybrid trains: concept development and possible applications”, *ICCEP’07*, pp. 82-88, Capri, Italy, May 2007.

[7] Bombardier website, “MITRAC Hybrid: the dual power propulsion chain”, accessed May 2018: https://www.bombardier.com/

[8] R. Barrero, J. van Mierlo, X. Tackoen, “Energy saving in public transport”, *IEEE Vehicular Technology Mag.*, vol. 3, no. 3, pp. 26-36, Sept. 2008.

[9] A.F. Burke, “Batteries and ultracapacitors for electric, hybrid, and fuel cell vehicles”, *Proc. of the IEEE*, vol. 95, no. 4, pp. 806-820, Apr. 2007.

[10] M. Osawa, “The NE train, first hybrid material in the world”, *Rail International*, vol. 35, no. AVR, pp. 16-23, Apr. 2004.

[11] R. Cousineau, “Development of a hybrid switcher locomotive the railpower green goat,” *IEEE Instrumentation & Measurement Mag., vol. 9, no. 1, pp. 25-29, Feb. 2006.*

[12] J. Baert, S. Jemei, D. Chamagne, D. Hissel, S. Hibon, D. Hegy, “Energetic macroscopic representation of a hybrid electric locomotive and experimental characterization of nickel-cadmium battery cells”, *EPE’13 ECCE Europe*, Lille, France, Sept. 2013.

[13] H. Shibuya, K. Kondo, "Designing methods of capacitance and control system for a diesel engine and EDLC hybrid powered railway traction system", *IEEE trans. on Industrial Electronics*, vol. 58, no. 9, pp. 4232-4240, Sept. 2011.

[14] B. Destraz , P. Barrade and A. Rufer "Power assistance for diesel-electric locomotive with supercapacitive energy storage", *IEEE-PESC’04*, June 2004.

[15] 1. Jaafar, C.R Akli, B. Sareni, X. Roboam, A. Jeunesse, A. "Sizing and energy management of a hybrid locomotive based on flywheel and accumulators", *IEEE trans. on Vehicular Technology*, vol. 58, no. 8, pp. 3947-3958, Oct. 2009.

[16] K. Ogawa, T. Yamamoto, T. Yoneyama, K. Kondo, T. Furuya, “Fuel cell powered railway vehicle and experimental test results”, *EPE’07*, Aalborg (Denmark), September 2007.

[17] K. Yedavalli, L. Guo, D.S. Zinger, “Simple control system for a switcher locomotive hybrid fuel cell power system”, *IEEE Transactions on Industry Applications*, vol. 47, no. 6, pp. 2384 – 2390, Nov./Dec. 2011.

[18] SNCF website, “Cutting our greenhouse gas emissions”, accessed June 2018: https://www.sncf.com/sncv1/en/our-commitments/consuming-less-energy

[19] C. C. Chan, A. Bouscayrol, and K. Chen, “Electric, hybrid and fuel cell vehicles: architectures and modeling”, *IEEE trans. on Vehicular Technology*, vol. 59, no. 2, pp. 589 – 598, Feb. 2010.

[20] M. Zandi, A. Payman, J.-P. Martin, S. Pierfederici, B. Davat, and F. Meibody-Tabar, “Energy Management of a fuel cell/supercapacitor/battery power source for electric vehicular applications”, *IEEE trans. on Vehicular Technology*, vol. 60, no. 2, pp. 433-443, Feb. 2011.

[21] F. R. Salmasi, “Control strategies for hybrid electric vehicles: evolution, classification, comparison, and future trends”, *IEEE trans. on Vehicular Technology*, vol. 56, no.5, pp. 2393-2404, Sept. 2007.

[22] L. Guzzella, A. Sciarretta, “Vehicle propulsion systems, introduction to modelling and optimization”, second edition, *Springer*, ISBN 978-3642094156, Oct. 2010.

[23] S. Ahmadi, S. M. T. Bathaee, “Multi-objective genetic optimization of the fuel cell hybrid vehicle supervisory system: fuzzy logic and operating mode control strategies”, *International Journal of Hydrogen Energy*, vol. 40, no. 36, pp. 12512-12521, Sept. 2015.

[24] K. Ettihir, L. Boulon, and K. Agbossou, “Optimization-based energy management strategy for a fuel cell/battery hybrid power system”, *Applied Energy*, vol. 163, pp. 142-153, Feb. 2016.

[25] A. Castaings, W. Lhomme, R. Trigui, A. Bouscayrol, "Real-time energy management strategies of a battery/supercapacitors system for electric vehicle under limitations", *Applied Energy,* vol. 163, pp.190–200, Feb. 2016.

[26] VTS Motor Vehicles Challenge 2019 website, accessed June 2018: http://www.uqtr.ca/VTSMotorVehiclesChallenge19

[27] A. Bouscayrol, B. Davat, B. de Fornel, B. François, J. P. Hautier, F. Meibody-Tabar, E. Monmasson, M. Pietrzak-David, H. Razik, E. Semail, M.F. Benkhoris, “Control structures for multi-machine multi-converter systems with upstream coupling”, *Mathematics and Computers in Simulation*, vol. 63, no. 3-5, pp. 261-270, Nov. 2003.

[28] A. Bouscayrol, J. P. Hautier, B. Lemaire Semail, “Systemic design methodologies for electrical energy systems: analysis, synthesis and management”, Chapter 3: graphic formalism for the control of multiphysical energetic system: COG and EMR, *ISTE and Wiley*, ISBN 978-1-84821-3888-3, 2012.

[29] C. Mayet, J. Pouget, A. Bouscayrol, W. Lhomme, “Influence of an energy storage system on the energy consumption of a diesel-electric locomotive”, *IEEE trans. on Vehicular Technology*, vol. 63, no. 3, pp. 1032-1040, March 2014.

[30] J. Pascal, A. Hoummas, T. Letrouvé, W. Lhomme, “Energetic benefits of trains by overrunning the heating system during the regenerative braking”, *IEEE-VPPC 2017*, Belfort, France, Dec. 2017.

[31] L. Zubieta, R. Bonert, “Characterization of double-layer capacitors for power electronics applications”, *IEEE trans. on Industry Applications*, vol. 36, no. 1, pp. 199-205, Jan./Feb. 2000.

[32] USDRIVE, “Fuel cell technical team roadmap”, *technical document*, June 2013.

[33] H. Chen, P. Pei, M. Song, “Lifetime prediction and the economic lifetime of proton exchange membrane fuel cells”, *Applied Energy*, vol. 142, pp. 154-163, March 2015.

[34] N. Herr, J. M. Nicod, C. Varnier, L. Jardin, A. Sorrentino, “Decision process to manage useful life of multi-stacks fuel cell systems under service constraint”, *FDFC’15*, Toulouse, France, Feb. 2015.

[35] A. Wilson, G. Kleen, D. Papageorgopoulos, “Fuel cell system cost - 2017”, *DOE Hydrogen and Fuel Cells Program Record*, Nov. 2017.

[36] H. Babazadeh, B. Asghari, R. Sharma, “A new control scheme in a multi-battery management system for expanding microgrids”, *IEEE PES ISGT 2014*, Istanbul (Turkey), October 2014.

[37] EMR website, “EMR library”, accessed June 2018: http://www.emrwebsite.org/library.html