CHEMICAL ENGINEERING TRANSACTIONS

VOL. 33, 2013

Guest Editors: Enrico Zio, Piero Baraldi

ISBN 978-88-95608-24-2; ISSN 1974-9791

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1333121

A Tool for Prediction and Optimization of Railway Traction Systems with Respect to an Expected Mission Profile

Monica Malvezzi[a] , Luca Pugi*[b] , Roberto Conti[b], Paolo Toni[b], Simone Tesi[c] , Enrico Meli [b], Andrea Rindi [b]

[a]University of Siena, Dept. of Information Engineering, Via Roma 26 53100 Siena, Italy
[b]University of Florence, Dept. of Industrial Engineering, Via Santa Marta 3, 50139 Firenze, Italy
[c] Ansaldo Bredra SPA, Via Ciliegiole 110, 51100 Pistoia, Italy
luca.pugi@unifi.it

In this work a tool called TrEnO aimed at evaluating efficiency, power dissipation and consequently the thermal behavior of several components of the traction system is proposed, in order to quantify the overall energy consumption and to provide instruments for its optimization. The tool takes into account the main line design parameters and more in general the required mission profiles. The model has been designed and developed in Matlab-Simulink™ environment, for mainly two purposes: firstly, this environment allows to easily develop overall optimization procedures of both braking and traction systems with respect to one or more design parameters and some fixed constraints on the line and/or on train components. Secondly, this type of develop tool allows a fast prototyping of the developed procedures for RT code, to be used for on board, diagnostic and prognostic systems.

1. Introduction

The design of fast and efficient models for the simulation and the optimization of railway traction systems is still an object of research and industrial interest, as stated by the recent contributions as for example (Baccari, 2012). This kind of models could be also used for the fast prototyping of model based controllers or integrated as a part of Hardware In the Loop testing system, as proposed for instance in (Pugi et al., 2012).

In particular among the various works currently available in literature it's possible to distinguish between models which are more specialized on the design of on board components and subsystems as in (Baccari, 2012) and models which are more devoted to the optimization of the complex interactions of the supply power systems, considering the interactions between different trains traveling on the railway net as the OpenPowerNet tool (Stephan, 2008).

In particular in the second scenario, the simulation of the interactions of the entire net considering both vehicles, power supply system including track and overhead line circuit, models used to simulate single components and in particular the on board ones, have to be drastically simplified in order to be maintained to an affordable level, required by the available computational resources.

However also in this case, a mixed approach can be considered, in which the level of detail, used for different components of the system is adapted to meet testing specifications (Stephen, 2008). For instance a detailed model of a train composition with its own on board subsystem should be interfaced with a tool able to simulate a railway net in which a much more simplified approach is adopted to model the other vehicles traveling on the line.

In this work a modular model of the onboard traction system of a railway vehicle is proposed. It is able to cover different applications ranging from low power DC metros and tram to high power applications such as high speed trains or heavy haul locomotives in order to calculate mechanical electrical and thermal behavior of components.

The following tools complete the model:

Please cite this article as: Malvezzi M., Pugi L., Conti R., Toni P., Tesi S., Meli E., Rindi A., 2013, A tool for prediction and optimization of railway traction systems with respect to an expected mission profile., Chemical Engineering Transactions, 33, 721-726
DOI: 10.3303/CET1333121

1) Mission Designer: a tool for the design of mission profiles including, line design, altimetric profile, intermediate stations, speed limitations introduced by the signaling system, and other mission targets or constraints;
2) Virtual Driver: a tool able to recreate a near to realistic sequence of maneuvers according the simulate state of the line, and of the simulated running condition of the train. The model should be used to simulate a virtual driver following different operating strategy which should be constrained by speed limitations and interventions curve of on board ATP, ATC (Automatic Train Protection and Automatic Train Control) systems. The system could be forced to a customizable logic of maneuvering which can simulate also unmanned on board systems such as ATO (Automatic Train Operation).
3) Mission-Vehicle Optimizer: it is an automatic iterative procedure for the optimization of mission or vehicle parameters with respect to customizable target functions such as energetic efficiency, thermal behavior of critical components, different driving strategies corresponding for instance to different blending of braking (electric and/or pneumatic) and/or to constraints arising from signaling system. Also a weighted target function considering a mix of different aspect to be optimized can be defined. Since an optimization procedure performed using an iterative approach can be computationally expensive, parallel computing and efficient code have been specifically designed for the application. The used algorithms are derived directly from the routines available in Matlab Optimization Toolbox™ for constrained problems (Byrd et al., 2000), (Coleman et al., 1996). As further option the optimizer could be also used to perform Montecarlo simulations of scenarios in which some parameters are randomly perturbed in order to assess the sensitivity or robustness of the system.

Parts of the developed code could be used for the design of model based controllers and prognostic tools, due to the modular structure of the code and to the possibility of compiling its modules for different kinds of C or C++ targets.
For instance compiled sub-models of the proposed tool could be integrated in distributed prognostic tools such as the one proposed by (Huanhuan, 2012) in which the protected system can be managed with respect to a virtual performance calculated by a simplified model running in real time.

2. Modular Model of Vehicle and Traction System

2.1 Mechanical Model

The mechanical behaviour of the vehicle is simulated according a quite efficient mono-dimensional model of the train which has been developed in previous research activities (Pugi et al., 2006) and described by equation (1):

$$
\begin{aligned}
&F_t + F_p + F_c + F_a + F_i = 0 \\
&F_t = \sum_i^n F_{ti} \quad \text{is the sum of longitudinal traction efforts on motorized wheels-axles of the train} \\
&F_p = -mg\sin\alpha \approx mgi \quad \text{Gravitational contribution due to slope} \\
&F_c = -mgi_c \quad \text{Lumped contribution to resistances due to curves and line design} \\
&F_i = -m_i\ddot{x} \quad \text{Inertial term} \\
&F_a = -mF_{am} = -m\left(av^2 + bv + c\right)
\end{aligned}
\tag{1}
$$

where m is the whole train mass, g is the gravity acceleration, i is the inclination angle, i_c is the inclination angle due to the curves, and m_i represents the equivalent inertia including the contribution of the rotanting masses of wheels, axles, brake discs and motors. In particular in order to consider degraded adhesion condition, longitudinal efforts applied to the wheels are saturated to a value that depends on the available adhesion simulated on the line.
For the pneumatic braking system a simplified model is adopted: a static gain G_b considering the scaling factor between the driver command and corresponding braking performance is introduced. Delays and more generally the dynamical behaviour of the pneumatic braking system is simulated using a non-linear first order filter (2), whose time constant τ is variable in order to reproduce different dynamical behaviour corresponding to different operating condition (service or emergency braking, release, WSP interventions etc.), which have been developed in a previous study relative to a complete and accurate model of pneumatic brake plant (Pugi et al.,2006).

$$F_b = \frac{G_b}{\tau s + 1} \quad (2)$$

Since a trend of modern metro and railway system is the maximization of electric braking respect to the pneumatic one, also the blending of the two kind of braking system is modelled considering a mutual dependency of pneumatic and electric effort, which in the more general condition can be modelled as a function of speed, load of the vehicles, kind of braking manoeuvre (service, emergency) and finally plant failures and degraded conditions.

2.2 Modular Model of On Board Traction System

In order to build up a parametric model of the traction system the reference models described in Figures 1/a and 1/b for current collection system are assumed. The electric model aims at evaluating efficiency, thermal behaviour, and the main mechanical outputs (torque, accelerations), so all the proposed models of the electric and electro mechanical components are implemented in terms of mean values, neglecting high frequency transients associated for example to switching of power electronic devices. Losses due to harmonics are introduced only in terms of tabulated values as a function of frequency, extracted from experimental data or extrapolated from dedicated models of the considered power electronic systems.

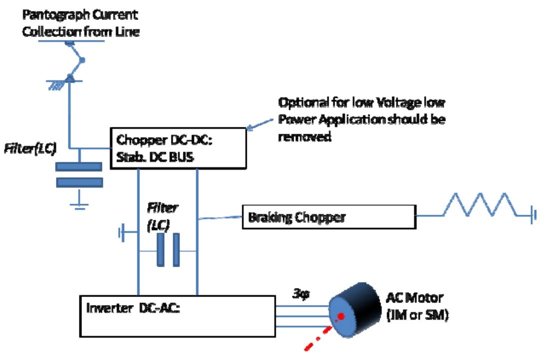

Figure 1/a: simplified scheme of traction circuit with DC current collection system

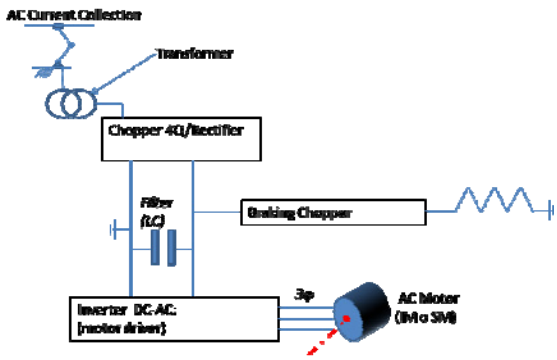

Figure 1/b: simplified scheme of a scheme of traction system with AC current collection system

In particular the following parametric components are modelled:

1) Motors: each motor is modelled as a sub-system in which mechanical, electrical, and thermal behaviour have to be considered as shown in the scheme of Figure 2. For the mechanical sub-model the exerted torque M_j of the j-th motor is an output which is converted in the corresponding traction effort F_{ti} of the i-th axle considering global transmission ratio and efficiency. It is worth to note that multiple axles should be connected to a single motor. With the same criteria the mechanical speed of the motor is an input calculated from train velocity considering pure rolling condition of wheels and equivalent transmission ratio. From an electrical point of view, squirrel induction machine motors are modelled according the approach proposed by (Krishan, 2001). Introducing slight modifications (including mutual induced fluxes and emf between winding of the two stars), also double star squirrel cage motors should be modelled, since they are sometimes used in locomotives as the Italian E464 (Mantero et al., 2000), (Pugi et al., 2009). Also PM or wounded synchronous motors are modelled following the simplified approach proposed by (Krishan, 2009). Motor operating conditions in terms of applied voltages and currents are calculated considering a simplified scheme of vector controller: in particular it's considered a F.O.C. (Field Oriented Control) scheme in which direct and quadrature components of stator currents respect to a synchronous reference are controlled in order to control both torque and magnetization of the motor (Krishan,2001). In this work an indirect F.O.C. controller is assumed for asynchronous machines. For Permanent magnet motors the corresponding implementation is described in (Krishan, 2009). Torque and flux references (in case of flux weakening) are calculated considering driver manoeuvre and assigned performances of the vehicle both for traction and electric braking. The dissipated power calculated through the electric model of the machine including magnetization and harmonic losses are used to calculate component efficiency and the thermal power dissipated in the motor and to evaluate a mean reference temperature of the motor, according to the simplified thermal model described by Eq. (3). The temperature value is then used to modify/change the corresponding impedances of motor circuits.

$$(T_{motor} - T_{ambient}) = \frac{W_d / B_{cool}}{\tau_{therm} s + 1}; \quad \tau_{therm} = \frac{C_{therm}}{B_{cool}}$$

$T_{motor}; T_{ambient}$ Temperatures of motor and ambient (3)

W_d dissipated power

$B_{cool}; C_{therm};$ Thermal exchange coefficient and capacity

2) Inverter: Motors are fed by inverters. Efficiency and consequently the power dissipated by the inverter is tabulated as a function of frequency, currents, and corresponding switching/operating mode. A simplified thermal model similar to the one described in (3) is used to calculate a reference temperature for the component.
3) Filters: losses due the impedance of inductive and capacitive filters (C and LC filters) are modelled considering also the dissipative effects introduced by bleeder resistances of capacitors. Also in this case a reference temperature of the component can be optionally calculated using the first order filter described in (3).
4) 4Q-Choppers-Rectifiers: Voltage of vehicle DC bus should be fed and stabilized using one, two or even more multiphase choppers. Chopper sub-model is quite simple, since they have to allow an easy customization of the model, in order to make possible the simulation of different traction schemes, including for instance more chopper groups in parallel or series (multiphase or multilevel systems). In this way despite the simplicity of the adopted model, it is possible to simulate a wide range of traditional and conventional traction schemes, for example those described in (Perticaroli, 2001), (Bieber, 2001) or even innovative or uncommon examples as the one described in (Marchesoni, 2002).
5) Transformer: on vehicles operating on AC lines, a transformer is usually installed, as shown in the simplified scheme of figure 1/b. From a thermal point of view this may be a quite critical component, since wrong or excessive optimizations aimed at reducing weight and dimensions may lead to an undersized design of the system, which has to be typically liquid cooled. For this reason the calculation of the power dissipated on this component is relatively more detailed with respect to other components, and it takes into account not only the resistive losses on primary, secondary and auxiliary windings but also of the pumps power dissipated in the cooling circuit.

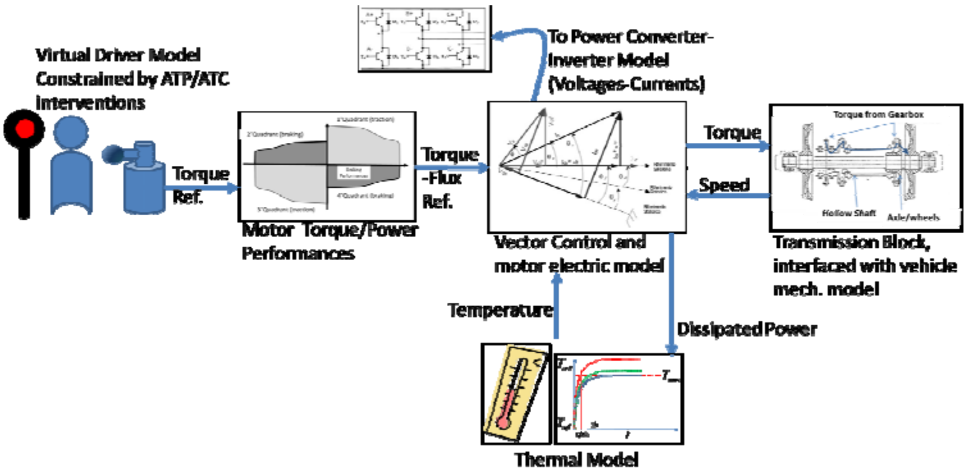

Figure 2: Simplified scheme of the motor subsystem including mechanical, electric and thermal model

3. Mission Profile and automatic driver

The proposed model takes as input the properties of the line on which the simulation is performed. These data includes line topographical features (e.g. line gradient, presence of curves, curve radii, presence of tunnels, train stops and stations), electrical features (voltage, type), the maximum speed allowed for each part of the line. These data are provided to the simulator in a tabular form, e.g. in an Excel file, as a function of the progressive distance from a reference starting point. Starting from a static speed profile, a dynamics one is evaluated: each time a downhill speed variation is present (for example, if the maximum

speed is decreased or in presence of a train stop or a station), starting from the target point and proceeding backward, the maximum speed value that can be safely reached by the train is evaluated taking into account its braking performance, including initial delays and transient behaviours, and line properties.
During the simulation, each time the train meets a positive variation of the allowed speed, the traction is activated, as the speed tends to reach the dynamic speed profile above defined, the traction is progressively released in order to smoothly reach the allowed speed. If, for any reason, the evaluated train speed overcomes the allowed one, it begins to brake, until the speed limit is satisfied. Each time a negative speed variation or a train stop is approaching, the train starts to brake in advance, the starting point of the braking phase is evaluated with the dynamic speed profile previously defined. Commonly the drivers tend to release the traction a while before the beginning of a braking, in this phase the train decelerate (or accelerate) according to the external aerodynamical resistance and line gradient. This phase, usually referred as *coasting*, can be simulated by the tool by specifying the distance before the braking start.

4. Preliminary Validation Process

Some preliminary validation tests were performed with different types of vehicles and scenarios, ranging from high-speed trains to urban vehicles like trams and metros. In this paper, for the sake of brevity, the results relative to an high speed train are presented.
The simulated train is the Ansaldo Breda EMU V250, simulating a standard mission profile on the railway line between Amsterdam and Bruxelles considering speed limitations imposed by line and signalling systems and voltage supply variations. The train is composed of 8 coaches and is designed to operate on 3kV DC, 1.5kV DC and 25kV 50 Hz AC overhead power supply, allowing operations on both Dutch and Belgian electrified networks. Traction is distributed with alternating powered (M) and trailer (T) vehicles in MTMTTMTM formation. Electric traction power is controlled by water-cooled IGBT inverters powering asynchronous motors. EMU V250 is fitted with ETCS Level 2 and local train safety systems (AnsaldoBreda, 2011).The results obtained from the proposed analysis tool have been compared with data and results provided by Ansaldo Breda, obtained with an internal software tool widely validated with experimental data and optimized with the experience of technicians and railway operators. In particular in Figure 3 some results in terms of train speed and power absorbed by one of the traction motors are shown. The figure shows how the train tends to follow the imposed speed profile by activating the traction each time a positive speed variation is met, and by activating the braking with a properly defined advance. The comparison between the results evaluated with TrEnO and those obtained with the standardly adopted internal tool are very close and substantially in accordance in all the operative conditions. This qualitative agreement between these results is confirmed by the statistical analysis of the error distributions, summarized in Table 1, that shows a overall error between the obtained results whose order of magnitude is about 1%.

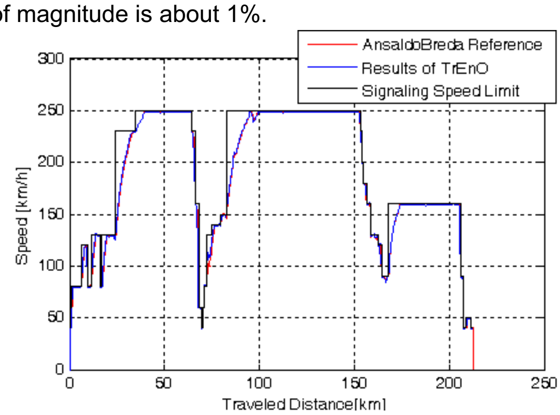

Figure 3/a: calculated speed profile of EMU V250 between Amsterdam and Bruxelles comparison between Treno Results and AnsaldoBreda reference data

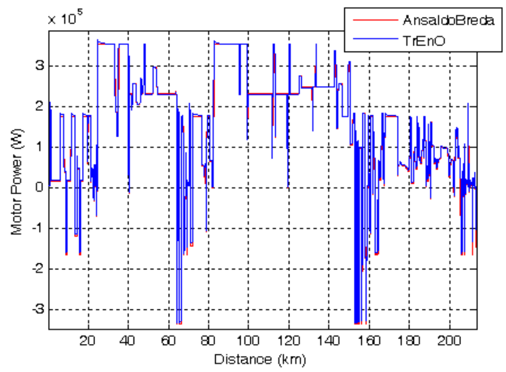

Figure 3/b: calculated power/motor profile of EMU V250 between Amsterdam and Bruxelles comparison between Treno Results and AnsaldoBreda reference data

Table 1: Mean (relative errors on time sampled results), statistical distribution of Errors (Emu V250 Amsterdam-Bruxelles line)

Speed	Collected Power	Power to motors	Electric Traction and braking effort	Pneumatic Braking Effort
Less than 0.5 %	less than 0.5 %	less than 0.4 %	about 1 %	about 1 %

5. Conclusion

The paper presents the main features of the tool TrEnO, developed to analyse and optimize the performance of a train from an energetic and efficiency point of view. Currently the development of TrEnO tool is practically complete, and some preliminary validation tests are quite encouraging. Further activities are on-going in order to validate the code especially for the part concerning thermal model, where less data were available during the first development phase and for which an extended experimental feedback is needed. Also a major effort has to be performed in order to extend and apply the use of TrEnO both for simulation and fast prototyping of prognostic and diagnostic applications.

Acknowledgements

Authors wish to thanks all the people of the group AnsaldoBreda SPA, and particularly Eng. Ghislanzoni, which have supported the research activities with data, know-how transfer and over expected cordiality.

References

AnsaldoBreda 2008, AnsaldoBreda high speed trains: *V250*. Available through Ansaldo website <www.hstrain.ansaldobreda.it>. Accessed [7 February 2011].

Baccari S., Cammeo G., Dufour C., Iannelli L. , Mungiguerra V., Porzio M., Reale G. and Vasca F., 2012, Real-Time Hardware-in-the-Loop in Railway: Simulations for Testing Control Software of Electromechanical Train Components, Railway Safety, Reliability, and Security: Technologies and Systems Engineering pp.221-248, IGI-GLOBAL, DOI: 10.4018/978-1-4666-1643-1.ch010

Bieber AC, 2001 Progress in railway mechanical engineering 1999-2000 survey-locomotives,. Proceedings of the 2001 IEEE/ASME Joint Railroad Conference

Byrd, R.H., J. C. Gilbert J.C., and Nocedal J., 2000 "A Trust Region Method Based on Interior Point Techniques for Nonlinear Programming," Mathematical Programming, Vol 89, No. 1, pp. 149–185,.

Coleman, T.F. and Y. Li, 1996. An Interior, Trust Region Approach for Nonlinear Minimization Subject to Bounds, *SIAM Journal on Optimization*, Vol. 6, pp. 418–445

Huanhuan L., 2012, Research of prognostics and health management for EMU, IEEE Conference on Prognostics and System Health Management. pp 1-6 (23-25 May 2012. PHM-2012 Beijing).

Krishan R., 2001, Electric Motor Drives, Modeling Analysis and Control, Prentice Hall, Upper Saddle River, NJ 07458 ISBN 013-091014-7.

Krishan R. 2009, Permanent Magnet Synchronous and Brushless DC Motor Drives, CRC Press, ISBN 9780824753849. Boca Raton, FL 33487-2742

Mantero, S., Monti, A.;Spreafico, C., 2000, DC-bus voltage control for double star asynchronous fed drive under fault conditions, IEEE 31st Annual Conference on Power Electronics Specialists

Marchesoni M.,Novaro, R.;Savio, S, 2002, AC locomotive conversion systems without heavy transformers: is it a practicable solution?, IEEE International Symposium on of the 2002 Industrial Electronics,ISIE 8-11 July 2002. Vol.4 pp. 1172 - 1177

Perticaroli F. 2001, "Electric Systems for Transportation" (in Italian), Casa Editrice Ambrosiana, Milan, Italy

Pugi L., Malvezzi M., Tarasconi A., Palazzolo A., Cocci G.& Violani M.,2006, HIL simulation of WSP systems on MI-6 test rig, Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility 44-Supplement 1, pp. 843-852, DOI:10.1080/00423110600886937

Pugi L., Malvezzi M., Bartolini F., 2009, Model of Parallel-Connected Multiple Induction Motors for HIL simulation of railway anti-skid-anti-slip systems, Procedings of XIX° AIMETA Congress Ancona Italy

Pugi L. ,Allotta B. 2012 Hardware-In-the-Loop Testing of On-Board Subsystems: Some Case Studies and Applications , Railway Safety, Reliability, and Security: Technologies and Systems Engineering pp. 249-280, IGI-GLOBAL, DOI: 10.4018/978-1-4666-1643-1.ch010

Stephan A. 2008, OpenPowerNet–simulation of railway power supply systems, WIT Trans. Built Environ., vol. 103, pp.449 -459