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Sizing and energy management of a hybrid locomotive based on flywheel and accumulators

Amine Jaafar, Cossi Rockys Akli, Bruno Sareni, Xavier Roboam, Alain Jeunesse

Abstract—The French national railways company (SNCF) is interested in the design of a hybrid locomotive based on various storage devices (accumulator, flywheel, ultracapacitor) and fed by a diesel generator. This paper especially deals with the integration of a flywheel device as storage element with a reduced power diesel generator and accumulators on the hybrid locomotive. Firstly, a power flow model of energy storage elements (flywheel and accumulator) is developed in order to achieve the design of the whole traction system. Then, two energy management strategies based on a frequency approach are proposed. The first strategy led us to a bad exploitation of the flywheel while the second strategy provides an optimal sizing of the storage device. Finally, a comparative study of the proposed structure with flywheel and the existing structure of the locomotive (diesel generator, accumulators and ultracapacitors) is presented.

Index Terms—Battery, Energy management strategy, Energy storage, Flywheel, Hybrid locomotive.

I. INTRODUCTION

BY comparison with aircraft and automotive systems, the railway transport is recognized as being a sustainable mode of transport with reduced carbon emissions. Indeed, most of passenger trains, especially in France where 85% are constituted of high speed trains (i.e. TGV) are electrically fed [1]. However, for particular segments such as sorting and local sideboards, the driving missions are generally achieved by diesel locomotives. In such cases, the diesel engine operates more than 60% of time at slow motion [2]–[4]. This leads to an excess of fuel consumption, polluting broadcasts and noise [5]–[8]. Diesel-electric hybridization then establishes an interesting solution before being completely “zero fuel” by means of new technologies of generators (fuel cells,...). It allows answering simultaneously economical and environmental objectives by reducing, on the one hand, the

fuel burn and on the other hand CO₂ emissions. The energy storage elements mostly used to hybridize diesel locomotives are accumulators, flywheels and ultracapacitors. "NewEnergy train (NE@Train)" [9] is the first railway hybrid locomotive put on rails. This suburb train has been built by the Japanese company JR-EAST. It is composed of a diesel generator of 230 kW electric associated with a lithium-ion batteries of 10 kW [10]. It allows a 20% reduction of the fuel burn and 50% of polluting broadcasts compared to a full diesel locomotive.

The Canadian company RailPower (RP) is the first railway builder producing hybrid locomotives assembling diesel and accumulator batteries in an industrial way [2], [3]. It commercializes two groups of locomotives. The Green Goat group of sorting is based on a 200 kW diesel generator (against 1500 kW for an equivalent diesel locomotive) and a great pack of batteries (Pb-1200 Ah under 600 V DC). The group RP of operation in two versions (RP20BH and RP20BD) embedding respectively 2 or 3 diesel generators of 500 kW and batteries of the same technology.

The CITADIS of Rotterdam is a hybrid streetcar Catenaries-Flywheel fabricated by the railway designer Alstom. It is dedicated for crossing the Erasmus bridge of Rotterdam without catenaries. Alstom built also in Nice a hybrid CITADIS with NiMH batteries for the crossing of Garibaldi and Massena places without catenaries [11].

In this context, the PLATHEE project (Energy Efficient and Environmentally Friendly Train Platform) is created between the French national railways company (SNCF), the LAPLACE laboratory (Laboratory Plasma and Conversion of Energy) and several other French partners as ALSTOM, INRETS, SOCOFER, SOPRANO [12]. This project is focused on the design i.e. architecture, sizing and energy management of an autonomous hybrid locomotive called "LHyDIE: Hybrid Locomotive for Demonstration and Investigations in Energetics". An existing equipment used by the SNCF was based on a BB63000 diesel locomotive dedicated to carry out missions of sorting, local sideboards and help in absence of catenaries. This locomotive is moved by four electric motors fed by a diesel generator of 610 kW. A former study consisted in replacing the diesel engine by a smaller one with batteries of accumulators and ultracapacitors as energy storage elements [1]. Complementarily to the previous design, the current study proposed in this paper has the objective to investigate the possibility of implanting a flywheel device on the future hybrid

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locomotive.

This paper is organized as follows. First, the power flow based modeling is presented for the energy storage elements. Second, the principle of the energy management strategy based on a frequency approach is explained. The integration of a flywheel on the LHyDIE locomotive in association with the diesel generator and the accumulator batteries is then studied by considering two different energy management strategies. Finally, a comparative study is carried out between the proposed solution with flywheel and the one existing with ultracapacitors.

II. THE EXISTING SOLUTION OF THE LHYDIE LOCOMOTIVE

The existing architecture of the LHyDIE locomotive is illustrated on Fig. 1. It has been built from an existing BB6300 diesel locomotive devoted to carry out sorting or local sideboards missions as well as help in absence of catenaries. This locomotive is moved by four DC electric motors fed by a diesel generator of 610 kW rated power. One first issue was to replace the diesel generator by a smaller one by building a hybrid system by inserting batteries of accumulators and ultracapacitors as energy storage elements. A first study [1], [4] then allowed to size the locomotive with a diesel generator of 215 kW rated power, 200 kWh of batteries (1200 Nickel Cadmium cells 135 Ah/1.2 V) and 7 kWh of ultracapacitors (1600 cells 5000 F/2.5 V). An energy management strategy has been proposed based on a frequency approach. The batteries are distributed in four parallel blocks of 300 cells in series; ultracapacitors are shared in eight parallel blocks of 200 cells in series. These blocks are connected to a 540 V DC bus through power converters.

III. FLYWHEEL ENERGY STORAGE

Flywheel energy storage has been used since the antiquity. In the last decades, it has equipped electromechanical applications to smooth the electric power demand or as secondary power supply to secure cases of electric cuts of weak duration. It is also used in uninterruptible power supplies where the short duration power changes damage the batteries lifetime. In the context of the autonomous energy production, flywheels are used in the field of transport and in spatial applications for energy transfer and especially to stabilize or to drive satellites (gyroscopic effect) [13]. Flywheel energy storage is characterized by its important lifetime (typically 20 years) [14], [15]. However, its main drawback is due to security issue, in particular for embedded systems.

The main flywheel energy storage devices are given in Fig. 2. The flywheel is usually a cylindrical mass which allows accumulating kinetic energy. It turns with high rotation speeds with reduced losses thanks to magnetic bearings. The motor/generator, coupled with a static converter, is used for the electromechanical energy conversion system. These elements are placed in a safety and vacuum envelope. This last one is waterproof and under vacuum of air so as to minimize friction losses [16], [17].

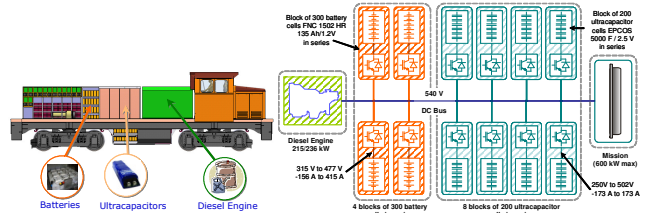


Fig. 1. The initial architecture of the hybrid locomotive

IV. THE POWER FLOW MODELING

The power flow model is a macroscopic modeling especially dedicated to a system approach for energetic devices. It treats energies and powers exchanged by the storage elements and the whole system. It also represents a sizing model. In fact, it allows determining the energy size of storage elements without taking into account their electrical characteristics or their interconnection architecture (i.e. series/parallel assembling). This model offers the advantage of minimizing computational cost especially as long-term driving missions are treated in this railway transport application: 5 seconds of computation time are needed for simulating 6 hours of driving mission, comparatively to 60 hours for simulating a complete “instantaneous electric model” [1].

A. Power Flow Model of the Diesel Generator

The power flow model of the diesel generator is given in Fig. 3. From the diesel generator power reference (P_{DGref}), it allows to obtain the “actual” diesel generator power (P_{DG}), the corresponding energy (E_{DG}), the quantity of fuel consumed (Q_{fuel}) and the corresponding quantity of emitted carbon dioxide (Q_{CO2}). The parameters of this model are the converter efficiency associated with the diesel generator (typically $\eta_{DG} = 96\%$), the diesel power limit (P_{DGmax}) and the Specific Fuel Consumption (SFC) characteristic. This characteristic has been extrapolated with a five order polynomial approximation as a function of the diesel generator power as follows [1]:

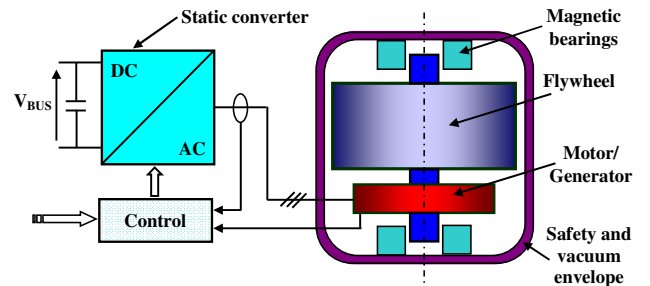


Fig. 2. The initial architecture of the hybrid locomotive

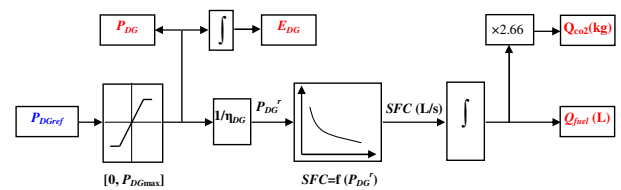


Fig. 3. The power flow model of the diesel generator

$$SFC(P_{DG}) = SFC_N \sum_{i=0}^5 b_i \left(\frac{P_{DG}}{P_{DGN}} \right)^i \quad (1)$$

where the polynomial coefficients are $b_0 = 1.94$, $b_1 = -6.44$, $b_2 = 18.57$, $b_3 = -27.22$, $b_4 = 19.72$, $b_5 = 1.94$. P_{DGN} denotes the rated power of the diesel generator and SFC_N represents the specific fuel consumption at this power estimated at 202.45 g/kW. The previous relationship has been validated for three diesel engines of the Fiat Powertrain Technologies Group [18], i.e. the N67 TM2A of 125 kW, the C78 TE2ES of 236 kW and the C13 TE2S of 335 kW. It should be noted that the specific fuel consumption is minimum when the diesel engine operates at its nominal power P_{DGN} . Therefore, the energy management controller tends to maintain the diesel generator power reference close to this power or to stop it. Note also that the maximal diesel engine power is considered 10% higher than the nominal power.

The emitted quantity of CO₂ in kilograms (Q_{CO2}) is directly proportional to the consumed fuel quantity in liters (Q_{fuel}) and is estimated as follows [19]:

$$Q_{CO2} = 2.66Q_{fuel} \quad (2)$$

B. The Power Flow Model of the Storage Elements

Fig. 4 describes the power flow model of the storage elements. The model is identical for batteries, ultracapacitors and flywheel so the s index in Fig. 4 can be replaced by BT for the battery pack, SC for the ultracapacitor pack and FW for the flywheel.

P_{Sref} is the power reference of the storage element computed from energy management strategy controller. This power has some limitations depending on the one hand, to the maximal power of charge and to the acceptable storage element discharge ($P_{Sschmax}$ and $P_{Sdchmax}$ respectively) and on the other hand to its state of charge (SOC_{min} and SOC_{max}). Various losses are considered by introducing the energy efficiency (η_S if $P_S < 0$ and $1/\eta_S$ if $P_S > 0$). Note that positive power values are equivalent to discharge the storage device while negative power values correspond to a storage device charging.

The storage element state of charge (SOC_S) is defined as the ratio between the instantaneous stored energy E_S and the maximal energy that can be stored E_{Smax} ($SOC_S (\%) = 100 \times E_S / E_{Smax}$). The energy calculation of the storage elements (E_S) is carried out from its instantaneous real power (P_S^r) and its initial state of charge (SOC_{S0}) according to the following relation:

$$E_S(t) = E_{S0} - \int_0^t P_S^r(\tau) d\tau \quad (3)$$

This energy allows then to calculate the state of charge of the storage element (SOC_S).

The parameters of this model and their values are given in Table I. Note that the total energetic capacity of a pack depends on the total number of cells and of the capacity of each cell.

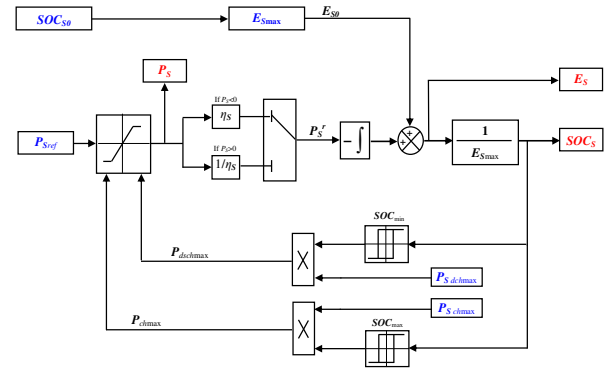


Fig. 4. The power flow model of a storage element pack (flywheel, batteries or ultracapacitors)

The main characteristics of the flywheel device considered in the study case of the LHyDIE locomotive are: a maximal charge/discharge power (± 325 kW), a maximal storage energy capacity $E_{FWmax} = 5.33$ kWh (4 kWh as useful energy) and the speed varies between 11000 and 22000 rpm.

Technological data values corresponding to EPCOS 5000 F/2.5 V ultracapacitor cells and Hoppecke FNC 1502HR battery cells of 135 Ah, used in the PLATHEE project, are detailed in [20].

V. ENERGY MANAGEMENT STRATEGY BASED ON A FREQUENCY APPROACH

In order to determine the mission part of each storage element, an energy management strategy based on a frequency approach was presented in [4] in the case of an hybridization with batteries and ultracapacitors. It is similarly used here with flywheel storage. Its principle resides in the following rule:

“The fast storage elements SC (ultracapacitors) or FW (flywheels) assure high frequency components of the mission (Fig. 5). The energy source DG (Diesel Generator) operates as often as possible at its nominal power and the remainder of the mission is devoted to the BT (batteries). In fact, for the actual system operation, a more complex “stop and go” strategy is adapted for the diesel generator management. Indeed, this latter source has to be switched off when the demanded power is low regarding the storage element SOC_S .

The «stop and go strategy» allows determining the diesel generator control reference based on the low frequency part of the mission (PDG+PBT) and on the battery state of charge (SOC_{BT}) as follows:

If $(P_{DG} + P_{BT}) > P_{BTschmax}$ or $SOC_{BT} < 90\%$ than “Start DG”=1, else “Start DG”=0.

TABLE I
THE PARAMETERS OF THE BATTERY, ULTRACAPACITOR AND FLYWHEEL POWER FLOW MODELS

	Ultracapacitors	Batteries	Flywheel
Efficiency (including the converter efficiency)	$\eta_{SC} = 91\%$	$\eta_{BT} = 80\%$	$\eta_{FW} = 90\%$
Discharge limit $P_{Sdchmax}$	475 kW	380 kW	325 kW
Charge limit P_{Schmax}	-475 kW	-97.2 kW	-325 kW

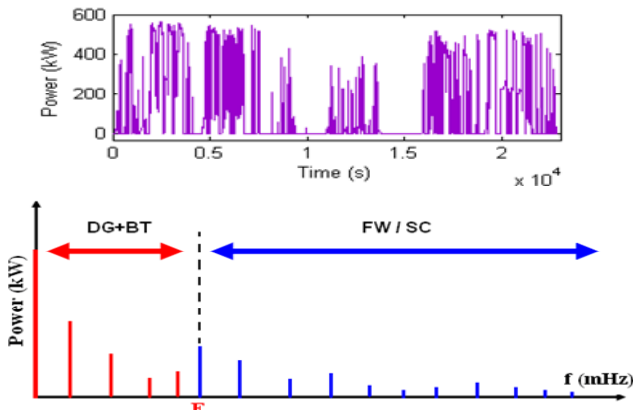


Fig. 5. Mission distribution according to a frequency axis

An hysteresis control process is introduced in order to fulfill a minimal operating duration before stopping and a minimal idling duration before starting.

From the whole locomotive power mission (P_{Loc}), a high pass filter allows sharing the high frequency part which is devoted to the flywheel (case of architecture DG, BT and FW). The mission of the batteries P_{BT} is obtained by subtracting the diesel generator power from the lower frequency part of the locomotive power mission (Fig. 6).

This management strategy secures the compatibility between the frequency components of the mission and the intrinsic characteristics of the different sources such as:

1. The nominal power is the optimal operating point of the diesel generator. At this point the fuel burn is minimum and the atmospheric pollution (CO_2) is also minimized [21].
2. Batteries are actual energy sources providing few slow dynamic cycles (about 1000 cycles). Furthermore batteries are subject to aging and the best way for prolonging their lifetime is to prevent them from fast dynamic currents and high number of cycles.
3. Contrarily to batteries, ultracapacitors are able to absorb fast dynamic currents and to provide a significant number of cycles (typically 500000 cycles) [22].
4. Flywheel are placed between these last two elements and characterized by a “quasi infinite” number of fast dynamic cycles of charge and discharge [23].

The table below gives a summary of the characteristics of the different sources:

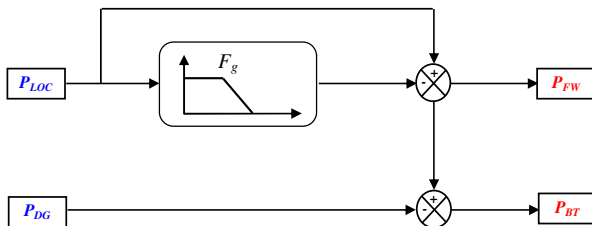


Fig. 6. Basic principle of the frequency based energy management strategy

The cost of the different energy sources is not mentioned in the table as it depends on many parameters like costs related to maintenance, lifetime and purchasing. More details can be found in [24].

VI. LHYDIE WITH DIESEL GENERATOR, BATTERIES AND FLYWHEEL

In this section, we study the hybridization of the locomotive LHyDIE which consists in removing the existing ultracapacitors and only considering the diesel generator (215/236 kW) with the batteries and the flywheel. Our objective is to define a management strategy guaranteeing an optimal sizing and operation of the locomotive. In that follows, we propose two energy management strategies confirmed by a power flow model. Our study is carried out for the mission of Fig. 7 considered as one of the most critical in terms of power/energy constraints: this latter mission is taken as reference in the design process.

A. Basic Management Strategy: The Flywheel Only Supplies High Frequency Harmonics

1) Principle

This first “basic” management strategy is identical to that one applied to LHyDIE in the case of ultracapacitors. The flywheel supplies the high frequency part of the mission and the rest is shared towards the diesel generator and the batteries. As long as the “low frequency” power part is lower than the nominal power of the diesel generator, this latter satisfies the required mission and also charges the batteries. In the opposite case, the diesel engine operates at its nominal power and the batteries guarantee the rest of the mission. Consequently, it is supposed at first, that the diesel engine supplies all the time its nominal power (P_{DGnom}). This power will be deduced from P_{Loc-LF} (low frequency part of the total mission and the filtered losses of the FW) to determine the reference mission of the batteries (P_{BTref}). A compensation loop of the low frequency part of the flywheel losses is added.

TABLE II
CHARACTERISTICS OF THE DIFFERENT ENERGY SOURCES

	Diesel Generator	Batteries	Ultracapacitor	Flywheel
Specific energy (Wh/kg)	93	20-200	1-10	10-95
Specific power (W/kg)	94	5-20	1000-3000	2000-4000
Charge time	-	1-5h	1-30s	>15s
Discharge time	-	0.3-3h	1-30s	>few min
Number of cycles	-	2000	>10 ⁵	>10 ⁵

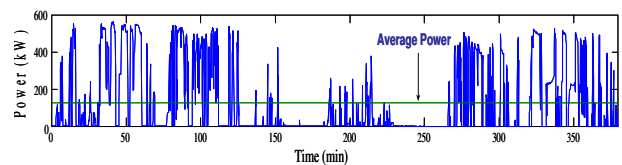


Fig. 7. Basic principle of the frequency based energy management strategy

The cut-off frequency (F_g) is chosen so that the flywheel does not reach saturations in discharge while staying in the frequency domain of the batteries. However saturations in charge are allowed. In this case, the charge power excess ($\Delta P_{FW} = P_{FWref} - P_{FW}$) is sent to the diesel generator in order to relieve it. Such power flow model of the energy management strategy based on a frequency approach is given in Fig. 8.

By sweeping the frequency axis, we notice that only the cut-off frequency is responsible for the flywheel power use. To avoid the power saturations in discharge, the minimal cut-off frequency must be increased at $F_g = 27$ mHz instead of 5 mHz initially used with ultracapacitors. In order to comply with the reference mission, the number of batteries cells is then increased to 1312 instead of 1200 initially. Remember that the useful energy stored in the considered flywheel is only 4 kWh while the one for ultracapacitors is 7 kWh.

2) Simulation results

The simulation results show that the flywheel fulfills its reference mission except for some acceptable saturations of charge (Fig. 9a). The state of charge shown in this figure proves that the flywheel saturation is only due to power demands while no energy saturations are observed. This storage device is then able, with this frequency of 27 mHz, to comply with all the required energy states during this reference mission. The energy vs power cycles of the flywheel in the Ragone's plan and its operating limit area are also given in Fig. 9a. This figure illustrates the behavior of the flywheel and the temporal evolution of the corresponding trajectories in Ragone's plan through a colour code. Indeed, the scale of time is represented by various colors going from the dark blue, at the beginning of the mission, until the red at the end of the simulation. Initially, the flywheel is totally charged ($SOC_{FW} = 100\%$), its energy is then equal to 5.33 kWh. By going through the complete mission, its state of charge does not go below 77.2% which corresponds to a stored energy of 4.1 kWh. This value is obviously superior to its minimal limit of discharge (1.33 kWh). Thus, one can conclude that the flywheel is not well exploited in terms of stored energy through this "basic" energy strategy management.

3) Comparison: architecture DG+BT+SC/DG+BT+FW

The previous study has shown that flywheels can substitute ultracapacitors under the condition of increasing the number of battery cells (112 cells have been added). The adequate cut-off

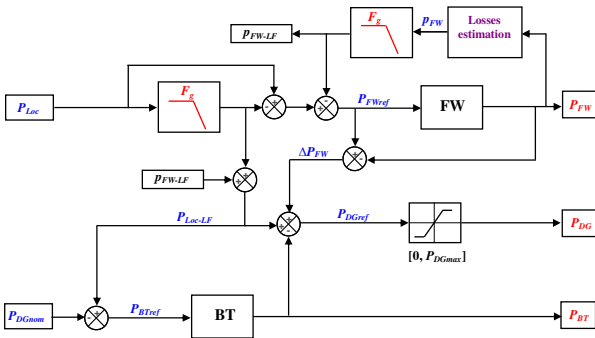


Fig. 8. Synoptic plan of the basic management strategy

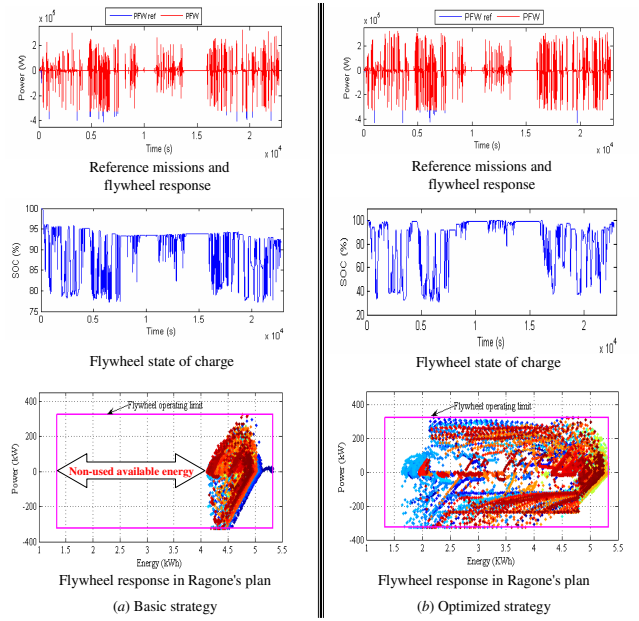


Fig. 9. Basic and optimized energy management strategies

frequency (27 mHz) is also upper than the one used in the case of ultracapacitors (5 mHz). This leads to an increase in the frequency of the batteries cycles and the appearance of more micro-cycles able to decrease the batteries life time.

By applying the same energy management strategy ("basic" strategy) used in the case of ultracapacitors and by means of a power flow model, we showed that the hybrid architecture with flywheel allows fulfilling LHyDIE's requirements in terms of power mission. However, the flywheel is not well exploited in terms of stored energy. In the next section, we propose a new management strategy allowing to better use the flywheel storage and to reach optimal sizing and operation of the locomotive.

B. Second Management Strategy: Optimized Management Strategy Based on a Frequency Approach

1) Principle

With the aim of a better exploitation of the flywheel, we shall keep the same management principle based on a frequency approach by introducing the following modification: besides the high frequency mission (P_{FWref0}) considered as "the priority", the flywheel makes, as possible, a "secondary mission" (P_{FWs}) extracted from the low frequency mission of the batteries, this to relieve them. Concerning the FW reference power, the priority is all the time given to the high frequency mission.

The secondary mission dedicated to the flywheel is determined in two steps. We firstly begin by defining a reserve for the flywheel power (R_{FW}) without any consideration of its state of charge (Fig. 10). The issue is here to define the instantaneous distance between the high frequency reference of the flywheel (P_{FWref0}) and the power limits, i.e. the maximal power $P_{FWdchmax}$ (325 kW) in case of discharge and the minimal range $P_{FWchmax}$ (-325 kW) in case of charge.

Secondly, the battery reference mission P_{BTref0} (mission of

the battery before injection of P_{FWS} is compared to the power reserve (R_{FW}) according to the following principle:

- Case of a flywheel discharge

At this stage, a control of the state of charge is necessary. A discharge of the flywheel to carry out the secondary mission can take place only if its state of charge is upper than 40%. This value constitutes a safety margin in term of energy to guarantee the priority of the high frequency mission P_{FWref0} .

If the power reserve R_{FW} is upper than P_{BTref0} , the battery is totally relieved (the reference of the battery after injection of P_{FWS} becomes $P_{BTref} = 0$) and the flywheel secondary mission (P_{FWS}) is then equal to P_{BTref0} (Fig. 11a). In the opposite case, the flywheel supplies the whole reserve and the batteries provide the necessary complement for the mission fulfillment (Fig. 11b).

- Case of a flywheel charge

In this case, the flywheel is charged from the charge mission of the battery (negative part of P_{FWref0}). This does not much degrade the battery state of charge because the maximal energy that can be stored in the batteries (about 200 kWh) is largely higher than that of the flywheel (4 kWh as useful energy). A charge of the flywheel, from the secondary mission, only take place if its state of charge is lower than 90%, otherwise, priority is reserved for the high frequency mission.

If the power reserve R_{FW} is lower than P_{FWref0} (i.e. greater in absolute value), we inhibit the battery charge ($P_{BTref} = 0$) and the secondary mission of the flywheel (P_{FWS}) is then equal to P_{FWref0} (Fig. 12a). In the opposite case (Fig. 12b), P_{FWS} will be equal to R_{FW} and the battery is less charged ($P_{BTref} = P_{FWref0} - R_{FW}$).

The synoptic scheme of this energy management based on a power flow model is given on Fig. 13. It is similar to the one used for the basic strategy except for the block inserted to generate the secondary mission of the flywheel.

2) Simulation results

Simulations are made for the daily mission of LHyDIE having duration of 380 minutes and corresponding to the most critical mission in terms of power/energy demand. The cut-off frequency of the filter used inside the management process is chosen so that the flywheel does not admit saturations in discharge while those in charge are acceptable. The minimal value to satisfy this condition is 17 mHz. Compared to the first basic management strategy ($F_g = 27$ mHz), the management filtering frequency is decreased. This decrease is in favour of the batteries because the cycling frequencies are reduced. Thus

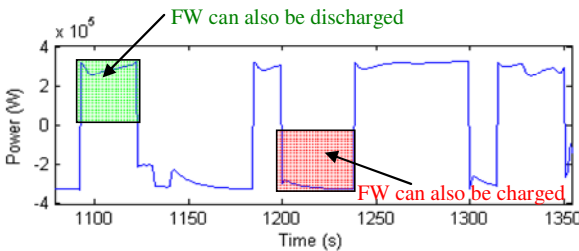


Fig. 10. Flywheel power reserve without any consideration of its state of charge

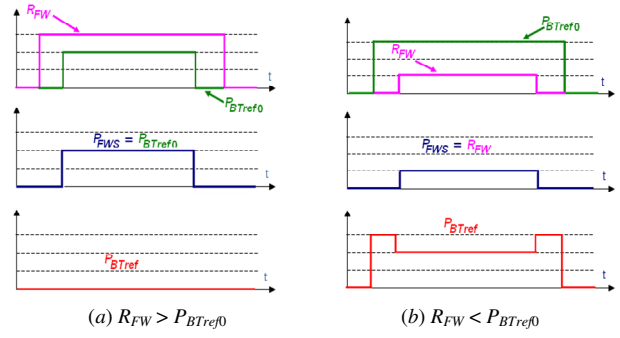


Fig. 11. Determination of the PFWS and the PBTréf in the case of a discharge

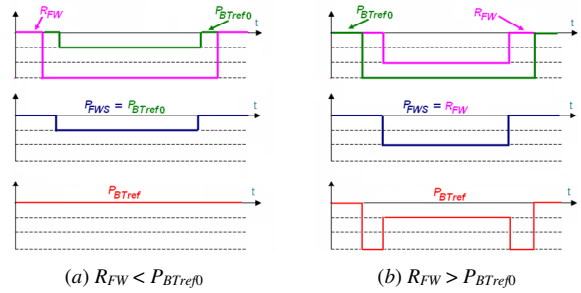


Fig. 12. Determination of the PFWS and the PBTréf in the case of a charge

a more important lifetime of the batteries can be expected.

Fig. 9b represents the reference mission of the flywheel ($P_{FWref} = P_{FWref0} + P_{FWS}$) and its response. The state of charge and the flywheel mission in Ragone's plan are also given in this figure. The flywheel response follows its reference mission except for some acceptable saturation in terms of charge power. The representation of the flywheel response in Ragone's plan shows that the storage device is optimized being close to the saturation limit of discharge which is related to the choice of the management frequency. However, in charge, the flywheel presents much saturation. The state of charge varies from 30% to 100%. Compared to the first management strategy where the flywheel is not well used in term of energy, the second management strategy allows a better exploitation of the flywheel, on the one hand by injecting parts of low frequency missions and on the other hand by amplifying high frequency mission by the decrease of the cut-off frequency

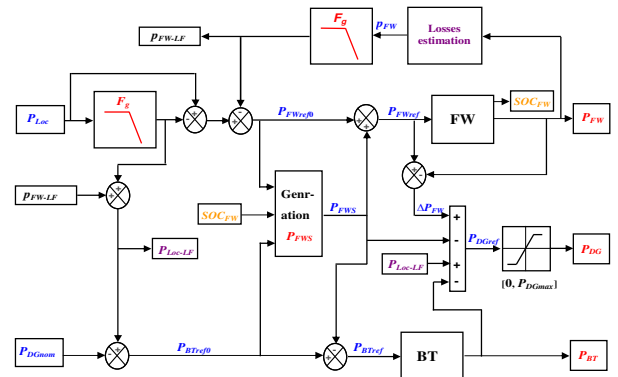


Fig. 13. Synoptic scheme of the optimized energy management strategy

($F_g = 17$ mHz). Indeed, the minimal state of charge goes from 77% to 30%. This clearly appears in Ragone's plan where the flywheel response, for the same daily mission, spreads out even more in the useful zone of the flywheel defined by its operating limits.

Fig. 14 shows that the batteries are able to supply all the required power. They undergo saturations in case of maximal power of charge ($P_{BT\ chmax} = -97.2$ kW) or when the batteries are totally charged. The diesel generator follows perfectly its reference mission. The dynamics of this last one are supposed rather fast with regard to the variations of its reference mission. The diesel generator works according to three different modes: with its maximum charge (236 kW), with batteries maximum charge power (97.2 kW) and for the stop mode when the batteries are totally charged and the locomotive is stopped.

VII. A SYSTEMIC COMPARISON OF FLYWHEEL AND ULTRACAPACITOR BASED ARCHITECTURES

A. The Geometric Sizing Model

The global volume available for the embedded energetic sources and their associated devices (static converters, thermal radiators, filter elements) is about 32 m^3 . Therefore, the volume of each component has been estimated with relations obtained from manufacturer data, in order to fulfill space constraints. The diesel generator volume Ω_{DG} in m^3 has been interpolated with a linear function as follows:

$$\Omega_{DG} = 3 \times 10^{-5} P_{DGN} + 0.03 \quad (4)$$

The ultracapacitor and battery volumes (Ω_{BT} and Ω_{SC}) are calculated from the corresponding unit cell volumes (Ω_{BT0} and Ω_{SC0}), considering the total number of cells and by means of assembly coefficients (λ_{BT} and λ_{SC}):

$$\begin{cases} \Omega_{BT} = \lambda_{BT} \times NP_{BT} \times NS_{BT} \times \Omega_{BT0} \\ \Omega_{SC} = \lambda_{SC} \times NP_{SC} \times NS_{SC} \times \Omega_{SC0} \end{cases} \quad (5)$$

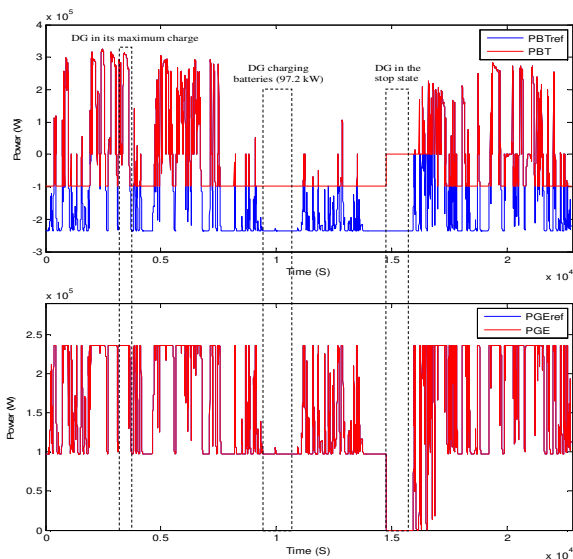


Fig. 14. Reference mission and corresponding response of the Batteries and diesel generator

where $\Omega_{BT0} = 4.33 \times 10^{-3}\text{ m}^3$, $\Omega_{SC0} = 9.9 \times 10^{-4}\text{ m}^3$, NP_{BT} and NS_{BT} are the number of parallel and series battery cells respectively while NP_{SC} and NS_{SC} are the number of parallel and series ultracapacitor cells respectively.

The assembly coefficients, which take into account of the interspaces between each cell, the volume of the static converters and the corresponding cooling devices are estimated to $\lambda_{BT} = 1.9$ and $\lambda_{SC} = 2.58$ [1].

The flywheel volume including that of motor/generator, static converter and safety envelope is given by the manufacturer:

$$\Omega_{FW} = 2.3 \times 1.4 \times 0.514 = 1.655\text{ m}^3 \quad (6)$$

The global system volume (Ω_{Σ}) is then:

$$\begin{cases} \Omega_{\Sigma} = \Omega_{DG} + \Omega_{BT} + \Omega_{SC} & \text{with SC architecture} \\ \Omega_{\Sigma} = \Omega_{DG} + \Omega_{BT} + \Omega_{FW} & \text{with FW architecture} \end{cases} \quad (7)$$

B. The Battery and Ultracapacitor Lifetime Models

The battery lifetime model is related to the number of cycles to failure (c_F) which can be expressed as a function of the depth of discharge (DOD , specified in %) [25]. A qualitative approximation of the c_F coefficient has been derived in [1] for the Hoppecke FNC 1502HR battery cells for rated conditions (temperature between 30°C – 40°C , charge at C_5 and discharge at $2C_5$):

$$c_F(DOD) = 966 \times DOD^{-2.37} \quad (8)$$

Considering the number of cycles to failure for $DOD = 100\%$ as a reference, we can express a ‘‘cycle weight’’ w_{CYCLE} for lower DOD s as:

$$w_{CYCLE}(DOD) = \frac{c_F(100\%)}{c_F(DOD)} \quad (9)$$

This weight evaluates the effect of a cycle for a given DOD in relation to a cycle for full DOD . Since battery SOC characteristics during a particular driving mission generally consist in various cycles with different DOD , a global battery stress estimator LFT_{BT} evaluates the battery lifetime from the total number of cycles N_{CYCLE} at a given DOD . To compute this estimator, the DOD range is divided into 10 uniformly spaced intervals. Then, the number of cycles $N_{CYCLE}(i)$ which occurs in a DOD interval i is determined from the battery SOC associated with the locomotive mission. Finally, the LFT_{BT} estimator is calculated by globalizing all cycles in all intervals, taking account their weight according to the corresponding DOD :

$$LFT_{BT} = \sum_{i=1}^{10} w_{CYCLE}(i) \times N_{CYCLE}(i) \quad (10)$$

where $w_{CYCLE}(i)$ denotes the cycle weight at the middle of the considered DOD interval i . The same approach is used for calculating the ultracapacitors lifetime considering linear distributed weights and a cycle to failure reference of 500 000 at 100% of DOD .

The computation of the cycle number is based on the ‘‘Rainflow counting method’’. More details about this method can be found in [1] and [26]. Note that the LFT_{BT} estimator is a

criterion which neglects microcycles. These latter are the cycles with a depth lower than 1% of the maximal storage capacity.

C. Comparison

The above comparison is based on the locomotive power mission of Fig. 7. It shows that the existing solution (S_{ex}) for the LHyDIE locomotive and the two flywheel based solutions with basic and optimized management strategy (S_{FW1} and S_{FW2} respectively) present rather close consumptions (See Table III and Fig. 15). This last solution (S_{FW2}) guarantees PLATHEE project objectives in terms of quantity of emitted CO_2 . The number of battery cycles is the same for both solutions (S_{ex} and S_{FW2}) while neglecting the microcycles and is a little more upper for S_{FW1} because the cut-off frequency is larger. However, we can declare that the number of microcycles (the cycles with a depth lower than 1% of the maximal storage capacity) supported by the batteries with the S_{FW2} solution is more important than the one obtained with the existing solution (S_{ex}). Note that the number of microcycles on battery cells is increased when the cut-off frequency is enlarged. According to the technology and the type of batteries, microcycles can degrade the batteries life time. Note also that a 7 kWh energy storage by means of ultracapacitors has been replaced by a 4 kWh energy storage with flywheel which can explain the difference between both solutions in terms of filtering frequency and consequent microcycles.

The flywheel solution (S_{FW2}) is advantageous from the point of view of the lifetime [14], [15] and the system volume. It

allows reducing the volume by $2.4 m^3$ compared to the locomotive existing solution and $0.9 m^3$ compared to the flywheel based solution with basic management strategy (S_{FW1}). Besides, the number of chemical elements to be recycled is much more important with the existing solution (1200 BT+1600 SC with the existing solution /1200 BT with flywheel solution).

VIII. CONCLUSION

In this paper, a power flow model of the whole traction device (diesel generator, energy storage elements) has been proposed as an efficient design tool for a "system approach". The principle of the energy management strategy based on a frequency approach is also described. In a second part, the integration of a flywheel device as element of energy storage on the LHyDIE hybrid locomotive in complement with the diesel generator and the batteries is studied. This study is made according to two energy management strategies based on the frequency approach. The first strategy is identical to the one previously used in the existing design solution with ultracapacitors: the flywheel only supplies high frequency harmonics. This has resulted in a non optimal exploitation of the flywheel and an increase of the battery cell number. With the aim of optimizing the use of flywheel and afterward the sizing of the locomotive, a second energy management strategy was proposed. It consists in injecting a part of the low frequency mission of the batteries into the flywheel while keeping priority for its high frequency mission. This last strategy allows decreasing the cut-off frequency and so decreasing the number of the battery cells and improving their lifetime. At the end, a comparative study of the present hybrid solution and the proposed solution according to a set of feasibility constraints and performance criteria is presented. Consequently, the proposed solution S_{FW2} (215 kW diesel engine, flywheel 5.33 kWh/325 kW and 1200 cells of batteries) with the optimized management strategy is a good candidate for the realization of a future hybrid locomotive.

Even though the locomotive sizing is based on local optimization methodology, the overall system optimisation is not guaranteed. Thus, the hybrid locomotive sizing can be investigated using a multiobjective optimization strategy. The criteria to be optimized could be the global system cost of the energetic sources and the carbon dioxide quantity emitted by diesel locomotive. Eventually, hybrid systems can be extended to new railway segments such as "last mile locomotive", auxiliaries of high speed trains, hybrid tramways and metros.

APPENDIX – LIST OF SYMBOLS

P_{DG} : Diesel generator power.

P_{DGref} , P_{DGmax} , P_{DGnom} : Reference, maximal and nominal diesel generator power.

E_{DG} : Diesel generator energy.

SFC : Specific fuel consumption.

Q_{fuel} : Consumed fuel quantity by the diesel generator.

Q_{CO2} : Dioxide carbon quantity emitted by the diesel generator.

TABLE III
FEASIBILITY CONSTRAINTS AND THE PERFORMANCE CRITERIA

	S_{ex} : existing solution with SC ($F_g=5$ mHz)	S_{FW1} : Basic strategy with FW ($F_g=27$ mHz)	S_{FW2} : optimized strategy with FW ($F_g=17$ mHz)
Cut-off frequency F_g	5 mHz	27 mHz	17 mHz
Nb of battery cells	1200	1312	1200
Nb of SC cells	1600	–	–
System volume (m^3)	16.5	14.9	14
Fuel Burn (L)	198	203	201

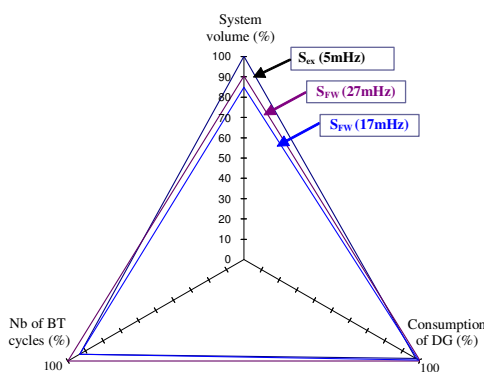


Fig. 15. Comparison according to the feasibility constraints and the performance criteria

η_{DG} : Diesel generator converter efficiency.
 P_S : Instantaneous power exchanged by the storage elements (index "s" corresponds to "BT" for battery, "SC" for ultracapacitors and "FW" for flywheel).
 P_S^r : Instantaneous real power exchanged by the storage elements.
 P_{Sref} : Reference power for storage elements.
 $P_{S\ dchmax} / P_{S\ chmax}$: Maximal charge/discharge power for the storage elements.
 E_S, E_{Smax} : Instantaneous and maximal stored energy of the storage elements.
 SOC_S : Storage element state of charge.
 η_S : Storage element energy efficiency.
 P_{LOC} : Locomotive power mission.
 P_{Loc-LF} : Total mission low frequency part and flywheel filtered losses.
 p_{FW} : Flywheel losses.
 P_{FW-LF} : Low frequency part of flywheel losses.
 ΔP_{FW} : Charge power excess for the flywheel.
 F_g : Cut-off frequency.
 P_{FWref0} : Power reference for the flywheel before P_{FWS} Injection.
 P_{FWS} : Flywheel secondary mission.
 R_{FW} : Flywheel power reserve.
 P_{BTref0} : Battery mission before injection of P_{FWS} .
 $\Omega_{DG}, \Omega_S, \Omega_\Sigma$: Diesel generator, storage element and global system volume.
 NP_{BT}, NS_{BT} : Number of parallel and series battery cells.
 NP_S, NS_{SC} : Number of parallel and series ultracapacitor cells.
 DOD : Storage element depth of discharge.
 c_F : Number of cycles to failure.
 N_{CYCLE} : Total number of cycles.
 w_{CYCLE} : "cycle weight".
 LFT_{BT} : Global battery stress estimator.
 S_{ex} : Existing solution for the LHyDIE locomotive.
 S_{FW1}, S_{FW2} : Flywheel based solution with basic and optimized management strategy.

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