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Energy management and sizing of a hybrid locomotive

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Keywords

«Rail vehicle», «Hybrid electric vehicle», «Energy system management», «Supercapacitor», «Locomotive», «Energy storage».

Abstract

The French national railways company (SNCF) is involved in a new project which aims at investigating and testing energy-efficient and environmentally friendly traction systems of a hybrid locomotive called LHyDIE. This paper presents a new methodology for the hybrid electric vehicle design which exploits an energy management strategy based on a frequency approach. In particular, the design of the LHyDIE prototype and the energy management strategy implemented aboard are presented. The study mainly focuses on the battery and supercapacitor sizing taking account of the intrinsic energetic characteristics of these sources (i.e. energy and power densities, typical operating frequency) in the energy management strategy. The analysis of feasible configurations of the traction device determined in compliance with the battery stress, the system cost and the diesel oil consumption criteria and volume constraints is presented.

Introduction

The inevitable drying up of petroleum reserves and of the more and more increasing environmental concerns motivate an extensive research in the field of electric transport systems. Investigations aim for the long term at designing “pure” Electric Vehicles with a sufficient autonomy. Until the new technologies of energy storage mature to ensure such performance, hybrid vehicles are an essential bridge between conventional petroleum vehicles and pure electric vehicles [1]. Even if the monopoly of the pollution in transport fall to the motorcars, the railway transport is also concerned with its huge park of diesel locomotives used for specific tasks (e.g. switching, shunting, assistance mission, train forming, intervention on catenaries) [2]. In this paper, energy storage device sizing techniques are studied. These techniques are used to design a prototype of hybrid locomotive called “LHyDIE” (Hybrid Locomotive for Demonstration and Investigations on Energetic), powered by a small diesel generator, batteries and supercapacitors. This hybrid locomotive is built from a conventional shunting and switcher diesel locomotive named “BB63000” moved by four electric motors fed by a diesel generator of 600 kW. LHyDIE is designed in order to fulfill the same missions as the “BB63000”. The volume constraints due to the exiguity of the space aboard the locomotive, the reduction of the diesel oil consumption and the optimization of the battery lifetime are considered by the design approach. Overall these criteria and

constraints the power consumption on board the future hybrid locomotive is the main key of the hybridization approach feasibility.

The idea of the hybridization comes from the observation of the power provided by the “BB63000” diesel generator in switching and shunting services. The Fig. 1 shows a typical “BB63000” power mission and the histogram of the diesel generator operating. The power peaks supplied by the diesel generator rise to 570 kW while the average power is close to 200 kW. Overall, the diesel generator operates most of the time (about 72% of the time) at lower load and only 11% of the time at its nominal power [2]. Knowing that the diesel generator energy efficiency and pollution are very bad at lower loads but are optimized (improved) at higher loads, it is then clear that the “BB63000” diesel generator is not optimally used. The hybridization consists in replacing the big diesel generator of 600 kW with a smaller capable of providing the average power, and in coupling it with energy storage devices (typically batteries and supercapacitors) in order to provide the fluctuating power. During the phases of lower demands (i.e. when the loading power is lower than the generator capacity) the storage devices accumulate the energy and restore it when the power demands exceed the diesel generator capacity. Under these conditions, a smaller diesel generator will operate most of the time at its nominal power and will reduce diesel oil consumption and pollution.

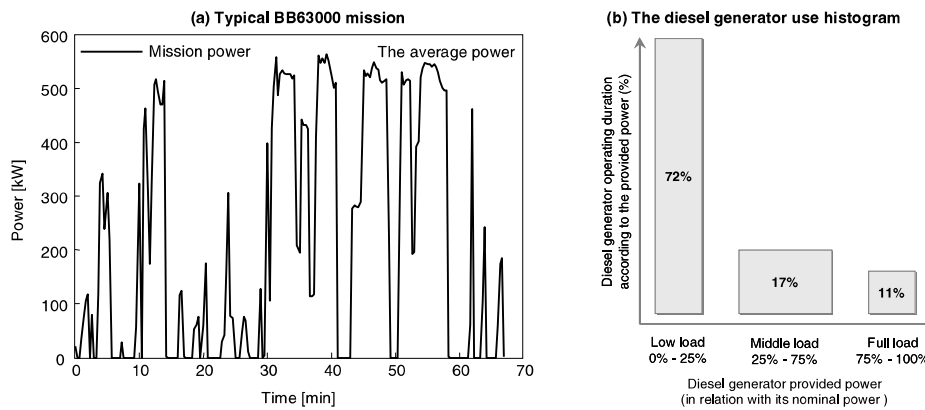


Fig. 1: A typical mission of the diesel locomotive and the histogram of diesel generator use

The paper is organized as follows. First, a study of the embedded sources on LHyDIE is presented. The energy management strategy based on a frequency approach is explained and used in order to determine the mission part of each source. Storage elements (i.e. batteries and supercapacitors) are then sized according to energy management strategy previously, defined. Finally the analysis of feasible configurations in compliance with the battery stress, the system cost, atmospheric pollution criteria, and volume constraints, is presented.

Study of energy sources embedded on LHyDIE

As the energy management strategy aims at improving the use of each embedded source, a brief survey of storage devices is presented. In particular, we remind in this section the intrinsic characteristics of diesel generators, batteries and supercapacitors.

Diesel generator

The diesel generator is the main energetic component of the hybrid locomotive. It produces all the energy required for the missions. Moreover, the atmospheric pollution and the diesel oil consumption are essentially linked to the diesel generator. This element is a very complex system. It is composed of a gasoline engine and an electric generator. The study focuses on the brake specific fuel consumption (BSFC) and gas emissions of the gasoline engine. The BSFC (g/kWh) depends on the provided power and the engine speed. Fig. 2 illustrates the optimal diesel oil consumption and engine speed curves of a

215 kW gasoline generator as a function of the provided power. Note that the BSFC consumption indicator is not good when the diesel engine operates at loads lower than the nominal load. On the contrary, BSFC is excellent for loads close to its nominal load (i.e. 215 kW). Therefore, for an optimal use of the diesel engine, it is advisable to operate at the nominal load. [3].

Concerning the atmospheric pollution, gas (CO, NO_x, and HC) and particle emissions depend on the engine nominal power. The bigger the engine is, the more it pollutes. The greenhouse gas (CO₂) directly depends on the diesel oil consumption. 250 liters of diesel oil produce one ton of CO₂. To conclude, the diminution of the diesel generator size and a constant use at its nominal operating point favor the reduction of diesel oil consumption and atmospheric pollution.

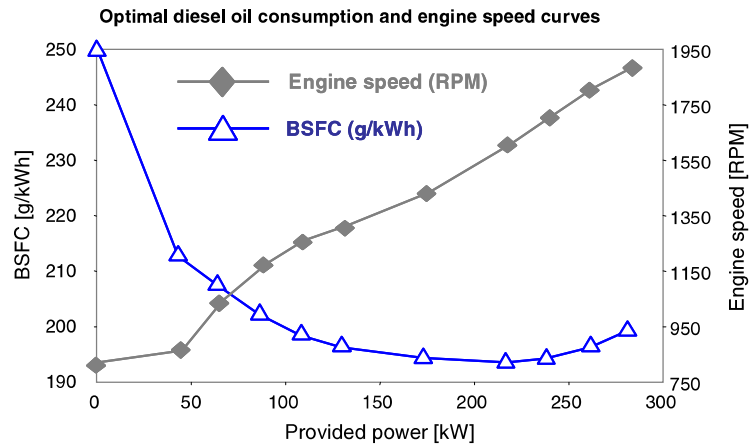


Fig. 2: The optimal diesel oil consumption and engine speed curves of a 215 kW gasoline generator as a function of the provided power.

Energy storage devices

Among the wide range of energy storage devices, only three are enough mature and well suited to be embedded on vehicles (i.e. batteries, supercapacitors and flywheels). This section mainly focuses on batteries and supercapacitors. As shown in Fig. 3, energy storage devices are classified according to their energy density, their power density and to the cycle dynamics they provide [4 and 5].

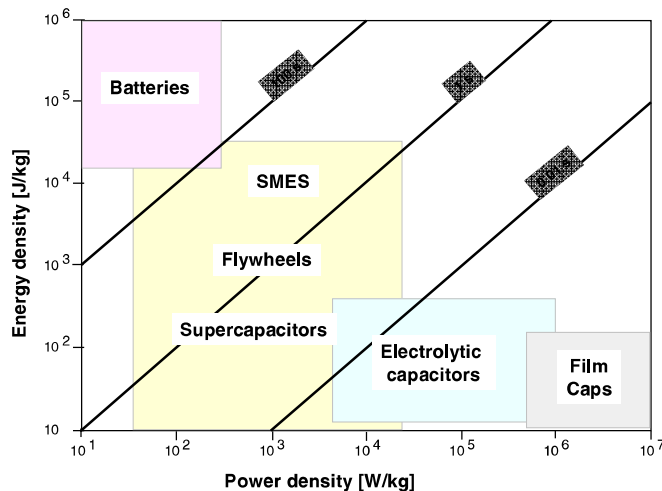


Fig. 3: Characterization of main energy storage devices (Ragone chart)

Batteries have the best energy density but a bad power density and provide slow dynamic cycles (more than 100 s). Contrary to batteries, supercapacitors have lower energy density (1000 times lower) but higher power density (100 times higher) and provide very fast dynamic cycles (close to 0.001s). Furthermore, batteries are lifetime limited devices providing few cycles (typically 1000 cycles). Battery lifetime depends on the operating temperature (about 20°C), on the number and on the depth of discharge cycles. To optimize the lifetime of the batteries, it is advisable to use them only for slow dynamic power cycles. On the other hand, supercapacitors can provide more cycles than batteries (500.000 cycles) and are well suited to very fast dynamic cycles [6]. Thus, batteries and supercapacitors are complementary in the frequency space.

Energy management strategy based on a frequency approach

Standard design methodologies are based on a sequential approach which consists in defining the system architecture, then in sizing the system elements and finally in defining an optimal energy management strategy. A new approach is proposed in this paper. First, the architecture is imposed by the kind of hybridization. LHyDIE is a serial hybrid locomotive. Fig. 4 shows a simplified architecture of LHyDIE. The diesel generator, batteries and supercapacitors exchange energy through their suitable converter in order to ensure the traction mission and to feed auxiliaries. Secondly, the energy management strategy is defined so as to determine the mission part of each source. Finally, energy sources are sized. Note that the inversion of the sizing and management strategy steps is motivated by the fact that energy storage devices are easily sizeable from their power mission. As the power missions associated with each storage element are determined by the energy management strategy, this justifies this particular design approach. Moreover, within this approach, we can take into account of the intrinsic characteristics of the embedded sources and the compliance of several criteria such as the battery stress, the system cost, the diesel oil consumption, atmospheric pollution and the system volume.

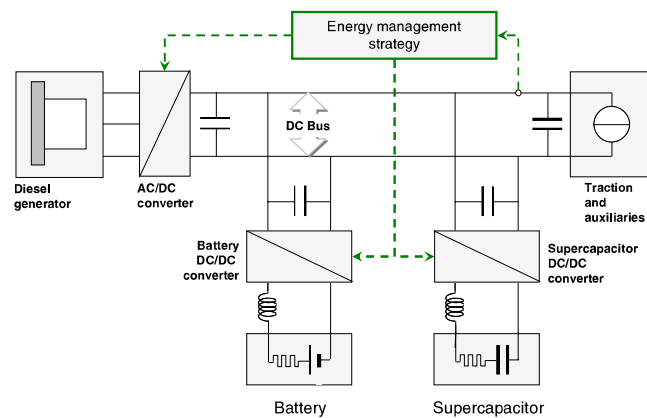


Fig. 4: Simplified architecture of the hybrid locomotive (LHyDIE)

We have underlined in the previous section (page 2) three fundamental points concerning the intrinsic features of the embedded sources.

1. The optimal operating point of the diesel generator is its nominal power. At this point the diesel oil consumption is minimum (Fig. 2) and atmospheric pollution is acceptable. Therefore, it is advisable to consider the generator as a continuous power source.
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. Contrary to batteries, ultracapacitors are capable of absorbing currents with fast dynamics, and to provide a significant number of cycles (typically 500000 cycles) [6].

The energy management strategy based on a frequency approach aims at distributing the global power mission of the locomotive into the sources in such a way that each source is optimally used. According to the three points mentioned above embedded energy sources can be classified in the frequency space as shown in Fig. 5 (a). The diesel generator is the lower frequency power source (approximately continuous power source) which provides continuously its nominal power so that atmospheric pollution and diesel oil consumption are optimized. Supercapacitors are higher frequency power sources which provide the micro-cycles and the fast dynamic power components. Batteries are “sandwiched” between the diesel generator and supercapacitors in the frequency space.

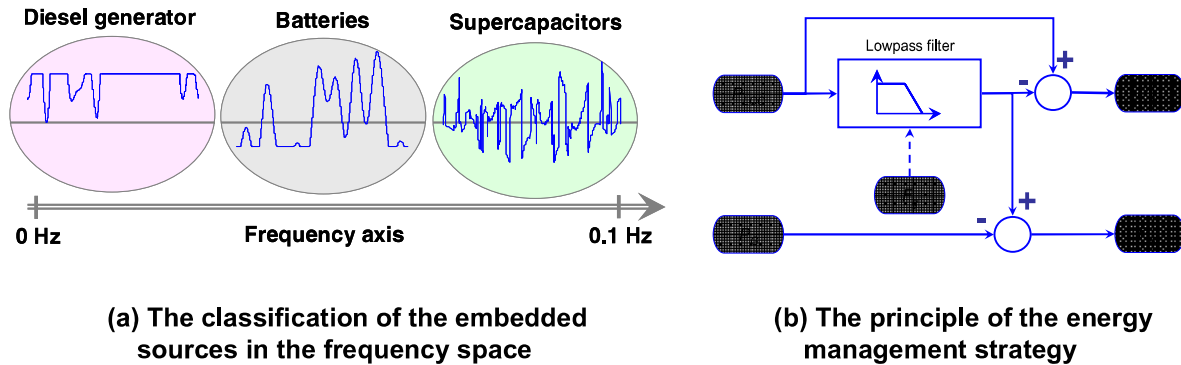


Fig. 5: Frequency classification of the embedded sources and principle of the energy management strategy based on a frequency approach.

Fig. 5 (b) shows the principle of the energy management strategy based on a frequency approach. The global locomotive mission power $P_{Loc}(t)$ is filtered by a lowpass filter. The high frequency part $P_{Sc}(t)$ of the locomotive mission power is devoted to the supercapacitors while the lower frequency part is shared between the batteries and the diesel generator. The diesel generator is supposed to provide continuously its nominal power P_G . Therefore the mission of the batteries $P_{BT}(t)$ is obtained by subtracting the diesel generator power from the lower frequency part of the locomotive mission power. The frequency distribution of the locomotive mission uses two control parameters which are the cutoff frequency (F_g) of the lowpass filter and the diesel generator nominal power P_G .

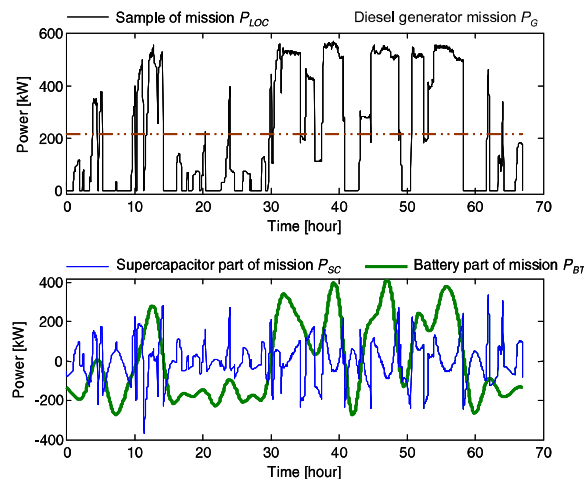


Fig. 6: Repartition of a sample of the locomotive global mission power based on the frequency energy management strategy.

As shown in Fig. 6, (note that positive power values are equivalent to a storage device discharging while negative power values correspond to a storage device charging) supercapacitors absorb multiple micro-cycles and the fast dynamic harmonics of the global mission so that batteries only ensure slow dynamic harmonics and a low number of cycles. Note that the association between batteries and supercapacitors should improve battery lifetime by reducing the battery stress. Finally, to conclude this section we mention, that the energy management strategy based on a frequency approach allows a suitable use of each embedded source.

To each value of the doublet (F_g, P_G) corresponds a new distribution of the mission and therefore a new sizing (configuration) of the system (diesel generator, batteries and supercapacitors). When varying the couple (F_g, P_G) many configurations of the system can be sized.

The battery and supercapacitor sizing

In this section, we aim at determining the number of elements for each storage device embedded in LHyDIE. The global power mission of the locomotive $P_{Loc}(t)$ is a 12 hours mission with an average power of 150 kW obtained from the concatenation of all the “BB63000” recorded missions. The mission $P_{Loc}(t)$ includes the traction power and feeding power of the auxiliaries. The energy management strategy defined in the previous section is used to determine the supercapacitor mission $P_{SC}'(t)$ and the battery mission $P_{BT}'(t)$ according to the doublet value (F_g, P_G) . Additional information is used to determine the number of elements of each storage device embedded in the hybrid locomotive. To take into account of the energy losses during the mission, average energy efficiency is applied to the initial mission of each storage device to get a more realistic mission. According to the sign convention defined above, the new missions are written in the form:

$$P_{SC}(t) = \begin{cases} 1/\eta_{SC} \cdot P_{SC}'(t) & \text{if } P_{SC}'(t) \geq 0 \\ \eta_{SC} \cdot P_{SC}'(t) & \text{if } P_{SC}'(t) < 0 \end{cases} \quad \text{and} \quad P_{BT}(t) = \begin{cases} 1/\eta_{BT} \cdot P_{BT}'(t) & \text{if } P_{BT}'(t) \geq 0 \\ \eta_{BT} \cdot P_{BT}'(t) & \text{if } P_{BT}'(t) < 0 \end{cases} \quad (1)$$

where the parameters η_{SC} and η_{BT} are respectively the energy efficiency associated with the supercapacitors and the batteries. These parameters are commonly set to 0.8 (η_{BT}) for Ni-Cd batteries and 0.95 (η_{SC}) for the supercapacitors [4].

The sizing of supercapacitor elements

The supercapacitor mission power $P_{SC}(t)$ is related to the higher frequency part of the global mission $P_{Loc}(t)$. Thus, $P_{SC}(t)$ only depends on the cutoff frequency F_g . Consider the sample of supercapacitor power mission $P_{SC}(t)$ of Fig. 7 (a). The maximum discharging power P_{SC}^D imposed by the mission and the maximum charging power P_{SC}^C available during the mission are respectively equal to 147 kW and 100 kW. The relative level of the supercapacitor energy $E_{SC}^R(t)$ during the mission is deduced from the power mission $P_{SC}(t)$ as follows:

$$E_{SC}^R(t) = -\int_0^t P_{SC}(\tau) d\tau \quad (2)$$

The active energy E_{SC}^A corresponding to the energy quantity transferred during the mission can be written in the form:

$$E_{SC}^A = \text{MAX}_t(E_{SC}^R(t)) - \text{MIN}_t(E_{SC}^R(t)) \quad (3)$$

By taking account of to the prescribed discharge rate k_{SC}^{DR} (set to 0.75 in this study), the supercapacitor energy storage capacity is given by:

$$E_{SC} = E_{SC}^A / k_{SC}^{DR} \quad (4)$$

These calculations are made on a mission sample of the supercapacitors (See Fig. 7 (a)). The supercapacitor energy storage capacity E_{SC} due to the needed active energy is not the only criterion used to determine the number of supercapacitors. The maximum power provided P_{SC}^{max} (i.e. the maximum value of P_{SC}^D and P_{SC}^C) should also be considered. A supercapacitor element is characterized by the energy E_{AV}^0 and the power P_{AV}^0 it can provide (available energy and available power). The total number of elements N_{SC} required to ensure the mission $P_{SC}(t)$ is given by:

$$N_{SC} = \text{MAX}(P_{SC}^{max} / P_{AV}^0, E_{SC} / E_{AV}^0) \quad (5)$$

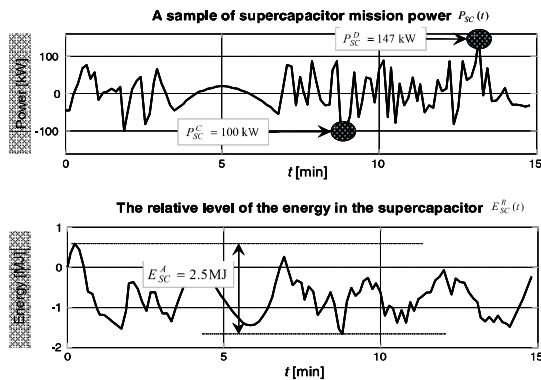
As explained above and shown in Fig. 7(b), the total number of supercapacitors N_{SC} varies according to the cutoff frequency F_g . It should be noted that the reduction of the cutoff frequency leads to an increase of the supercapacitor number since the supercapacitor part of the global mission is also increased.

The sizing of the battery elements

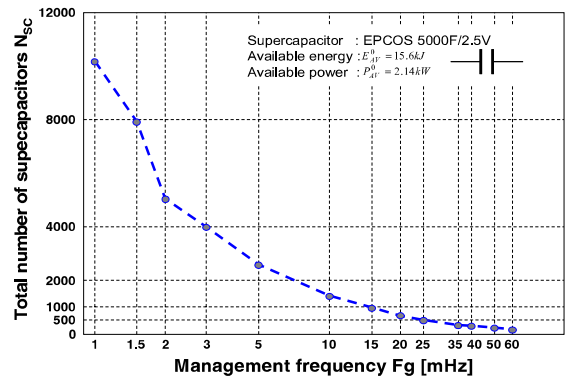
The determination of the number of battery elements is more complicated than in the case of supercapacitors. Battery charging and discharging current limitations imply two constraints related to the energy storage capacity E_{BT} , the maximum charging power P_{BT}^C and the maximum discharging power P_{BT}^D .

$$\begin{cases} P_{BT}^D \leq E_{BT} / T_D \\ P_{BT}^C \leq E_{BT} / T_C \end{cases} \quad (6)$$

where T_D (respectively T_C) is the minimum duration of battery discharging at P_{BT}^D (respectively the minimum duration of battery charging at P_{BT}^C). Generally, T_D is set to a value between 1/5 h (hour) and 1 h, while T_C is set to a value between 1 h and 2 h. In the case of the LHyDIE locomotive T_D and T_C are respectively set to 1/3 h and 1 h.



(a) Supercapacitor design illustration



(b) Supercapacitor sizing according to the management frequency

Fig. 7: Supercapacitor design illustration and sizing of supercapacitor elements embedded on LHyDIE

The battery mission $P_{BT}(t)$ depends on the cutoff frequency F_g and of the nominal power P_G of the diesel generator. Thus, to each value of the doublet (F_g, P_G) corresponds a battery mission $P_{BT}(t)$. However, the real battery mission is not known at this step. Indeed, the battery power mission is composed of charging and discharging cycles. In the battery sizing process, we take into account during the mission the integral of all the discharging power and that of the charging power if the charge level is below the initial energy level. The charging power corresponds to some available energy that batteries could store according to their state of charge and their charging power limitation. Thus, the active energy needed to ensure the power mission $P_{BT}(t)$ depends on the maximum charging power P_{BT}^C provided by the batteries. For different values of P_{BT}^C the battery mission is corrected in order to take account of the charging power limitation and the active energy E_{BT}^A is evaluated. Contrary to the supercapacitor active energy calculation (Eq. 2 and 3), the battery active energy is evaluated with an upper saturated integration calculation to avoid oversizing. This procedure avoids considering additional energy in the batteries when the accumulator cells are fully charged (see Fig. 8).

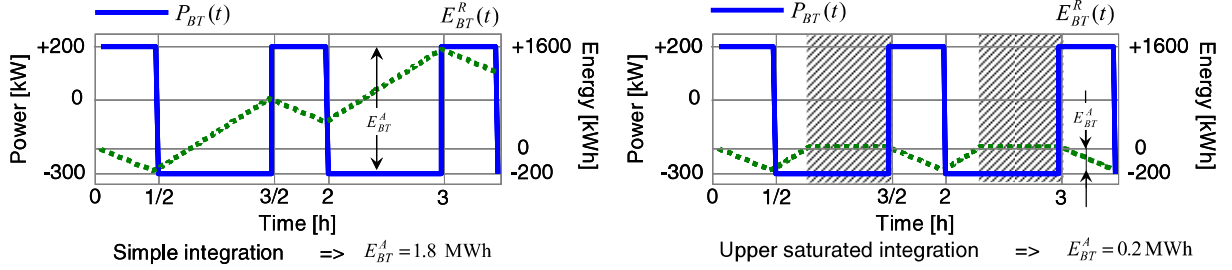


Fig. 8: Battery active energy calculation with saturated integration operation

$$E_{BT}^R(t) = - \int_0^t P(\tau) d\tau \quad \text{and} \quad E_{BT}^A = \text{MAX}_t(E_{BT}^R(t)) - \text{MIN}_t(E_{BT}^R(t)) \quad (7)$$

upper saturated integration

By taking account of the prescribed discharge rate k_{BT}^{DR} (set to 50 % in this paper), the battery energy storage capacity is given by:

$$E_{BT} = E_{BT}^A / k_{BT}^{DR} \quad (8)$$

Two constraints have to be fulfilled for the sizing of the batteries. One should consider the valid sizing area defined by Eq. 6 and the function $E_{BT}(P_{BT}^C)$ which estimates the battery storage capacity according to the charging power limitation. The battery sizing graph of Fig. 9(a) is obtained by considering these constraints. The intersection point A of the storage capacity function and the charging power limitation line corresponds to the optimal sizing point. At this point the required active energy (i.e. the storage capacity) is the smallest of the valid area. Generally, the storage capacity $(E_{BT})_A$ corresponding to the point A is enough to provide the discharging power $(P_{BT}^D)_{M1}$ required by the mission. If not (e.g. in the $(P_{BT}^D)_{M2}$ case) the battery sizing point migrates to the point B less optimal than the point A.

As explained above and shown in Fig. 9(b) the total number of battery cells N_{BT} varies according to the cutoff frequency F_g and the diesel generator nominal power P_G . Reducing the diesel generator size obviously leads to increase battery cell number. On the other hand, the cutoff frequency has little effect on the battery sizing especially for small diesel generators.

Sizing analysis and final choice

In this section, multiple configurations of the locomotive are analyzed in accordance with four criteria. The first criterion is the battery stress indicator k_{BSI} [cycles/day] corresponding to the number of cycles provided by the batteries per day. This indicator is directly linked to the battery lifetime. As shown in Fig. 10(a), the battery stress decreases as the number of supercapacitors increases. This proves that supercapacitors help to prolong battery lifetime. The second criterion is the diesel generator energy efficiency. As explained in the paragraph devoted to the diesel engine study, the diesel generator oil consumption is optimal when the diesel engine operates at its nominal power. Because of the battery charging power limitation and of the charging inhibition when batteries are full, the diesel engine can not always operate at its nominal power. The tendency of the diesel engine to operate at its nominal power is an indicator of the diesel oil consumption (i.e. the diesel engine efficiency k_{DEE}). As shown in Fig. 10(b) this efficiency decreases when the nominal power of the diesel engine increases. Fig.10(c) shows that the system volume (limited to diesel generator, batteries and supercapacitors) varies according to the diesel generator size and the number of supercapacitors. The bigger the diesel generator is the less voluminous is the system. This proves that vehicle hybridization does not necessary lead to a space gain. Reducing diesel generator size in order to improve energy efficiency as well as the atmospheric pollution, and increasing the number of supercapacitors with the aim of reducing the battery stress, tend to violate the volume constraints. Finally, the system cost is evaluated in (Fig. 10(d)). Conclusions related to the system cost are similar to the case of volume constraints.

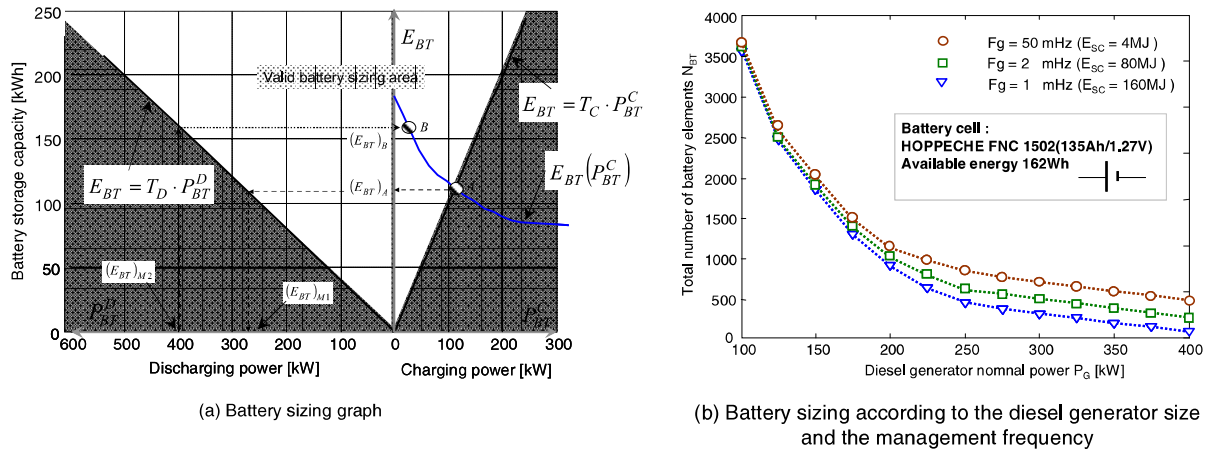


Fig. 9: Battery sizing graph and number of battery elements embedded on LHyDIE

This analysis shows that it is not possible to simultaneously conciliate energy efficiency, the system cost, volume constraints and the improvement of the battery stress. For the final sizing of the locomotive, a compromise has been chosen consisting in a 215 kW diesel generator, 200 kWh of batteries (1200 cells of 135 Ah batteries) (see Fig. 9(b)) and 1600 cells of 5000 F/2.5 V supercapacitors (corresponding to a cutoff frequency of 10 mHz in Fig. 7(b)). Batteries are divided in 4 blocks and supercapacitors in 8 blocks. Fig. 11 shows the final architecture and sizing for LHyDIE.

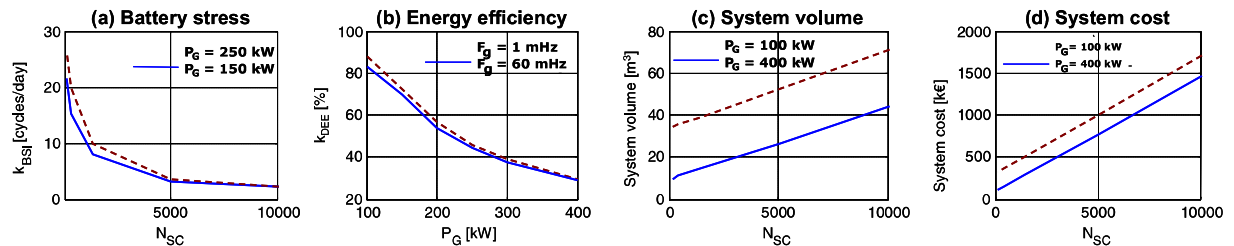


Fig. 10: Analysis of feasible configurations of the locomotive

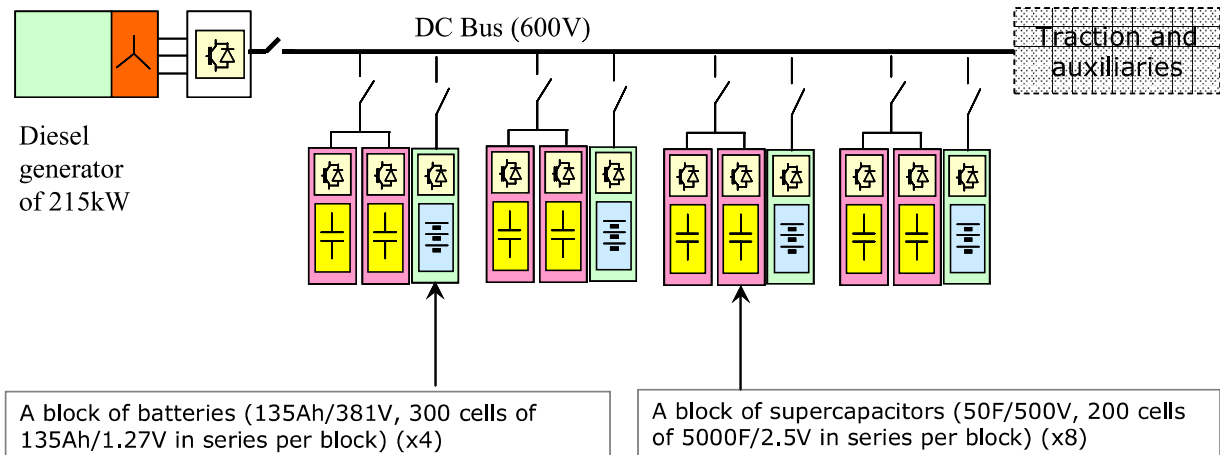


Fig. 11: The final LHyDIE architecture and the associated sizing

Conclusion

In this paper, an energy management strategy and an associated sizing procedure have been proposed to design a hybrid locomotive. In particular, the frequency feature of the storage devices has been considered as a primary criterion, allowing an optimal use of each embedded source. It is shown that supercapacitors help to reduce the battery stress by absorbing micro-cycles and fast dynamic harmonics of the global mission. The analysis of the feasible configurations of the locomotive has shown that it is not easy to simultaneously conciliate the energy efficiency, the system cost, volume constraints and the improvement of the battery stress. In the future, a global sizing approach based on multiobjective optimization will be investigated in order to find best tradeoffs between the design objectives and the technological constraints.

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