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Abstract. In this paper, the Integrated Optimal Design (IOD) approach for energetic system design is discussed. IOD aims at concurrently optimizing the architecture, the element sizing and the energy management in an energetic system. IOD leads to complex optimization problems (typically mixed variable problems with several constraints and multiple objectives) which can be solved with direct optimization methods. We illustrate the interest of this approach through the design of a hybrid environmentally friendly locomotive moved by four DC motors supplied by a diesel engine generator in association with electric storage elements (batteries and ultracapacitors).

1. Introduction

The design of electrical energetic systems represents a societal challenge. The increasing demands in terms of energetic needs and efficiency requirements for energetic systems have to be fulfilled. Instead of current devices which are generally oversized in relation to their power needs, innovative systems should now be designed as accurately as possible to avoid energetic wastes. The difficulties related to the optimization of such systems are related to several features:

- these systems are characterized by a high level of complexity, being composed of multiple subsystems whose architecture and dimensioning have to be determined to reach optimal performance
- these systems are strongly heterogeneous, multi-domain, being composed of elements with different physical types (electric, mechanic, thermal) and multi-time scaled models. This leads the designer to raise the question of the level of representation for the system elements and the corresponding model types (analytical, numerical such as algebra-differential equations or finite element models) in relation to a compromise associated with accuracy and computational costs. Because of these main difficulties, the design process was usually simplified by using a sequential approach divided in three different steps:

- step 1: find the most suitable system architecture
- step 2: optimize the element sizing
- step 3: find an optimal energy management strategy for the system

Note that step 2 and step 3 are sometimes reversed for hybrid systems. However, couplings existing between these factors and their influence on the global system efficiency require the evolution toward a global optimization approach. Various methodologies have been recently developed for design optimization including Multidisciplinary Design Optimization in aeronautics [1,2], Integrated Design in Electronics and Power Systems [3–5] or Simultaneous Design in Automatic and Control Systems [6,7].

In this work a typical example of IOD problem in electrical engineering is presented, illustrating the design of a hybrid locomotive devoted to non-electrified areas. The French national railways company (SNCF) and research academic institutes are involved in a project called PLATHEE[1] [8] which aims at investigating and testing energy efficient and environmentally friendly traction systems. In this context, a platform called LHyDIE (Hybrid Locomotive for Demonstration and Investigations in Energetics) is developed. Even if the platform specifications have already been determined from earlier studies [9,10] with a traditional sequential approach of the design, this work compares the obtained results with those resulting from a global IOD methodology.

2. The locomotive architecture and the energy management strategy

LHyDIE 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. One goal of the PLATHEE project is to reduce the diesel engine size by hybridizing this energetic source with batteries and ultracapacitors (see Fig. 1). All sources are coupled to a DC bus through static converters. Batteries (or ultracapacitors) are composed of NP_{BT} blocks (respectively NP_{SC} blocks) connected in parallel to the DC bus, each block containing NS_{BT} battery cells (respectively NS_{BT} ultracapacitor cells) in series. The energy management in the locomotive is based on a frequential approach which dispatches the power (P_M) required by the driving mission according to the dynamic of the embedded energetic sources (see Fig. 2). The high frequency part of the power demand is devoted to the ultracapacitors (P_{SC}) while the lower frequency part is shared between the batteries (P_{BT}) and the diesel engine generator (P_{DE}). The frequency distribution of the locomotive mission uses two control parameters: the cutoff frequency (F_c) of a lowpass filter and the diesel generator power P_{DE}.

The locomotive is devoted to shunting services and should fulfill the mission profile of Fig. 3. It has been shown in [9] that this profile dominates in terms of power and energy other usual missions. Therefore, the mission of Fig. 3 is considered as the most difficult mission and is taken as reference in the design process.

3. The energetic models

All models dedicated to the locomotive IOD have been developed in Matlab/Simulink. They concern the energetic behavior, the embedded energetic source volumes, the global system cost and the battery lifetime

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[1]PLATHEE is a French acronym which means "Energy Efficient and Environmentally Friendly Train Platform".
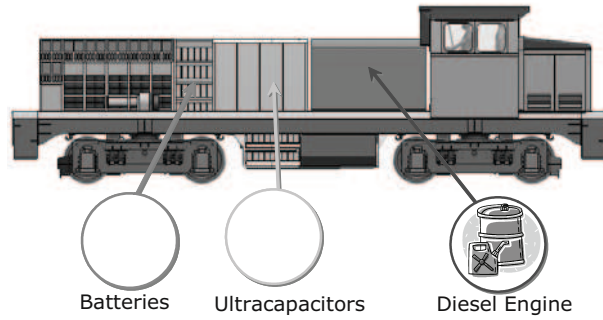
Fig. 1. The LHyDIE locomotive architecture.
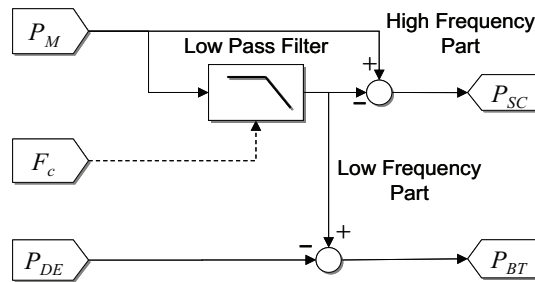
Fig. 2. The main principle of the energy management strategy.
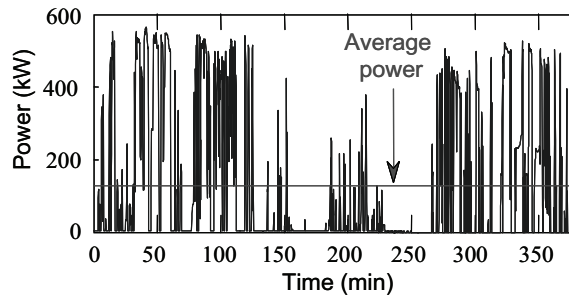
Fig. 3. A typical difficult locomotive mission profile.

3.1. The power flux model

The power flux model determines the characteristics of the power sources of the locomotive i.e. the power (P), the energy (E) and the state of charge (SOC) for the storage elements. Considering a given power mission P_M, an energy management controller provides the power reference values for the diesel engine (P_{DEref}), the ultracapacitors (P_{SCref}) and the batteries (P_{BTref}). These references are obtained according to the principle of Fig. 2 and by taking power losses in the storage elements and the associated state of charge limits. The power flux model of the diesel engine is given in Fig. 4. It allows us to obtain from the diesel engine power reference (P_{DEref}) and a start/stop command (SS_{DE}) the diesel engine power (P_{DE}), the corresponding energy (E_{DE}), 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

Table 1
The parameters of the battery and ultracapacitor power flux models

	Ultracapacitors	Batteries
Efficiency (including the converter efficiency)	$\eta_{SC} = 91\%$	$\eta_{BT} = 80\%$
Discharge limit	$P_{dchmax} = 475$ kW	$P_{dchmax} = 380$ kW
Charge limit	$P_{chmax} = -475$ kW	$P_{chmax} = -192$ kW

Fig. 4. The power flux model of the diesel engine.

efficiency associated with the diesel engine (typically $\eta_{DE} = 96\%$), the diesel power limit (P_{DEmax}) and the Specific Fuel Consumption (*SFC*) characteristic. This characteristic has been extrapolated with a five order polynomial as a function of the diesel engine power as follows [9],
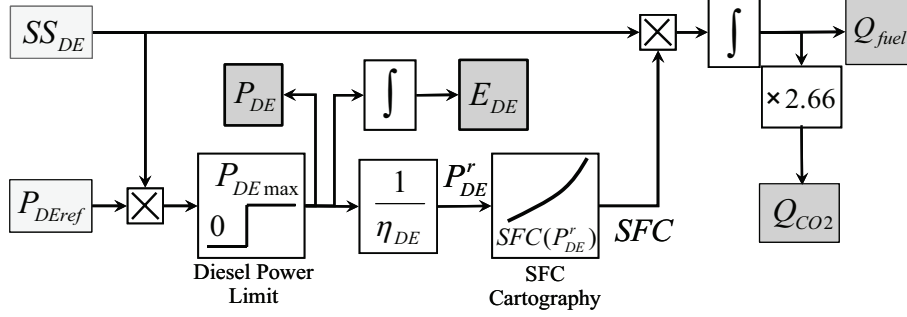
$$SFC(P_{DE}) = SFC_N \sum_{i=0}^{5} b_i \left(\frac{P_{DE}}{P_{DEN}} \right)^i \tag{1}$$

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_{DEN} denotes the nominal power of the diesel engine and *SFC*$_N$ represents the specific fuel consumption at this power estimated at 202.45 g/kW. The previous relation has been validated for three diesel engines of the Fiat Powertrain Technologies Group. Note that the specific fuel consumption is optimal when the diesel engine operates at its nominal power P_{DEN}. Therefore, the energy management controller tends to maintain the diesel engine power reference close to this power.

The quantity of CO_2 emitted (in kg/L) is directly proportional to the fuel quantity consumed and is estimated as follows [11]:

$$Q_{CO2} = 2.66 \times Q_{fuel} \tag{2}$$

The power flux model of the storage element packs is given in Fig. 5. The model is identical for batteries and ultracapacitors so the s index in Fig. 4 can be replaced by *BT* for the battery pack and *SC* for the ultracapacitor pack. The parameters of this model and their values are given in Table 1.

3.2. The electric model

The *electric model* specifies voltages and currents from the power flux model. A *RC* electric model is used to obtain the electrical variables in an utltracapacitor or battery cell (see Figs 6 and 7). Technological data values corresponding to EPCOS 5000 F/2.5V ultracapacitor cells and Hoppecke FNC 1502HR
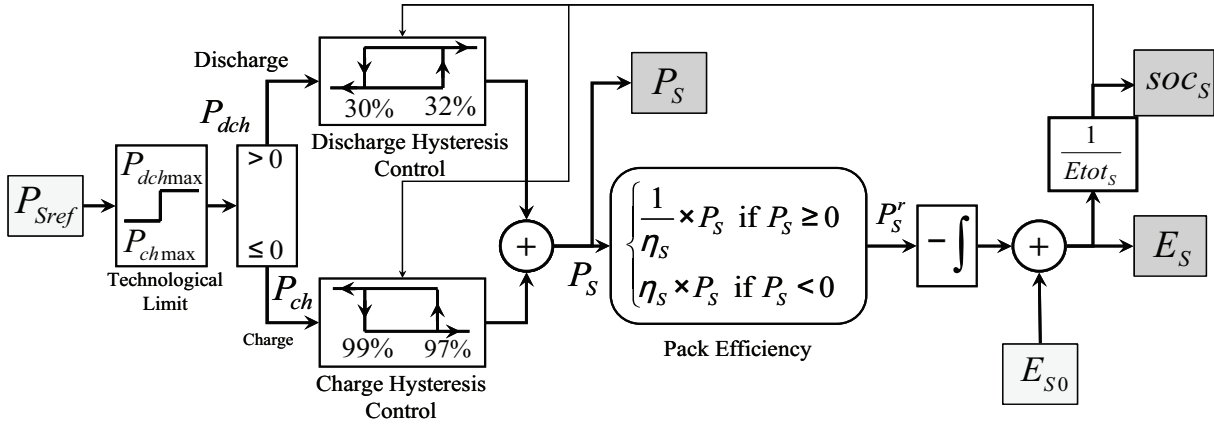
Fig. 5. The power flux model of a storage element pack (ultracapacitors or batteries).
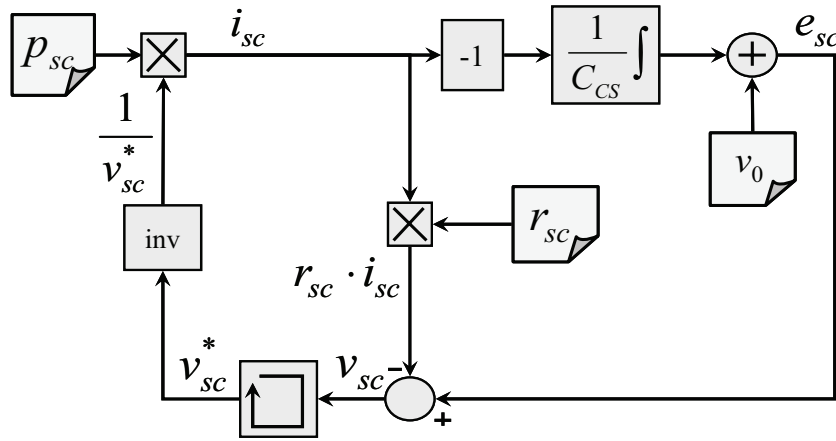
Fig. 6. The electric model of an ultracapacitor cell.

battery cells of 135 Ah are considered in these models. In particular the battery resistance r_{BT} and its emf e_{BT} are interpolated from the manufacturer data as a function of the cell state of charge q:

$$\begin{cases} r_{BT} = 2.83 - 12.88q + 24.88q^2 - 20.83q^3 + 6.28q^4 \\ e_{BT} = 0.99 + 1.06q - 1.82q^2 + 1.11q^3 \end{cases} \tag{3}$$

The ultracapacitor resistance is supposed to take a constant value of 350 mΩ. Current and voltage in a cell are computed from the cell power (p_{SC} or p_{BT}) as follows:

$$\begin{cases} p_{SC} = P_{SC}/(NP_{SC} \times NS_{SC}) \\ p_{BT} = P_{BT}/(NP_{BT} \times NS_{BT}) \end{cases} \tag{4}$$

where NS_{BT} and NP_{BT} denote the number of battery cells in series and the associated number of branches in parallel. NS_{SC} and NP_{SC} represent the same variables for ultracapacitors.
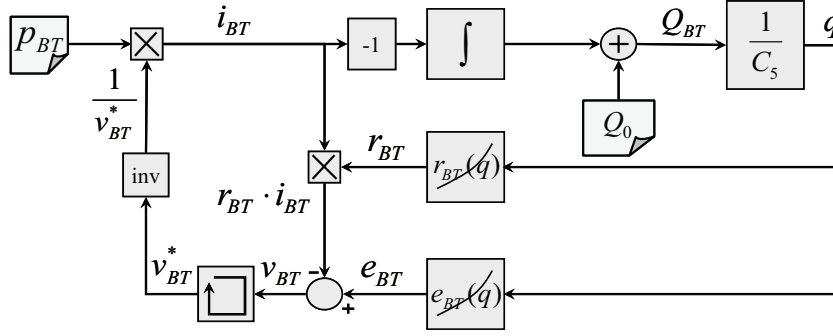
Fig. 7. The electric model of a battery cell.

3.3. The sizing model

The global volume available for the embedded energetic sources and their associated devices (static converters, thermal radiators, filter elements) is about 32 m³. Therefore, the volume of each component has been estimated with empiric relations from manufacturer data, in order to fulfill space constraints. The diesel engine volume Ω_{DE} in m³ has been interpolated with a linear function as follows:

$$\Omega_{DE} = 3 \times 10^{-5} \, P_{DEN} + 0.03 \tag{5}$$

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

$$\begin{cases} \Omega_{BT} = \lambda_{BT} \times NP_{BT} \times NS_{BT} \times \Omega_{BT0} \\ \Omega_{SC} = \lambda_{SC} \times NP_{SC} \times NS_{SC} \times \Omega_{SC0} \end{cases} \tag{6}$$

where $\Omega_{BT0} = 4.33 \times 10^{-3}$ m³ and $\Omega_{SC0} = 9.9 \times 10^{-4}$ m³. The assembly coefficients, which take into account of the interspaces between each cell and the corresponding cooling devices are estimated to $\lambda_{BT} = 1.8$ and $\lambda_{SC} = 2.3$. The volume of the static converters associated with ultracapacitor and battery blocks (Ω_{CSC} or Ω_{CBT}) is approximated with the corresponding filtering inductance volume Ω_S (i.e. Ω_{LSC} or Ω_{LBT}). Each static converter is composed of n_l parallel chopper legs with a filtering inductance L_S (i.e. L_{BT} or L_{SC}) defined as

$$L_S = \frac{V_{bus}}{4 F_{SW} \Delta i_S} \tag{7}$$

where F_{SW} denotes the converter switching frequency, V_{bus} represents the bus voltage and Δi_S is the current ripple (typically limited to 60 A) in the inductance. The number of chopper legs is chosen as the minimum integer value which maintains the IGBT current below 450 A, i.e.

$$\frac{i_{S\,\max}}{n_l} + \frac{i_S}{2} \leq 450 \tag{8}$$

where $i_{S\,\max}$ denotes the maximum current in the storage cell (i.e. $i_{BT\,\max}$ or $i_{SC\,\max}$). The maximum energy in the filtering inductance is obtained as follows:

$$W_{\max} = \frac{1}{2} L_S \left(\frac{i_{S\,\max}}{n_l} + \frac{i_S}{2} \right)^2 \tag{9}$$

The corresponding inductance volume Ω_{LS} is calculated from the maximum energy using a second order polynomial which interpolates manufacturer data

$$\Omega_{LS} = a_0 + a_1 W_{\max} + a_2 W_{\max}^2 \tag{10}$$

where $a_0 = 1.3392$, $a_1 = 0.1549$, $a_2 = 0.0014$. Finally, the global converter volumes associated with the ultracapacitor and battery packs are deduced from the corresponding filtering inductance volumes, the number of parallel blocs in each pack, the number of chopper legs and a correction coefficient λ_C (typically $\lambda_C = 1.2$) taking into account of electronics parts (IGBTs and associated cooling devices).

$$\Omega_{CS} = \lambda_C\, n_l N P_S\, \Omega_{LS} \tag{11}$$

3.4. 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 %) [12]. A qualitative approximation of the c_F coefficient has been derived in [9] for the Hoppecke FNC 1502HR battery cells for nominal conditions (temperature between 30°C–40°C, charge at C_5 and discharge at $2C_5$):

$$c_F(DOD) = 966 \times DOD^{-2.37} \tag{12}$$

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:

$$w_{CYCLE}(DOD) = \frac{c_F(100\%)}{c_F(DOD)} \tag{13}$$

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 $N_{CYLE}(i)$ 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*:

$$LFT_{BT} = NP_{BT} \times NS_{BT} \times \sum_{i=1}^{10} w_{CYCLE}(i) \times N_{CYCLE}(i) \tag{14}$$

where $w_{CYCLE}(i)$ denotes the cycle weight at the middle of the *DOD* interval i considered. 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*.

3.5. The cost model

The global cost in € of the diesel engine C_{DE}, including its installation, can be interpolated by a linear function versus the nominal power:

$$C_{DE}[\text{€}] = 0.28 P_{DEN} + 14500 \tag{15}$$

To take into account repairs and maintenances, the previous relation has been modified. It has been estimated by the SNCF that the cost of the diesel engine over 10 years is 3 times higher than the purchase cost. Therefore, the previous relation becomes:

$$C_{DE}[\text{€/year}] = \frac{3}{10}(0.28P_{DEN} + 14500) = 0.084P_{DEN} + 4350 \tag{16}$$

The cost of the battery cells is calculated from the *cycle cost* which allows taking account of purchase costs (including installation costs) as well as maintenance costs (directly related to the battery lifetime). A battery *cycle cost* has been estimated to 0.122 €. By considering the LFT_{BT} stress estimator, the battery cost per year C_{BT} can be expressed as:

$$C_{BT}[\text{€/year}] = 0.122 \times LFT_{BT} \times \frac{\Delta\tau_{\text{year}}}{\Delta\tau} \tag{17}$$

where $\Delta\tau_{\text{year}}$ represents the locomotive exploitation in one year (typically 8 hours per days, i.e. 2880 hours per year) and where $\Delta\tau$ denotes the total mission duration. Note that the ultracapacitor and battery cells are fully charged at the beginning of a mission. If their state of charge at the end of the mission differs from their initial state, it is advisable to maintain the diesel engine in order to fully recharge the storage elements. Therefore, an additional charging period $\Delta\tau_{\text{charge}}$ is added to the standard mission duration $\Delta\tau_M$ to calculate the global mission duration $\Delta\tau$. The ultracapacitor cost per year C_{BT} is similarly computed by considering a cycle cost of 3×10^{-4} €.

Finally, as the gasoline cost is about 1.35 € per liter, the global cost per year is estimated as

$$C_{fuel}[\text{€/year}] = 1.35\, Q_{fuel} \frac{\Delta\tau_{\text{year}}}{\Delta\tau} \tag{18}$$

4. The initial configuration of the locomotive

Because of time constraints in the PLATHEE project, the LHyDIE platform was first designed using a traditional approach which sequentially optimizes the system architecture, the energy management strategy and the element sizing [10]. Multiple trade-offs associating energy efficiency, volume, cost and battery stress were considered but no optimization was actually performed at a global system level. The initial configuration consists in a diesel engine generator of 215 kW nominal power connected to a 540 V DC bus, in association with 8 blocks of 200 ultracapacitor cells in series and 4 blocks of 300 battery cells in series.

5. The integrated optimal design of the hybrid locomotive

Instead of finding the locomotive characteristics through a sequential process and by a priori setting some design variables, we investigate an integrated design approach based on a global optimization.

5.1. The design variables

The design variables and their associated bound are shown in Table 2. Four of them are discrete and three are continuous.

Design variable	Nature	Bounds
Number of battery cells in series	Discrete	$0 \leq NS_{BT} \leq 542$
Number of battery blocks in parallel	Discrete	$0 \leq NP_{BT} \leq 32$
Number of ultracapacitor cells in series	Discrete	$0 \leq NS_{SC} \leq 262$
Number of ultracapacitor blocks in parallel	Discrete	$0 \leq NP_{SC} \leq 60$
Nominal diesel engine power [kW]	Continuous	$50 \leq P_{DEN} \leq 600$
DC bus voltage [V]	Continuous	$50 \leq V_{bus} \leq 650$
Converter switching frequency [kHz]	Continuous	$1 \leq F_{SW} \leq 10$

5.2. The design constraints

Six inequality constraints classically formulated in terms of minimization (i.e. $g_i \leq 0$) have to be fulfilled to ensure the locomotive design feasibility. These constraints can be separated into two groups. The first three constraints do not require the simulation of the locomotive behavior to be computed. They are qualified as *pre-simulating* constraints. On the other hand, the other three constraints are evaluated from the locomotive simulation on its driving mission. They are qualified as *post-simulating* constraints. The computational time devoted to the simulation of the driving mission is about 35 s on a standard PC computer. To improve the CPU time of the optimization process, the simulation of the locomotive on its driving mission is not performed if a pre-simulating constraint is not fulfilled. In this case, post-simulating constraints receive the maximum penalty ($g_i \to +\infty$).

5.2.1. Pre-simulating constraints

The first constraint g_1 verifies that the global volume of the embedded energetic sources is lower than 32 m^3.

$$g_1 = \Omega_{SC} + \Omega_{BT} + \Omega_{DE} - 32 \leq 0 \tag{19}$$

By considering the boost structure of the DC-DC converters related to the storage elements, the maximum values for the battery and ultracapacitor packs are limited by the maximum duty cycle α_{max} (typically $\alpha_{max} = 93\%$) which implies two additional constraints

$$g_2 = NS_{BT} v_{BT\,\max} - \alpha_{\max} V_{bus} \leq 0 \tag{20}$$

$$g_3 = NS_{SC} v_{SC\,\max} - \alpha_{\max} V_{bus} \leq 0 \tag{21}$$

where v_{SCmax} and v_{BTtmax} represent the maximum voltage values for ultracapacitor and battery cells ($v_{SCmax} = 2.5$ V and $v_{BTmax} = 1.34$ V).

5.2.2. Post simulating-constraints

From the locomotive simulation on its mission, we can obtain the maximum current in all utracapacitor and battery cells. Then, it is possible to better approximate the system volume with the computation of static converter volumes. The previous volume constraint can be updated as follows

$$g_4 = \Omega_{SC} + \Omega_{BT} + \Omega_{DE} + \Omega_{CBT} + \Omega_{CSC} - 32 \leq 0 \tag{22}$$

The charging period $\Delta\tau_{\text{charge}}$ required at the end of the driving mission to fully charge the storage elements is limited in relation to the standard mission duration $\Delta\tau_M$ with the g_5 constraint defined as:

$$g_5 = \frac{\Delta\tau_{\text{charge}}}{\Delta\tau_M} - 0.4 \leq 0 \tag{23}$$
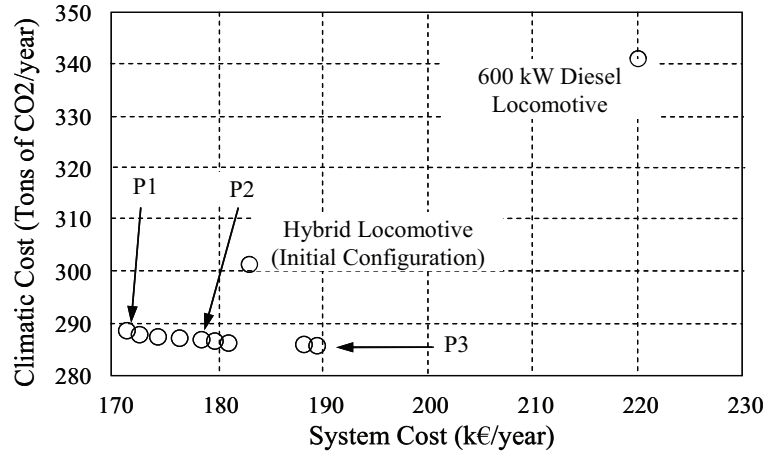
Fig. 8. The Pareto-optimal configurations of the hybrid locomotive.

Finally, the last constraint is related to the mission fulfillment. Solutions are supposed to be feasible if they are capable of complying with the mission defined in Fig. 3 or if the energetic deficit E_d on the mission in relation to the global energy required E_m, is lower than 1%. This leads to the following constraint

$$g_6 = \frac{E_d}{E_m} - 0.01 \leq 0 \tag{24}$$

5.3. The locomotive optimization

The main goal of the PLATHEE project resides in the reduction of the carbon dioxide quantity emitted by diesel locomotives. Therefore, the first objective f_1 to be minimized is a *climatic cost* per year, defined as

$$f_1 = Q_{CO2} \frac{\Delta\tau_{\text{year}}}{\Delta\tau} \tag{25}$$

where $\Delta\tau_{\text{year}}$ and $\Delta\tau$ are defined as previously. The second objective f_2 is related to the global system cost of the energetic sources (including purchase costs, component lifetime and fuel consumption)

$$f_2 = C_{DE} + C_{BT} + C_{SC} + C_{fuel} \tag{26}$$

The non-dominated sorting genetic algorithm (NSGA-II) [13] is used to solve this multiobjective problem. The crossover and mutation probabilities are $p_c = 1$ and $p_m = 0.1$. The population and archive sizes are set to 100 and the generation number is $G = 500$. Five independent runs are made to take into account of the NSGA-II stochastic feature. The Pareto-optimal configurations of the hybrid locomotive obtained from these runs are shown in Fig. 8. In this figure, the LHYDIE initial configuration and a 600 kW diesel locomotive (non-hybrid architecture) are compared with three Pareto-optimal solutions whose characteristics are given in Table 3. It can bee seen that several optimized solutions clearly dominate the initial configuration of the locomotive, designed with a traditional sequential approach.

The flat shape of the Pareto-front and the small number Pareto-optimal configurations found can be explained by the dominance of the annual fuel cost in relation to the global system cost. It can be

Table 3
Design variables and main objectives of three Pareto-optimal configurations
compared with the initial hybrid locomotive (LHyDIE)

Design variables and objectives	LHyDIE	P1	P2	P3
Number of battery cells in series	300	249	230	143
Number of battery blocks in parallel	4	8	9	10
Number of ultracapacitor cells in series	200	175	20	20
Number of ultracapacitor blocks in parallel	8	1	1	1
Diesel engine nominal power [kW]	215	174	162	151
DC bus voltage [V]	540	645	631	625
Converter switching frequency [kHz]	2	7	8	10
Climatic cost (tCO2/year)	301	288	287	286
System cost [k€/year]	183	172	178	189
Fuel cost (k€/year)	153	146	145	145
Diesel engine cost (k€/year)	22.4	19	18	17
Battery and ultracapacitor cost (k€/year)	7.6	7	18	27

seen from Table 3 that it represents about 80% of the global cost for all hybrid architecture. Since both objectives are mainly correlated with fuel consumption there is no clear trade-offs which leads to a "weak" Pareto-front. It is interesting to note for this application that climatic and environmental concerns coincide with economic interests... The climatic cost minimization is achieved for the "just enough sized" solution (i.e. P3) which presents the lower diesel engine nominal power and a small number of ultracapacitor and battery cells. However, the system cost is not optimal in this case because batteries and ultracapacitors are subject to a higher number of cycles during the driving mission. This explains the increase of the cost related to ultracapacitors and batteries, which is penalized trough the lifetime estimators.

6. Conclusions

In this work, an original integrated design approach based on multiobjective optimization with genetic algorithms has been developed for the design of a hybrid locomotive devoted to non-electrified areas. This approach aims at concurrently optimizing the system architecture, the element sizing and the energy management strategy instead of separating the global optimization problem into local sub-problems which can be sequentially solved. On the other hand, it considers multiple heterogeneous objectives (climatic and economic costs, lifetime) taking account of several constraints (volume, driving mission compliance). This approach has shown to be efficient by finding hybrid locomotive configurations that dominate those obtained with traditional methodologies based on problem simplification.

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