Proceedings of 7th Transport Research Arena TRA 2018, April 16-19, 2018, Vienna, Austria

Techno-Economic Optimization of Railway Power Substation Hybridization

Tony Letrouvé a*[*], Julien Pouget a, Nanfang Yang a, Hedi Mohamed Kharrat b

[a]*SNCF Innovation and Research Dept., 75012 Paris, France*
[b]*SNCF Engineering and Project Dept., Electric Traction, 93210 Saint Denis, France*

Abstract

With the rising of railway traffic flow, railway system suffers problems like voltage drop, unbalance, etc. One promising solution, studied in this paper, is the hybridization of railway power substation. The design of this hybrid architecture is complex and depends on a lot of techno-economic parameters. This paper develops techno-economic models used for optimization that takes into account all Life Cycle Cost. An example of AC power substation is studied and results reveal that the return of investment (ROI) period is around 4 years with the integration of energy storage system and wind power system.

Keywords: Railway smart grid; optimization; hybridization; energy storage system; renewable energy; Life Cycle Cost (LCC).

[*] Corresponding author. Tel.: +33-157-236-251.
E-mail address: tony.letrouve@sncf.fr

Nomenclature

$Cost_{HRPS}^{Eco}$	The annual cost of a hybrid railway power substation
$Cost_{network}$	The cost associated with the public electricity grid usage
$Cost_{market}$	The cost to buy energy from the market
$Cost_{invest}$	The investment cost of a hybrid power substation
$Cost_{network}^{Transport}$	The cost of electricity grid usage for power consumption
$Cost_{network}^{injection}$	The cost of electricity grid usage for power injection
$Cost_{market}^{combine}$	The cost of combined long-term consumers in energy market
$Cost_{market}^{DayAhead}$	The cost of energy brought in day-ahead energy market
$Cost_{Transf}$	The cost of transformer
$Cost_{conv}$	The cost of power converter between catenary and DC bus
$Cost_{prop}$	The cost of property by renting or buying
$Cost_{invest}^{ESS}$	The cost of energy storage system
$Cost_{invest}^{Prod}$	The cost of local generation system
$Cost_{j}^{LCC}$	The Life Cycle Cost (LCC) of the *j*th generation system;
$Cost_{j}^{Maint}$	The maintenance cost of the *j*th generator
$Cost_{j}^{Purch}$	The purchase of the *j*th generator
$Cost_{j}^{Install}$	The installation cost of the *j*th generator
$Cost_{j}^{Remov}$	The removal cost of the *j*th generator
$Cost_{j}^{Recy}$	The recycling cost of the *j*th generator
$Cost_{j}^{Conv}$	The cost of associated power converter for the *j*th generator
$Cost_{j}^{con.}$	The cost of the connecting cable
$L_{j}^{con.}$	The length of connecting cable between generators and the power substation
$Fqcy_{j}^{Maint}$	The frequency of maintenance per year
$Fqcy_{j}^{install}$	The frequency of installation operation per year
$rate^{actualisation}$	The market actualization rate
$P_{subscribe}$	The subscribed power
$taux^{CTA}, a_2, d_t, k_t, \alpha$	The fixed coefficients subjected to contract according to the connecting voltage level
$P_{load}^{cons}(p)$	The load power
$P_{Stock-loc}^{i}(p)$	The power absorbed by the ESS
$P_{Prod-loc}^{j}(p)$	The power supplied by generation systems
$P_{HVnet-neg}(p)$	The power supplied by electric grid
$P_{HVnet-pos}(p)$	The power fed back to electric grid during regenerative phases
$Coef_{j}^{ProdDesign}$	The design coefficient of production system (number of production system)
η_{j}^{Prod}	The efficiency of global production system
$Pa_{j}^{Prod}(p)$	The absorbed power of energetic potential during the studied period
$Coef_{i}^{StockOverDesign}$	The over design coefficient of ESS to limit deep discharge of batteries
$P_{charge-neg}^{Stock\,i}(p-1)$	The negative power sent from the load to the ESS
$\eta_{Stock-ch}^{i}\ \eta_{Stock-disch}^{i}$	The efficiency of storage element in charge and discharge
$Coef_{i}^{Stock-self-disch}$	The ESS self-discharge rate

1. Introduction

In France, 53% of railway infrastructures are electrified, which carries 88% of national railway traffic flow, RFF (2014). The other 47%, mostly in suburbs, are considered not economic to carry out electrification. In France, two major electric railway networks are available: 1500V DC and 25kV AC networks, Hill (1994). Each network has different problematics for the railway network or for the upstream electric grid. Considering the DC grid, power substation is usually not reversible and braking energy can't be recovered due to its architecture. If no train located on the same catenary uses this power, the voltage would rise and rheostats onboard or/and at wayside have to be used to dissipate this energy. The other drawback of DC lines is transmission grid losses. Indeed, the equivalent DC resistor of catenary and rail is pretty significant. The voltage drop due to this line resistor may put trains in non-nominal modes, decrease traffic capacity of the line and also consequently increase the number of power substation. On the other side, for AC grid, problems are different: the single-phase network introduces unbalance in the upstream grid. The power substations are connected to different phases, such that they cannot be connected in parallel by using single-phase catenary, and separation parts (neutral sections) are unavoidable. During these sections the trains are not powered. Furthermore, with the liberalization of electricity market, railway sector, as the largest electricity consumer in France (8 TWh per year, takes around 1.5% of total national consumption), faces not only these technic issues but also economic behaviors.

A lot of solutions have been investigated to tackle these techno-economic issues, Celik (2003). For example, adding another feeder in parallel, which allows multiplying rated power of the railway power substation; and also decreases the impact of line resistor on the quality of power supply, Aeberhard (2010) and Vial (2010). Another solution is to reinforce the substation power and/or the connection with the transmission grid. Moreover the adaption of FACTS (Flexible AC Transmission System) in single-phase AC grid can decrease the unbalance phenomenon to the upstream network. Besides, installing an inverter in parallel with the rectifier to make the DC substation reversible is also a good alternative. The last solution of this non-exhaustive list is the hybridization of the existing power substation by adding Energy Storage System (ESS) and local power generation system at the substation or wayside, also called as Hybrid Railway Power Substation (HRPS), Romo (2005), Okui (2010), Andriamalala (2013), Gillespie (2014). Although it can supply a good solution to aforementioned problems, the optimal design of this multiple-source system is still a challenge.

The objective of this paper is to propose an optimal sizing method for HRPS from the views of economics and technology. After reviewing the present HRPS methods including in a railway smart grid, two models are developed: economic and technic. The second section of this paper deals with the optimization process. Finally, one example of this optimal sizing process is completed and discussed.

2. Studied system and models

In this section, the architecture of HRPS is introduced. Then, the studied HRPS architecture is modelled taking into account two aspects: economic and power flows.

2.1. Substation hybridization

A conventional railway power substation is composed of the transformer connected to transmission grid in single-phase for the AC case and three-phase for DC grid. In AC grid, the single-phase transformer is directly connected to the catenary. In DC grid, a rectifier is used as an AC to DC converter. That is why the DC power substation is not reversible. As shown in Fig. 1, its hybridization adds ESS and power generators (renewable or not) directly at the power substation or at another point in the network. In a complete vision of a railway smart grid, connections between the catenary, the railway station's low voltage grid (lightings, elevators, etc.) and electro-mobility (electric vehicle charging station, etc.) are achieved. This paper only considers ESS and renewable generation systems at the power substation. Neither connections with the railway station nor the electro-mobility are taken into account. To sum up, the studied HRPS is composed of: renewable generation systems, energy storage system and the corresponding energy management system. To design this studied system in an optimal way, its models have to be developed. In following subsection, all elements of this studied system will be modelled in economic and physical ways.

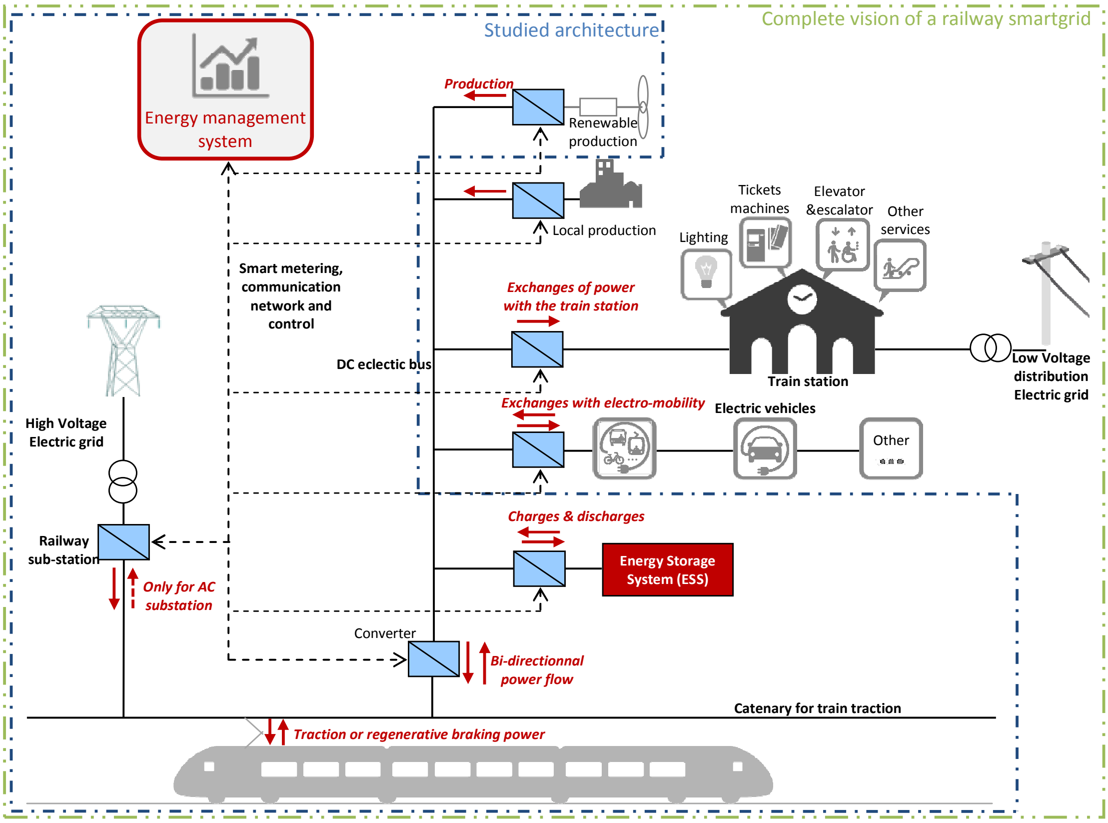

Fig. 1 Structural description of the studied HRPS

2.2. Economic model of the HRPS

The first model developed in this paper considers the economic flow, as presented by dashed arrows in Fig. 2. Moreover, to design in an optimal way and compare fairly different solutions, the entire Life Cycle Cost (LCC) has to be adopted. This LCC considers: systems investments, the maintenance cost during the components life, installation, removal and recycling costs but also some constraints as the volume and weight limits for additional hybrid installations and thus the cost of renting or buying land.

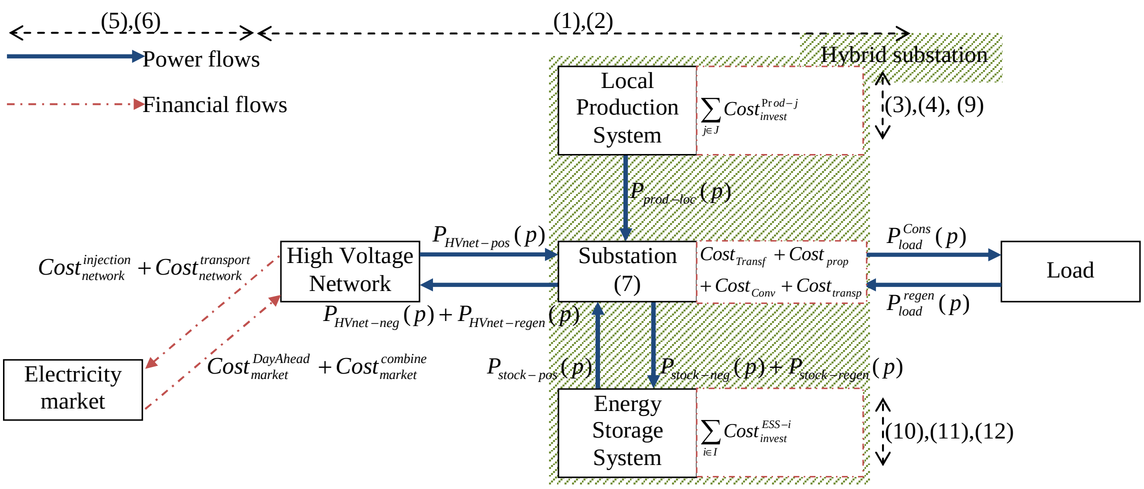

Fig. 2 Economic and power flows of the studied HRPS

Global economic model of hybrid substation - The global annual cost of a HRPS is described by (1), which takes into account the public electric grid usage, the cost of electricity bought on electricity market and the cost of investment in components composing the HRPS.

$$Cost_{HRPS}^{Eco} = Cost_{network} + Cost_{market} + Cost_{invest} \tag{1}$$

These costs can be developed by this way:

$$\begin{cases} Cost_{network} = Cost_{network}^{Transport} + Cost_{network}^{Injection} \\ Cost_{market} = Cost_{market}^{combine} + Cost_{market}^{DayAhead} \\ Cost_{Invest} = Cost_{Transf} + Cost_{prop} + Cost_{Conv} \\ \qquad + \sum_{i \in I} Cost_{invest}^{ESS-i} + \sum_{j \in J} Cost_{invest}^{Prod-j} \end{cases} \tag{2}$$

The property cost is linked to the space that will be occupied by the HRPS. Indeed, the railway infrastructure operator can choose if the needed place is bought (3) of rent (4). In the case of buying property the cost is amortized during an amortized period.

$$Cost_{prop} = Cost_{prop}^{buy} S_{HRPS} \frac{Period_{study}}{Period_{amortissement}^{Buy}} \tag{3}$$

or

$$Cost_{prop} = Cost_{prop}^{rent} S_{HRPS} Period_{study}.12 \tag{4}$$

Economic model of a generalized generator – The generator model has been generalized in this paper, such that different technologies can be compared. It is possible to study the relevance of different production systems knowing energetic potentials of a place (wind, irradiance, etc.). During the choice of renewable generation systems, two scenarios can be considered. The first one supposes to sell produced energy to electric transmission or distribution grid. The second possibility imposes to use this produced energy in local. In this paper, the second possibility is favored. The economic model of a generalized generation system based on LCC, Bernal-Agustín (2006) and Dufo-Lopez (2007), takes into account the purchase, installation, removal, recycling, maintenance and connection prices.

$$\begin{aligned} Cost_{Prod}^{j} &= Coef_{j}^{ProdDim} \cdot Cost_{j}^{LCC} \\ Cost_{j}^{LCC} &= Cost_{j}^{Maint} \cdot Nb_{j}^{Maint} + \\ &\left(\begin{aligned} Cost_{j}^{Purch} + Cost_{j}^{Install} + Cost_{j}^{Remov} + \\ Cost_{j}^{Recy} + Cost_{j}^{Conv} + Cost_{j}^{con} \cdot L_{j}^{con} \end{aligned} \right) \cdot Coef_{j}^{amorti} \end{aligned} \tag{5}$$

The number of maintenance operation and the amortization coefficient are defined in (6), along the studies.

$$\begin{aligned} Nb_{j}^{Maint} &= Fqcy_{j}^{Maint} \cdot Period_{study} \\ Coef_{j}^{amorti} &= \left[(1-q) \Big/ \left(1 - q^{1/Fqcy_{j}^{install}} \right) \right] \cdot Period_{study} \\ q &= 1 \Big/ \left(1 + rate^{actualisation} \right) \end{aligned} \tag{6}$$

Economic model of generalized ESS – For the same reason as the generation system, the energy storage system can be modelled as a generalized ESS. In this case three factors have to be taken into account: the dynamics, energy and power. The LCC of this generalized ESS is modelled in the same way as the generalized production systems ((5) and (6)).

Economic model of the electric network - The public electric grid usage tariff (TURPE in France) is charged separately for the high-voltage electricity users in France. Two types of price range are taken into account in this paper: TURPE4 without seasoning price (7) (only one subscribed power throughout the year) and TURPE4 with seasoning price. This cost is composed of the annual power transferred cost and the Monthly Excess Subscribed Power (MESP) cost.

$$\begin{aligned}
&Cost_{Network}^{PT} = (1+taux^{CTA}) \cdot a_2.P_{subscribe} + b.\tau^{c}.P_{subscribe} \\
&\tau = \frac{E_{extract}}{Duration_{Year}.P_{subscribe}} \\
&E_{extract} = \sum_{p \in P} P_{network-pos}(p) \cdot \Delta t^{Sim} \\
&Cout_{Network}^{MESP} = \sum_{m \in Month} \alpha. \sqrt{\sum_{r \in R^m} \left(\Delta P_{pos}(r)^2\right)}
\end{aligned} \tag{7}$$

The annual power transfer is calculated from energy transferred ($E_{extract}$), ΔP is the monthly excess power compared with the subscribed power calculated on 10 minutes integrated period ($\Delta t^{network}$) (8).

$$\Delta P(r) = \left(\sum_{p=1+\frac{\Delta t^{Net}}{\Delta t^{Sim}}\cdot(r-1)}^{\frac{\Delta t^{Net}}{\Delta t^{Sim}}\cdot r} \left(P_{Net-pos}(p) - P_{subscibe}^{t}\right) \right) \cdot \frac{\Delta t^{Sim}}{\Delta t^{Net}} \tag{8}$$

2.3. Power flow model

Once economic models are developed, power flow models of the HRPS have to be accomplished. The following equations describe each element that composes the studied system. Moreover, the Energy Management Strategy (EMS) that has been developed is a simple one. It is assumed that the design is highly dependent on it. But this paper is a first step to the global design including optimal EMS.

Global power flow model of HRPS - The global power flow model of the HRPS is described by equation (9). The sum of powers from and to high voltage network, energy storage systems, local production and consumers (i.e., trains and substation ancillaries) is equal to zero.

$$\sum_{i \in I} P_{Stock-loc}^{i}(p) + P_{HVnet-pos}(p) + \sum_{j \in J} P_{Prod-loc}^{j}(p) + P_{HVnet-neg}(p) + P_{load}^{conso}(p) = 0 \tag{9}$$

The regenerative power of the load is either sent to the ESS or to the network. So, this power is not included in the energetic balance (10).

$$P_{load}^{regen}(p) = P_{HVnet-regen}(p) + \sum_{i \in I} P_{stock-regen}^{ESSi}(p) \tag{10}$$

Power flow model of production system - The model of the generalized production system supplying the local load (self-consuming) is defined as follow: The number of element is multiplied (the optimization variable: $Coef^{ProdDesign}$) by the power of one element including its efficiency.

$$P_{Prodloc}^{j}(p) = Coef_{j}^{ProdDesign} \cdot \eta_{j}^{Prod} \cdot Pa_{j}^{Prod}(p) \tag{11}$$

From this generalized model, two examples are shown on Table 1: Wind Energy Conversion System (WECS) and solar cells.

Table 1. Example of the use of generalized model to wind and solar Energy.

Variables	Solar Energy	WECS
$Coef_{j}^{ProdDim}$	S_{PV}	Nb_{Eol}
Pa_{j}^{Prod}	$P_{local}^{solaire}$	$\frac{\mathrm{Cp_{Eol}}}{2}\rho_{air}\pi\frac{\mathrm{Pale_{Eol}}^2}{4}P_{local}^{vent^3}$
$\eta_{j}^{Prodloc}$	η_{PV}	η_{Eol}
$Coef_{j}^{ProdVol}$	$Coef_{PV}^{Conv}$	0

Power flow model of generalized ESS - As the power generation system the coefficient that has to be optimized is $Coef^{StockDesign}$. This coefficient is determined by storage cells considering its specific power ($Pspec^{stock}$(W/cell)), and energy ($Espec^{Stock}$ (Wh/cell)), the maximal energy stored or used during the studied duration (Ea^{Stock}) or the net ESS power (Pa^{Stock}).

$$Coef_i^{StockDesign} = Coef_i^{StockOverDesign} . \max\left[\frac{\max\left(Ea_i^{Stock}(p)\right)}{Espec_i^{Stock}};\frac{\max\left(\left|Pa_i^{Stock}(p)\right|\right)}{Pspec_i^{Stock}}\right] \quad (12)$$

The power of the ESS is define from the positive $P_{stock-pos}$ and negative power $P_{stock-neg}$ of the system including its efficiency (η_{Stock}):

$$Pa_i^{Stock}(p) = \frac{P_{Stock-pos}^i(p)}{\eta_{Stock-disch}^i} + \left(P_{Stock-neg}^i(p) - P_{charge-neg}^{Stock\,i}(p-1)\right)\cdot \eta_{Stock-ch}^i \quad (13)$$

From (9) the energy is calculated as follow:

$$Ea_{Stock}^i(p+1) = -Pa_i^{Stock}(p)\cdot \Delta t^{Sim} + Ea_{Stock}^i(p) - Coef_i^{Stock-self-disch}\cdot Ea_{Stock}^i(p) \quad (14)$$

3. Optimization formulation

To achieve the optimization of the HRPS in a structured way, it is important to formulate the optimization problem. This part deals with the optimization objectives, constraints and resolution.

3.1. Optimization objective

Once the techno-economic model is established, the following step is to formulate the optimization problem. In this stage, there are two questions to answer:

- Which and how many local energy production system and/or ESS have to be used?
- Which optimized power has to be subscribed to the electric grid?

It should to be highlighted that the optimal design of HRPS highly depends on the energy management strategy. Thus, this optimization problem is only based on predictive aspect, and its objective is to minimize the energy bill ahead of time (i.e., optimize the electricity purchased in electricity markets) regarding the railway power substation consumption, renewable energetic potential at substation and energy market price. To minimize the energy bill, the optimization problem can acts on the design of ESS, the number of renewable energy generators and the subscribed power level. Table 2 summarizes the optimization problem formulation.

Table 2. Design optimization problem

Objectives	Constraints	Decision variables
Optimize subscribed power and decrease the energy bill.	Predictive consumption (P_{load}), renewable energetic possibility (P_{enr}) at substation and energy market price ($Cost_{market}$)	Subscribed power decision, Renewable Energy, local production and ESS design

3.2. Objective function and constraints

The objective function of the optimization problem is to minimize the following equation:

$$Cost_{HRPS}^{Eco} = Cost_{network} + Cost_{market} + Cost_{invest} \quad (15)$$

To achieve this aim, the algorithm can perform on decision variables highlighted in equation (2) to (8):

- $Coef^{ProdDesign}$ the number of local production elements,
- $Coef^{StockDesign}$ the number of local energy storage elements,

A lot of constraints have been considered in this optimization problem, they are listed as follows:

- Power balance in HRPS:

$$P_{load}(p) + \sum_{i\in I}\left(P_{ESS-neg}^i(p) + P_{ESS-pos}^i(p)\right) + \sum_{j\in J} P_{Prodloc}^j(p) + P_{Net-pos}(p) + P_{Net-neg}(p) = 0 \quad (16)$$

- The ESS stays in its energy and power limits:

$$\begin{cases} E\max_i^{Stock} \geq Ea_i^{Stock}(p) \\ P\max_i^{Stock} \geq Pa_i^{Stock}(p) \\ P\min_i^{Stock} \leq Pa_i^{Stock}(p) \end{cases} \tag{17}$$

- Keeping the objective of implementation of energy storage systems and renewable sources, the limits of land surface and volume available have to be respected. These criteria are modelled by following equations :

$$\begin{aligned} &\sum_{i\in I} Coef_i^{StockSurf} \cdot Coef_i^{StockDim} + \sum_{j\in J} Coef_j^{ProdSurf} \cdot Coef_j^{ProdDim} + S_{Transfo} \leq S_{IFTEH}^{Max} \\ &\sum_{i\in I} Coef_i^{StockVol} \cdot Coef_i^{StockDim} + \sum_{j\in J} Coef_j^{ProdVol} \cdot Coef_j^{ProdDim} + V_{Transfo} \leq V_{IFTEH}^{Max} \end{aligned} \tag{18}$$

3.3. Optimization problem resolution

As the time horizon designed for this optimization problem is pretty long (1 year), thus the number of variables is huge. The original nonlinear system requires a lot of calculation time to obtain the results, thus some simplifications (linearization) are adopted to form a linear problem which can be solved using the known simplex or interior point method.

For ESS and renewable energy system, the design coefficient describes the number of needed elements. If the optimization results are not an integer, the needed installations are a multiplication of the design coefficient with one defined unit. Some solvers are available on the market or are free. CLP solver has been chosen (more information available in Forrest (2016)).

4. Optimization results

4.1. Optimization results of an AC substation

In this section the sizing problem which allows defining the optimal ESS and local generator design during a strategic time scale (one year) is tested in a real substation. This optimal sizing has the objective to reduce the energy bill following the liberate energy market. To do so, it is necessary to know the consumption and local renewable energy potential at the substation. The load power has been measured at the substation Commune as shown in Fig. 3 during one year, which is an AC power substation located on Paris-Lyon High Speed Line. The renewable energy potentials have been measured by French meteorological organization near the substation. The electricity prices taken are those of the precedent year.

Fig. 3 Studied power substation and line

To achieve a realistic design, not only the load consumption profile and energetic potential are required but also the principal elements adopted by the HRPS. Expertise on maintenance phases and manufacturer's datasheets available in manufacturer's website allow filling the different system behaviors needed. According to the energy storage requirement, annual solar irradiation, average wind speed at the site, the following components have been chosen to conduct the optimal sizing:

- Lithium-ion SAFT Battery - Intensium Max 20M M with an energy capacity of 580 kWh and a continuous discharge/charging power of 1100 kW, SAFT, 2016
- Photovoltaic system Sharp ND 240QCJ, Sharp, 2016
- WECS Alstom Power 80 with a specific power of 1670 kW, Alstom, 2016

The results of this optimization problem are listed in Table 3. Indeed, the number of battery found is less than one. That means that around half of the studied battery is sufficient. The solar photovoltaic panels are too expensive to be cost effectiveness in our case. Nearly 10 wind turbines are required regarding the local renewable energy potential. Results shown in Fig. 4 give the distribution of power flows in this system during one week. It can be observed that the power extracted by WECS has a great impact on the energy bought in the energy market. The ESS has a great interest to absorb the energy from train braking and/or excess WECS energy and to use it to either supply the load when the market price is high either sold energy to the market. This energetic buffer can also be used for other services that will be explained in discussions part.

Table 3. Result of optimization algorithm on decision variables.

Number of Battery SAFT Intensium Max 20M	Surface of Solar Cell Sharp - ND 240QCJ	Number of WECS Alstom - power 80
0.6	0	9.5

4.2. Economic analysis of the AC substation

In this economic analysis, the study horizon is chosen 20 years and the electricity inflation has been fixed at 2%. The return on investment (ROI) period is around 4.5 years with an initial investment of 27 M€.

Table 4. Economic results of the study.

Return On Investment [Year]	Profitability rate [%]	Investment cost [€]
4.5	27	27 M

4.3. Discussions

The ESS working as an energetic buffer gives more freedom to the railway power substation in energy market and makes it less dependent on market’s fluctuations. In the case of non-reversible DC power substations, the ESS can also recover braking energy and store it for other usage. Moreover, ESS can serve a lot of other services either for railway infrastructure, as exposed in this paper, or for upstream transmission grid. To decrease the ROI of the studied HRPS, the battery can be used to participate demand-response programs. This kind of substations has more interest in rural area, because the required land for the battery pack in urban is pretty expensive not to mention the 1.5MW WECS.

5. Conclusion

In this paper, techno-economic models have been developed to describe the behavior of HRPS not only in term of power flow but also in term of investment and economic flow. A ROI period around 4.5 years can be achieved with optimized ESS and renewable energy systems.

This paper is a first step to design in an optimal way a HRPS which is composed of ESS and renewable energy system. The energy management strategy is assumed simple in this paper. The impact of this strategy on the component sizing will be high and one perspective of this work is to focus on it and to develop a tool that can be used to size future hybrid substation.

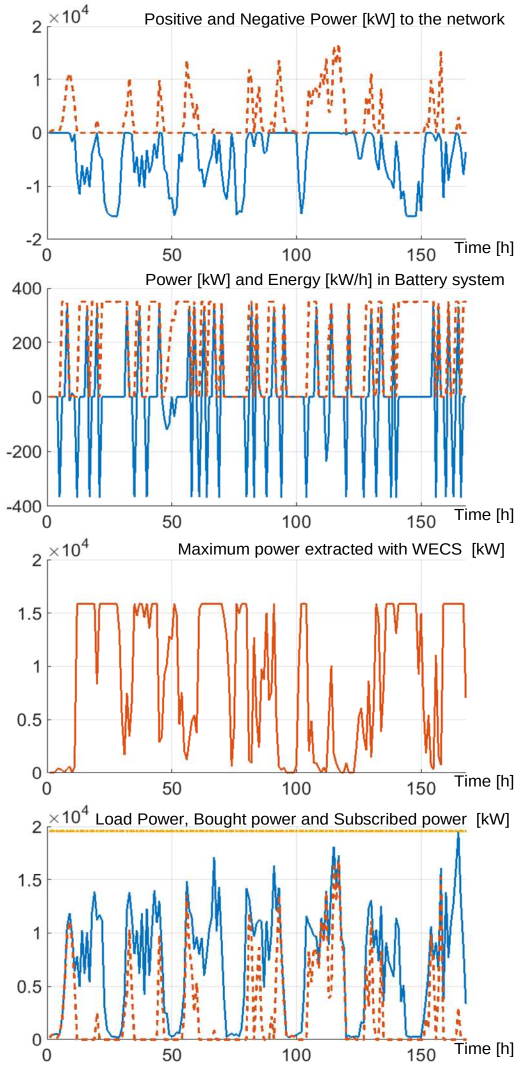

Fig. 4 Power flow results of optimal studied HRPS

6. References

RFF, Réseau Ferré de France, "Electrified lines network for railway traffic", internet document available at SNCF RESEAU website, 2014.

R. Hill, "Electric railway traction III: Traction power supplies", Power Engineering Journal, vol.8, pp. 275-286, 1994.

A. N. Celik, "Techno-economic analysis of autonomous PV-wind hybrid energy systems using different sizing methods", Energy Conversion and Management, vol. 44, pp. 1951-1968, 2003.

M. Aeberhard, C. Courtois, P. Ladoux, "Railway traction power supply from the state of the art to future trends", International symposium on Power Electronics, Electrical Drives Automation and Motion (SPEEDAM), pp. 1350-1355, 2010.

R. Vial, D. Riu, N. Retière, "Simulation calculations and optimization design of a new HVDC supply power for light rail system", IECON 2010, pp. 2364-2369, 2010.

L. Romo, D. Turner, L. Ng, "Cutting traction power costs with wayside energy storage systems in rail transit systems", Rail Conference 2005, pp. 187-192, 2005.

A. Okui, S. Hase, H. Shigeeda, T. Konishi, T. Yoshi, "Application of energy storage system for railway transportation in Japan", International Power Electronics Conference (IPEC 2010), pp. 3117-3123, 2010.

R.N. Andriamalala, B. Francois, J. Pouget, B. Robyns, "Study and analysis of possible services offered by an energy storage system inserted in a railways grid substation", 15th European Conference on Power Electronics and Applications EPE, Lille, France, 2013.

A. Gillespie, E. S. Johanson, D.T. Montvydas, "Energy Storage in Pennsylvania: SEPTA's Novel and Innovative Integration of Emerging Smart Grid Technologies", IEEE vehicular technology magazine, vol. 9 no.2, pp. 76-86, 2014.

J.L. Bernal-Agustín, R. Dufo-López,D.M. Rivas-Ascaso, "Design of isolated hybrid systems minimizing costs and pollutant emissions", Renewable Energy, vol.31, no.14, pp. 2227-2244, 2006.

R. Dufo-López, J.L. Bernal-Agustín, J. Contreras, "Optimization of Control Strategies for Stand-Alone Renewable Energy Systems with Hydrogen Storage", Renewable Energy, vol.32, no.7, pp. 1102-1126, 2007.

J. Forrest, D. De la Nuez. R. Lougee-Heimer, "CLP User guide", on http://www.coin-or.org/Clp/userguide/, 2016.

SAFT INTENSIUM MAX, SAFT Website, "Battery information sheet" on http://www.saftbatteries.com/, 2016.

Sharp Solar Electricity, "240 WATT – SHARP – Datasheet" on http://files.sharpusa.com/, 2016.

ALSTOM POWER 80, "datasheet from ALWTOM Wind Energy Conversion System Power 80", http://alstomenergy.gepower.com/, 2016.