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# Hybridization of Energy Storage Units for Energy Transition Applications: A Focus on Control and Coordination Approaches

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**Abstract**—Hybridization of energy storage units is a topic of interest in the nowadays context of transition towards more sustainable ways of energy production and consumption. Extensive research continues to be devoted to this topic, whereas various technical solutions have already been successfully implemented for a plethora of applications. This paper aims in a first step at overviewing the necessity of storage units in an increasingly renewable-based, decentralized energy production, then at explaining the role of hybridization of different storage technologies for more versatility and flexibility in what is generally known as a smart grid context. Then, the focus is on how to make the different energy storage sources to optimally and robustly cooperate towards a common goal. It is about obtaining a “fusion” of different heterogeneous sources. The answer to this problem obviously requires advanced control approaches being employed. An overview of most effective and widely used control strategies is envisaged – accompanied by some illustrative application results – out of which robust control techniques are given a special attention. This paper ends by attempting a look towards the future, namely by identifying some open questions and research directions worthy to further investigate.

**Index Terms**—energy transition, smart grid, control of microgrids, hybridization of energy storage units, robust control of multi-source electrical-energy systems

## I. INTRODUCTION: CONTEXT OF THE GREEN ENERGY TRANSITION

### A. Necessity of energy storage

The green energy transition is nowadays recognized as a necessity in response to growing environmental concerns resulted from depletion of fossil fuels. Practically all types of human activity have lastly benefited of advantages of renewable-energy conversion systems (RECS), enabled by the rapidly developing power conversion technology towards mitigating RECS unpredictability due to their stochastic dependence on natural conditions [1], [2]. Indeed, RECS grid integration is challenging, mainly due to voltage and frequency instability, poor power quality and load following [3]. In this context, energy storage systems (ESS) come as a solution to increase RECS dispatchability, operation effectiveness and grid penetration [4]– [6]. Various ESS technologies include

electrical, electro-chemical, chemical and mechanical storage systems, out of which batteries with different chemistries are now increasingly interesting, especially for grid stabilization purposes. An analysis of ESS and battery features, limitations and suitable applications is given in [7].

The global energy storage market has continuously expanded in the last decade, partially as a result of national policies and subsidies provided by governments of developing nations to reach their eco-friendliness and sustainability goals. This is suggested by the evolution of their installed power and capacity (Fig. 1 [8]), where the historically prevalent pumped hydro storage begins to leave more place to lithium-ion batteries. Indeed, the last ten-year cumulative sum of both installed rated power and capacity for the electro-chemical battery and chemical storage exhibits a steady exponential increase [8]. The adoption of electro-chemical and chemical storages for various grid applications, as shown in Fig. 2 [8], suggests again the growing interest of batteries, in particular redox flow and lithium-ion technologies.

### B. Benefits of energy storage hybridization

Decision of integrating energy sources of different types and technologies must obviously be based on the conclusion that these sources behave better together than each alone. Indeed, as ESS are limited either by their power or energy capacity, a combination of several technologies may be suitable with regard to employ each storage respectfully of its specificity [9]. A synthetic vision of HES adoption in energy grids is given in Fig. 3, emphasizing the HES great potential of improving grid flexibility and resilience [7]. Thus, a key feature supporting the storage hybridization decision is the *complementarity between the sources*, whose meaning will be detailed next and which can be exploited as a first good premise, such as to lead further to their *coordinated* – possibly *optimal* with regard to some well-defined criterion – *behaviour*, whose guarantee can only be ensured by control action [10]– [12].

The interconnection topology of HES within a grid/microgrid determines the controllability, dynamic

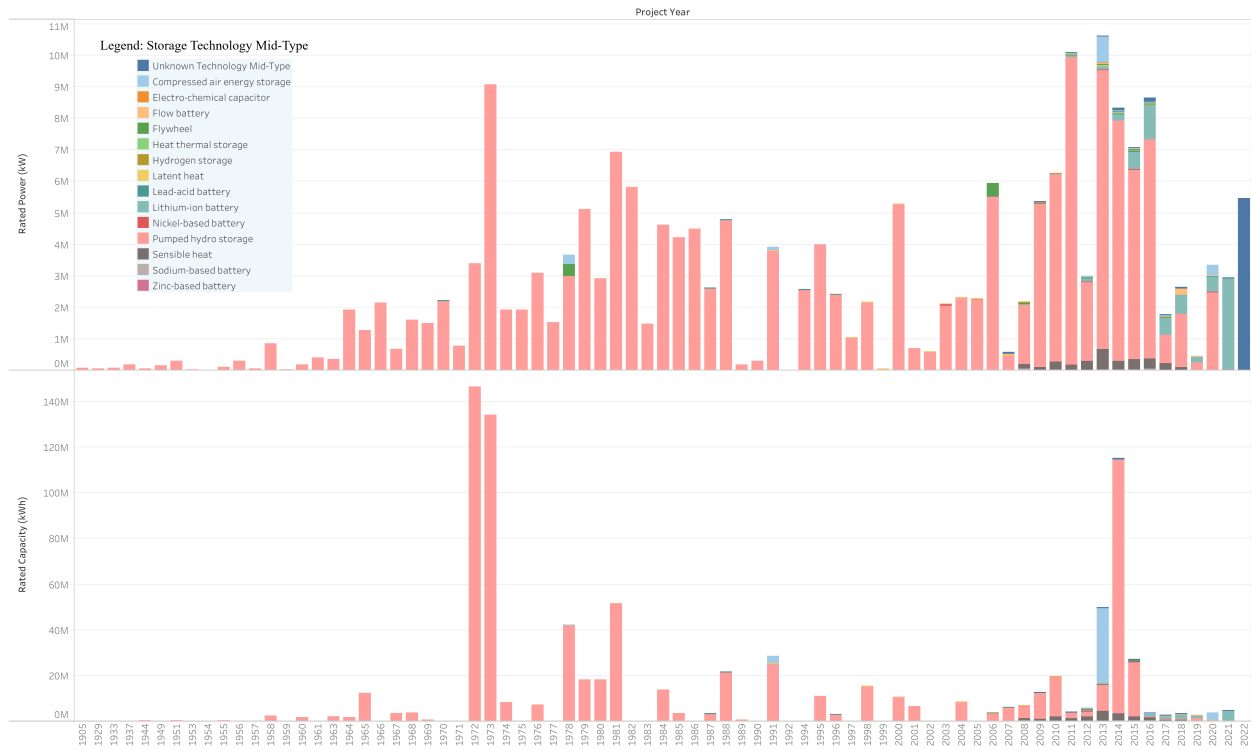


Fig. 1. Installed rated power and capacity per year for all types of storage: electro-chemical battery and chemical, electro-mechanical and thermal [8].

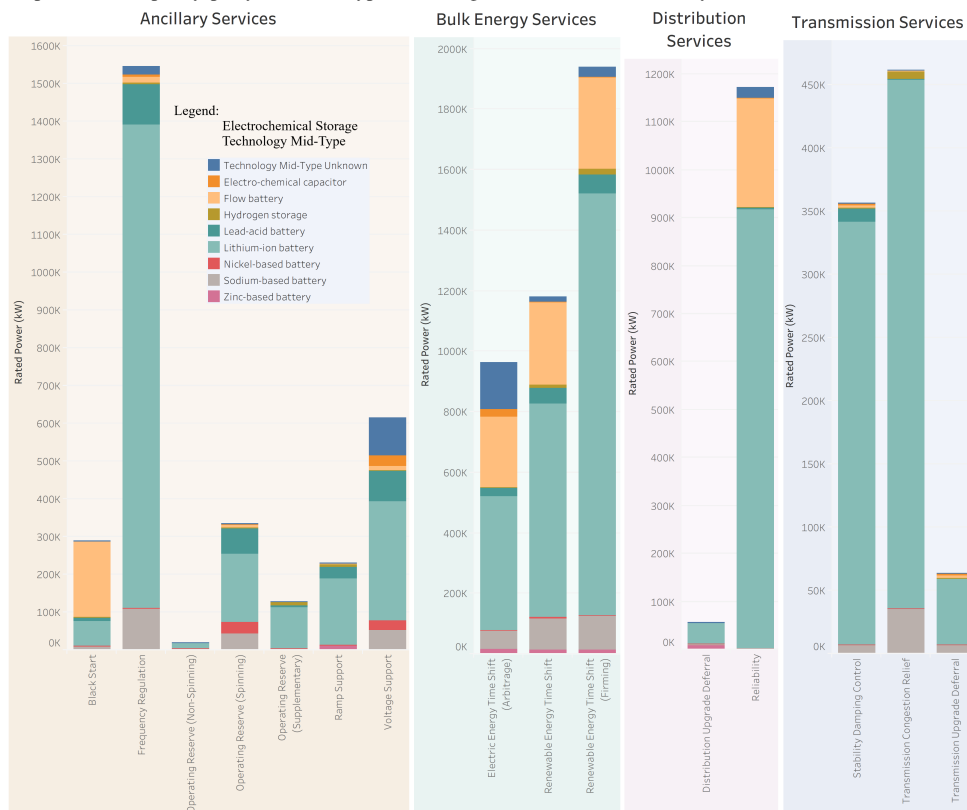


Fig. 2. Installed rated power of the electro-chemical battery and chemical storage per grid application [8].

performance, efficiency and lifetime of the involved storages. In particular, connection by means of power-electronic converters ensures the degrees of freedom required for a

flexible control and operation, unlike direct grid connection, which is in turn cost effective and relatively not complex. Fig. 4 [7] presents an *active* topology – materializing a

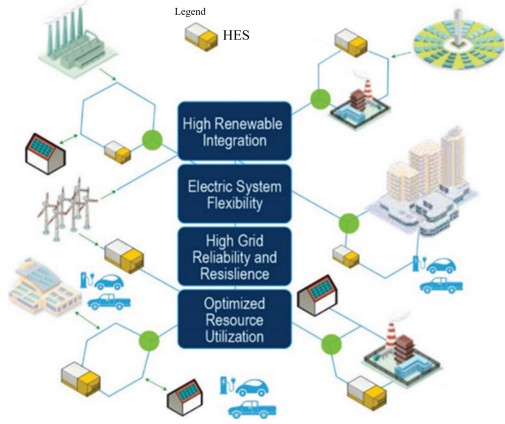


Fig. 3. A vision of the roles and benefits of HES within a grid [7].

so-called common DC link that ensures the power transfer towards the AC grid/microgrid – where both HES and HPS (high-power storage) are fully controllable by means of dedicated DC-DC converters. This structure can be particularized as a *semi-active* topology if the HES converter is absent, or as a *passive* one if both DC-DC converters are absent (neither storage is controllable).

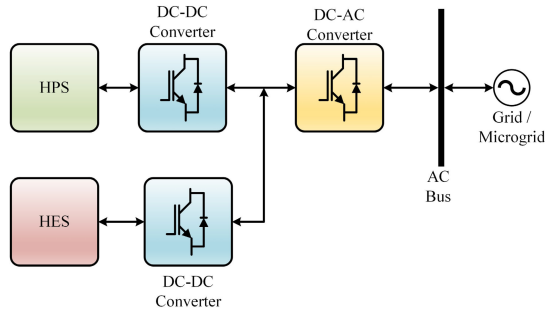


Fig. 4. Active power-electronic interconnection topology in a multi-source system, giving by particularization either passive or semi-active topology [7].

## II. CONTROL AND COORDINATION WITHIN HYBRID-ENERGY-STORAGE (HES)-BASED SYSTEMS

### A. Complementarity-based problem statement

To fix ideas, active-interconnection-based configurations of a generic multi-source microgrid are considered next, like the one in Fig. 5, which is equipped of *classical* – Diesel generator, thermal generator – as well as *renewable* sources – solar pannels, wind turbine – of *storage units* of various technologies – batteries, supercapacitors (ultracapacitors), fuel cells – and also of (possibly both) AC and DC loads. Partial versions of this configuration are also illustrative. Such a microgrid can operate in either *grid-forming* (stand-alone or autonomous) or *grid-connected* mode. In either case, sources' power flows are managed by a *Power Management System (PMS)*, mainly consisting of the control algorithm ensuring proper coordination of sources towards a common goal. Power flow management acts at a shorter time scale than the *Energy Management System (EMS)*; hence, PMS is placed nearer to the plant and lower in a possible multiple-layer control hierarchy. In particular, one of the PMS functions is to ensure

the effective coordination between sources, such as to exploit their complementarity. Thus, the complementarity between two power source technologies will further specifically refer to their relative *dynamic abilities in providing energy in a longer or a shorter term*. Hence, complementarity supposes dynamic behaviours at different time scales; its *dynamic* substrate enables complementarity to justify and be also used for control and coordination purposes.

*Dynamic specialization* of storages is best emphasized by Ragone plot [13] – see, for example, Fig. 6 for a quite complete view. Thus, *dynamic specialization range* of each storage can be identified through the relation between its *energy density (specific energy)* and its *power density (specific power)*. A large span of storage technologies is illustrated: from *high-specific-energy* storage sources, such as fuel cells – able to provide energy in a long term and hence called “*energy sources*”, so specialized in the *low-frequency* range of energy variations – to the *high-specific-power* sources, such as ultracapacitors (supercapacitors) – able to provide energy very quickly, hence called “*power sources*” and specialized in the *high-frequency* range. Different electrochemical storages (*e.g.*, batteries) or mechanical storages (*e.g.*, flywheels) are placed in between the two extremes. Notion of *characteristic (own) frequency of a source/storage* quantifies more precisely its dynamic specialization range:

$$f_p = \rho_p / \rho_e, \quad (1)$$

where  $\rho_p$  is the power density, in W/kg and read on the abscissa of Ragone plot, and  $\rho_e$  is the energy density, in J/kg and read on the ordinate. Characteristic frequency values for some of the main storage technologies are indicated in Fig. 7.

A given source behaves best when operated in its specialization range – *i.e.*, when it must supply power variations placed *around its own frequency* – as its *reliability* and *lifetime* are best guaranteed this way. For sake of reliability, a high-energy-density source, also identified as *main source* can be suitably complemented – otherwise said, *hybridized* – by a high-power-density one, also named *auxiliary source*, in order to protect the first from possible harm due to unappropriate exploitation outside its specialization range (Fig. 8). Initial sizing and rating of a HES system rely upon two classes of indicators for hybridization, namely: *power potential of hybridization (PPH)*, based on the possibility of reducing the main source's size – *i.e.*, rated power, weight, cost, *etc.* – due to the presence of the auxiliary one, and *energy potential of hybridization (EEH)*, based on taking into account variation spectrum of load power and also regularity of charging/discharging cycles of the main source if this is a storage one.

In a hybrid main-auxiliary source tandem the auxiliary source will supply the high-magnitude fast variations of power demand, which the main source is not able to supply without some risks for its longer-term operation. The simple decision to put together such two types of sources is not enough to guarantee their *reliability-aware operation*, a *multi-source PMS* being thus required to suitably coordinate them. Irrespective of the underlying method, this action relies upon *dynamic* or,

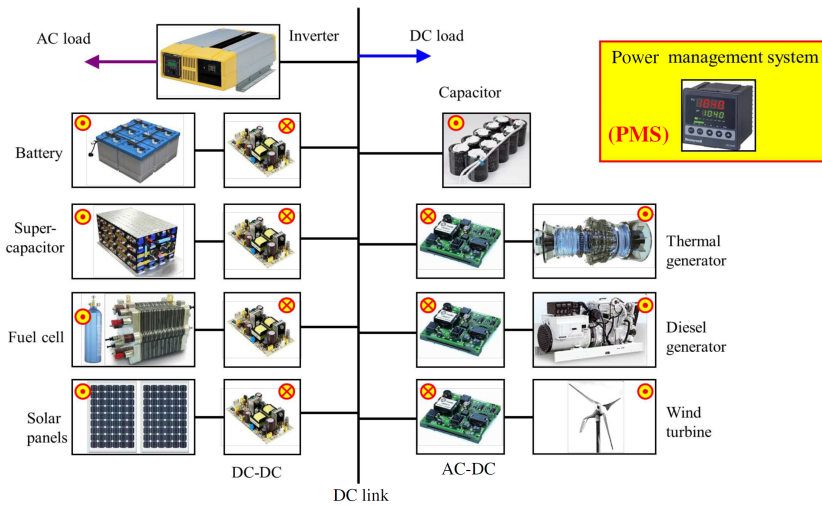


Fig. 5. General configuration of a microgrid with classical and renewable sources and various types of storage, coupled in parallel on a common DC link, supplying both AC and DC loads.

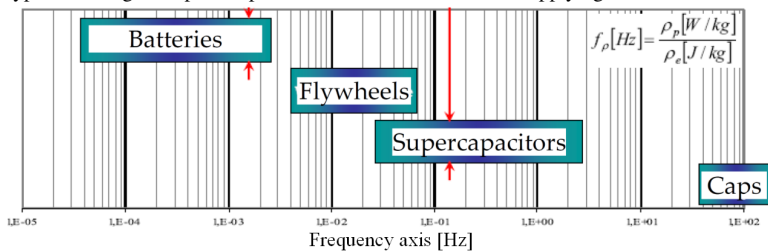


Fig. 7. Identification of main storage technologies by their characteristic frequencies.

equivalently, *frequency separation* of sources. Moreover, in order to address all optimization possibilities, *PMS design may already be considered in the phase of initial system sizing*, an approach that is called *system-control co-design*.

### B. A brief look at the PMS design state of the art

Next, the focus will naturally be on hybrid (multi) energy storage used in microgrid applications. In a multi-source microgrid, design of EMS and PMS can be formalized as control problems, namely to ensure a *desired load power sharing* between the different sources, while *preserving reliability of all sources* and extending their remaining useful life by exploiting their complementarity [14]. More precisely, the interest will be on the DC part of an active-interconnected microgrid (Fig. 4), *i.e.*, the common DC link, which can easily accommodate fully controllable multiple storages, namely as *current sources*. This is a topic related to DC microgrids, which have lastly gained growing interest *vs.* AC ones, mainly because they do not need synchronization. Autonomous applications in avionic, automotive and marine industries, as well as power supply of remote areas exploit this advantage, among others [15], [16].

A plethora of methods can be used to design efficient PMS. Model Predictive Control (MPC) – with its nonlinear and/or stochastic versions – may be employed in a multivariable control framework for stand-alone microgrids, with or without renewables, as it can take account of multiple constraints [10], [17], [18]. However, need of an adequate plant mathematical model and of a *a priori* knowledge of load variation to predict

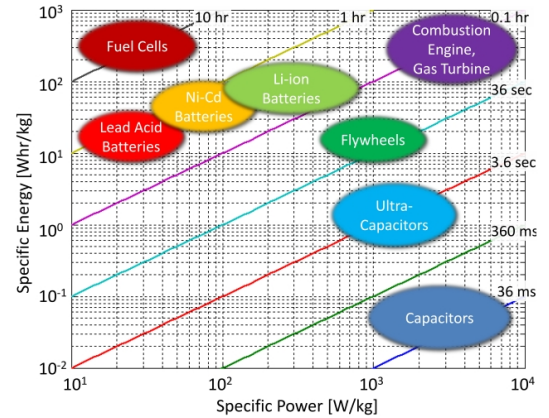


Fig. 6. Ragone plot: dynamic specialization of different source/storage technologies.

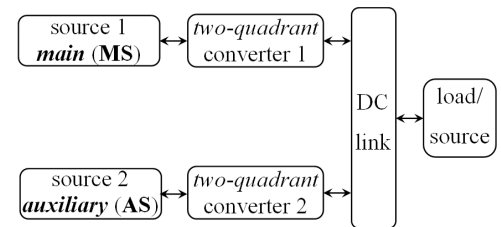


Fig. 8. Simplified block diagram of a hybrid two-storage-unit supply system in a stand-alone microgrid.

the behaviour appear as drawbacks. For example, in the case of electric vehicles (EVs), the resulted PMS depends on the driving cycle. More sophisticated approaches, such as nonlinear [11], [12] or multi-agent-based and games theory [19] may also offer viable solutions.

*Reliability-aware operation of each source* may appropriately be embedded into a PMS design, for example, “translated” and/or adapted from its data sheet, leading to multi-criteria techno-economical optimization. Thus, *reliability-aware PMS design* usually implements optimization methods that integrate complex degradation and ageing models of storage units [20]. The HES multi-time-scale nature justifies hierarchical control structures [21], composed of dynamically separated layers, according to sources being exploited in their “specialization” range of variations (see Ragone’s taxonomy in Fig. 6), respectful of their reliability [22]. The idea is that high-power-density sources (*e.g.*, ultracapacitors), to protect high-energy-density sources (*e.g.*, fuel cells or batteries), whose current variations should be smoother. To this end, filtering ensures the most explicitly the dynamic separation, by restricting variations of current of each source within in a predefined frequency interval [23], [24], while an optimal LQG approach may also work, but limited to only two sources [25].

Continuing the idea of expressing the dynamic separation of sources by means of an optimization index based on their respective own frequencies leads to the *generalization of the optimal approach for an arbitrary number of sources*, namely by introducing more degrees of freedom. Thus, the PMS

design by using *weighting functions* within an  $\mathcal{H}_\infty$  *robust control design* allows the flexibility needed for suitably conditioning the sources' dynamic closed-loop behaviour, in addition to guaranteeing *robust stability and performance*. Possible combination with *Linear Parameter Varying (LPV)* techniques – e.g., in a *polytopic approach* that generalizes gain scheduling techniques – extends the domain of PMS effectiveness. The robust approach is detailed next.

### III. ROBUST HES PMS DESIGN AND PERFORMANCE IN SOME ILLUSTRATIVE CASE STUDIES

#### A. Generic three-storage microgrid for PMS design statement

Without loss of generality, a generic, *three-storage – fuel cell, battery and supercapacitor* – microgrid operating as a power supply on board of an electric vehicle (EV) is here considered (Fig. 9 [26], [27]). The storage active parallel configuration has the advantage of flexibility (sources' independent operation, facility to replace/add power sources, etc.). The number of sources, three, was chosen to illustrate the applicability of the approach to any number of sources (whereas only two sources could have been viewed as a particular case). The *fuel cell* acts here as the *main* source, it is *unidirectional*, so connected to a one-quadrant DC-DC converter. The two *auxiliary* sources – the *battery* and the *supercapacitor*, both *bidirectional* – must supply the relatively fast power demand variations and collect the reversed power (during braking phase), so they are connected each to a two-quadrant converter allowing charging/discharging. The electrical motor and its converter materializes the load. A key task of the PMS is to maximize benefits of hybridization, which supposes that each source to operate in its dynamic specialization range.

First, a classical two-level control structure is adopted, where the upper-level LPV/ $\mathcal{H}_\infty$ -based PMS provides references to the DC-DC converters' current control loops on a lower level (Fig. 10 [27]). The dynamic (frequency)-separation operation of the three storages is accompanied by some other constraints, so the following control objectives must be met:

- maintain the DC-link voltage constant, around a predefined  $V_{dc}^*$  setpoint, regardless of the load current variations. This goal applies to all configurations with different sources paralleled on a common DC link. It is this requirement that allows the HES PMS design statement as a disturbance-attenuation problem in the  $\mathcal{H}_\infty$  framework;
- ensure dynamic separation of storages, i.e., each storage supplies power with respect to its own frequency according to Ragone's plot (see (1) and Fig. 6). To this end, *appropriate shaping of weighting functions associated to  $\mathcal{H}_\infty$  control design* is a crucial step in the design;
- keep supercapacitor's state of charge (SoC) loosely around 50%, thus enabling continuously absorbing/providing power in response to instantaneous load power demand;
- impose a desired steady-state power sharing between the "slow" storages, fuel cell and battery. In this way, the fuel cell may operate at a desired working point, e.g., the maximum-efficiency one. Steady-state behaviour could

determine battery long-term charging cycle, according to its technology.

Regarding the *low-level control design*, as the DC-link voltage  $V_{dc}$  is kept constant at  $V_{dc}^*$  by the PMS, converters' currents have fairly linear dynamics, so *classical PI* tracking controllers can be used. The low level is designed to be fast enough to be neglected at the slower-dynamic upper level, so the following equalities hold next:  $I_{fc}^* = I_{fc}$ ,  $I_{bat}^* = I_{bat}$  and  $I_{sc}^* = I_{sc}$ . The three tracking low-level loops have the converters' duty cycles,  $\alpha_{fc}$ ,  $\alpha_{bat}$  and  $\alpha_{sc}$ , as control inputs. In the LPV framework, these duty cycles compose the *varying parameter vector*:  $\rho = [\rho_1 \ \rho_2 \ \rho_3]^T \equiv [\alpha_{fc} \ \alpha_{bat} \ \alpha_{sc}]^T$ .

The sought-for LPV controller  $\mathbf{K}(\rho)$  in Fig. 10 must ensure closed-loop stability, whereas minimizing the effect of load current,  $I_{load}$ , acting as a disturbance on the DC-link voltage. Control design is thus tackled in the  $\mathcal{H}_\infty$  framework applied to LPV systems, based on the so-called  $\mathbf{P-K}$  form of control block diagram [28] in Fig. 10, with the plant  $\mathbf{G}(\rho)$  being extended with the *weighting functions* – denoted by  $\mathbf{W}$  – whose selection should obey the above-listed performance requirements. In Fig. 10  $\mathbf{G}(\rho)$  plant's state vector is  $\mathbf{x} = [V_{dc} \ V_1 \ V_2 \ V_0]^T$  (with notations in Fig. 9), the exogenous vector,  $\mathbf{w}$ , contains the disturbance signal,  $I_{load}$ , and the reference signals,  $\mathbf{u}$  is the control vector,  $\mathbf{y}$  is the output vector composed of the errors in relation to references and  $\mathbf{z}$  is the controlled output vector, containing the "shaped"-by-weighting-function errors and control inputs. The detailed design procedure, including selection of weighting functions, can be found in [26].

Next, in order to provide a proof of concept of the robust HES PMS design methodology, real-time validation results are briefly presented in two illustrative case studies: a first one concerning an *electromobility* application and a second one in a *frequency-regulation* application in a stand-alone microgrid.

#### B. Case study 1: HILS validation of a PMS for a three-storage DC power supply on board of an EV

*Hardware-in-the-loop simulation (HILS)* is nowadays widely known and used for control law rapid prototyping and preliminary validation, before any real-site implementation. Since its definition and introduction some thirty years ago for developing and testing control structures in the automotive industry using the MATLAB<sup>®</sup>/Simulink<sup>®</sup> software on a dSPACE<sup>™</sup> real-time system [29], HILS concept has increasingly been used and evolved to the status of a standard. This concept mainly consists in closing the loop around the controller embedded on a real device and the plant, which is only emulated and/or numerically simulated, because it is too expensive to use the real plant.

The first case study concerns a three-storage power supply on board of an EV and corresponds exactly to the configuration in Fig. 9. HILS validation results were obtained on a test bench designed in collaboration with FEMTO-ST Laboratory in Belfort, France, where real battery and supercapacitor, as well as a complete real-time fuel cell emulator developed at FEMTO-ST Laboratory [30] were used. For sake of reducing



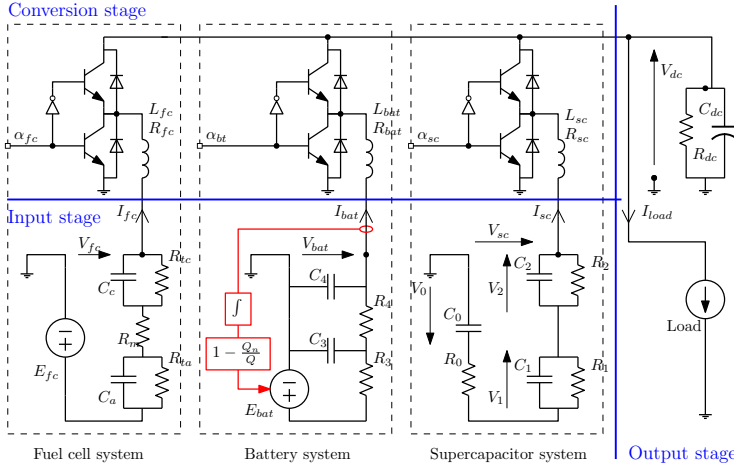


Fig. 9. Schematic of a three-storage – fuel-cell–battery–ultracapacitor – power supply system, detailing the equivalent electrical models of the storage units [27].

real-time implementation complexity, a reduced-order version of the controller was employed in real time, according to the order reduction method proposed in [31]. Fig. 11 exhibits an expanded view of the different parts composing the assembled test bench. The *IFSTAR (Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux – French Institute of Science and Technology for Transport, Development and Networks)* driving cycle profile [26], representative of various urban driving conditions – comprising acceleration, deceleration, fixed speed and full brake – was chosen for being sufficiently rich in frequency content, such as to challenge the DC-bus voltage regulation and to illustrate the sources “fusion” in satisfying the power demand. The active load variation is controlled to correspond to the chosen driving cycle scenario by means of a rapid-prototyping platform based on the dSPACE™ MicroAutoBox® II device.

HILS validation required some adaptations, including in the selection of control references and weighting functions – see [27] for details. Dynamic separation of storages is confirmed by time evolutions of the corresponding currents in Fig. 12.

### C. Case study 2: HILS validation of a frequency-regulation PMS for a two-storage AC microgrid

Results presented within this subsection were obtained in a technology transfer project between 2018 and 2020 [32], whose aim was to prove the practical feasibility of an  $\mathcal{H}_\infty$ -based HES PMS solution and quantify its economical benefits. The use case was that of the *primary frequency regulation* in a *two-storage*-equipped stand-alone microgrid also containing both classical (Diesel generator) and renewable (PV) sources. The topology is a partial version of the one in Fig. 5, where a tandem *battery–ultracapacitor* materializes the HES.

Here, hybridization is justified by the large penetration rate of the renewables. The battery is employed to supply the load slow, long-term, low-frequency variations, while the supercapacitor, specialized in supplying fast, instantaneous, high-frequency (and possibly high-magnitude) load variations, is used as a “quick” backup storage that protects the battery. In this way, battery lifetime is saved, with some quantifiable

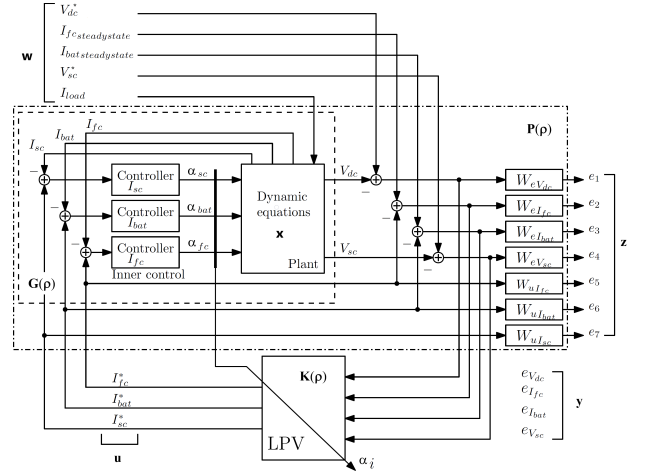


Fig. 10. Closed-loop P–K form according to the LPV/ $\mathcal{H}_\infty$  formalism, where the extended plant contains the weighting functions [27].

economical benefits. Whereas the same HES PMS design methodology, generalizable to any number of storages/sources, was applied, however, for this case study some design and implementation details are purposely omitted, for reasons of intellectual property protection.

A test bench composed of a HILS-based demonstrator and a real battery pack together with its boost DC-DC converter – whose photo is presented in Fig. 13 – was built to allow submitting the battery pack to cycles relevant to the frequency-regulation use case, in order to further evaluate its aging parameters, out of which the *residual capacity of discharge* was the most relevant. To this end, the HES PMS version adapted to the frequency-regulation use case was embedded on a general-purpose TI C2000 microcontroller to allow predicting *more than 50% increase of battery lifetime* based on post-cycling measurements, which suggests significant economical benefits of hybridization combined with robust HES PMS – more details can be found on the project website [32].

The HES-PMS-managed microgrid closed-loop dynamic performance was challenged with the most unfavourable load power scenario, *i.e.*, consisting of a series of step variations. Dynamic separation of battery and supercapacitor currents was concluded by analyzing the time evolutions of the concerned currents; explicit plots are skipped here for sake of space saving. On the other hand, a more general result was obtained in the frequency domain, which is shown in Fig. 14. It is about a histogram-based comparison of no-storage- vs. storage-based PMS: average of the microgrid frequency values are closer to the rated one (here 50 Hz) if the storage is present. This result offers a quantitative indication of the storage beneficial role in renewable-based microgrid control.

## IV. CONCLUSION AND SOME PERSPECTIVES

The actual context of the green energy transition should rely upon extensive use of energy storage units, to support larger grid penetration and improve dispatchability of renewables. Hybrid energy storage (HES) has proven to improve grid eco-friendliness, flexibility and resilience. To this end, HES must be effectively managed by Power Management Systems (PMS).

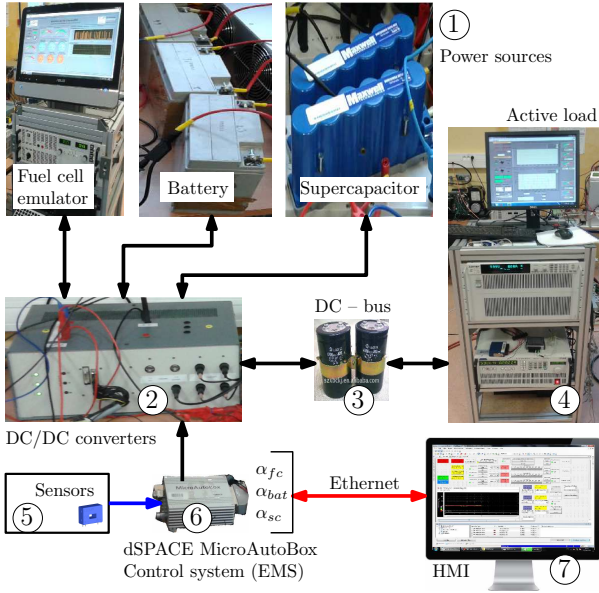


Fig. 11. Topology of the rapid-prototyping test bench at FEMTO-ST Laboratory in Belfort, France, used to validate the LPV/ $\mathcal{H}_\infty$  HES PMS [27].

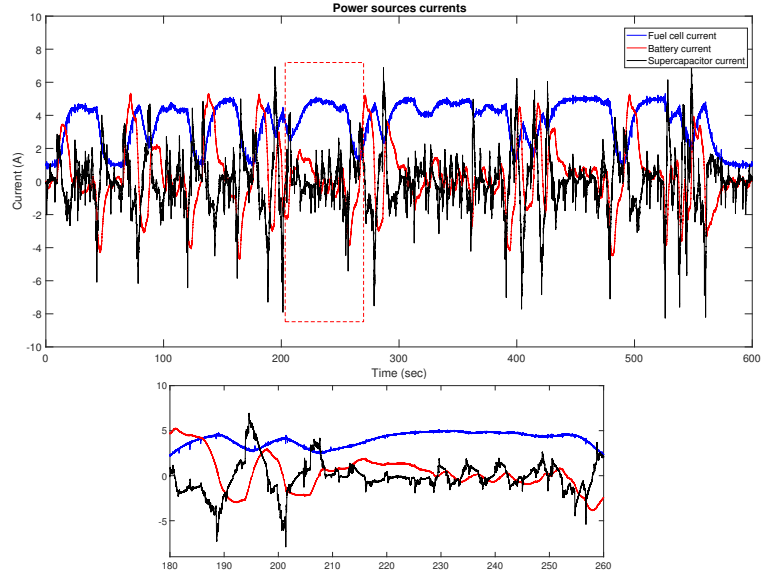


Fig. 12. Real-time results obtained on the test bench in Fig. 11 [27]: the three power sources' currents corresponding to IFSTTAR driving cycle and zoom.

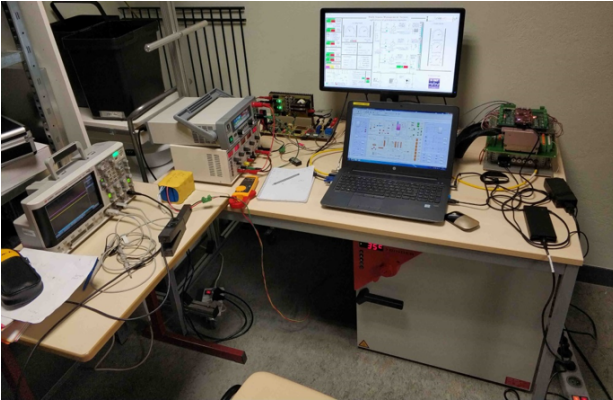


Fig. 13. Photo of the HILS test bench at GIPSA-lab, replicating a battery-ultracapacitor PMS-controlled microgrid, used for *battery cycling* in the primary-frequency-regulation use case.

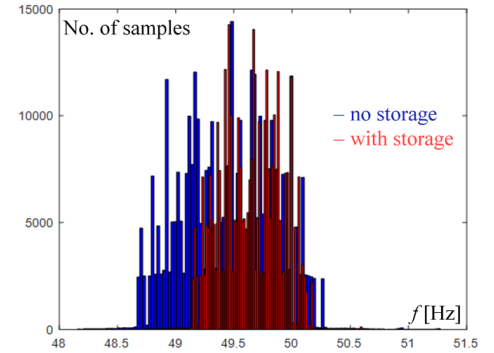


Fig. 14. Histogram of microgrid primary-regulated frequency values, with and without storage.

This paper has argued the necessity of using advanced control methods for this purpose. Thus, details of systematically applying robust  $\mathcal{H}_\infty$  control for the HES PMS design, as well as two illustrative case studies, have been presented.

To conclude, our proposed PMS design methodology requires input data representative of the dynamic specialization of storages, according to datasheet information and placement on the energy-density-vs.-power-density Ragone plot. A key notion is that of “own frequency” of a storage technology, as it precisely quantifies its dynamic properties. Such an approach is coherent with a reliability-aware, thus sustainable design.

The HES PMS design has been stated as an *S/KS mixed-sensitivity problem* in the  $\mathcal{H}_\infty$  formalism, further allowing *systematic robustness analysis*. Analysis of the two HES-based microgrid case studies has shown that “fast” storages – e.g., supercapacitors – are robustly well-performing in both improving overall closed-loop performance – in primary frequency regulation – and also in smoothing current variations of other “slower” storages – e.g., batteries – thus protecting them

from over-solicitation outside their “specialization” operation range, so prolonging their life and service time. In a more philosophical sense, the proposed PMS control design vision emphasizes the idea of *harmonious fusion* between different power sources/storages and can be regarded as an instance of a more general consensus principle.

Some interesting future research directions may be identified, as follows. Integrated into a microgrid control, the proposed robust HES PMS design may require a computationally heavy LMI-based optimization problem being solved as the number of sources/storages increases. Even if *scalability of the  $\mathcal{H}_\infty$  -LPV design* seems to be affordable for a small number of sources (two or three), it still needs some formal guarantees. Possible complexity alleviation by order reduction methods is a way to comforting the real-world application acceptability.

As the HES PMS must take account of roles of each storage within a given application, it must be compatible with some individual, possibly built-in, power management systems – a Battery Management System (BMS) is a typical example, with the



multiple functions it can provide in the case of some advanced versions, such as, for example, real-time estimation of state of charge and state of health. Thus, either clearer separation, or “fusion” of functions between the individual and global (HES) level may be envisaged. Also, from a system-control co-design viewpoint, specific economical benefits of storage service time extension by hybridization must be compared against initial investment and operation costs, to be able to really conclude on improving key performance indicators, such as CAPEX (capital expenditure) and OPEX (operation expenditure). Such an approach supposes complex, multi-objective optimization problems being appropriately formulated.

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#### REFERENCES

- [1] O. Ellabban, H. Abu-Rub, and F. Blaabjerg, “Renewable energy resources: Current status, future prospects and their enabling technology,” *Renew. Sustain. Energy Rev.*, vol. 39, pp. 748–764, Nov. 2014.
- [2] F. Blaabjerg, R. Teodorescu, M. Liserre, and A. V. Timbus, “Overview of control and grid synchronization for distributed power generation systems,” *IEEE Trans. Ind. Electron.*, vol. 53, no. 5, pp. 1398–1409, Oct. 2006.
- [3] A. Kyritsis, D. Voglitsis, N. Papanikolaou, S. Tselepis, C. Christodoulou, I. Gonos, and S. A. Kalogirou, “Evolution of PV systems in Greece and review of applicable solutions for higher penetration levels,” *Renew. Energy*, vol. 109, pp. 487–499, Aug. 2017.
- [4] L. W. Chong, Y. W. Wong, R. K. Rajkumar, R. K. Rajkumar, and D. Isa, “Hybrid energy storage systems and control strategies for stand-alone renewable energy power systems,” *Renew. Sustain. Energy Rev.*, vol. 66, pp. 174–189, Dec. 2016.
- [5] V. R. Krishnakumar, K. R. Vigna, V. Gomathi, J. B. Ekanayake, and S. K. Tiong, “Modelling and simulation of variable speed pico hydel energy storage system for microgrid applications,” *J. Energy Storage*, vol. 24, Aug. 2019, Art. no. 100808.
- [6] M. I. Hlal, V. K. Ramachandaramurthy, A. Sarhan, A. Pouryekt, and U. Subramaniam, “Optimum battery depth of discharge for offgrid solar PV/battery system,” *J. Energy Storage*, vol. 26, Dec. 2019, Art. no. 100999.
- [7] T. S. Babu, K. R. Vasuvedan, V. K. Ramachandaramurthy, S. B. Sani, S. Chemud, and R. M. Lajim, “A comprehensive review of hybrid energy storage systems: converter topologies, control strategies and future prospects,” *IEEE Access*, vol. 8, pp. 148702–148721, Aug. 2020.
- [8] \*\*\*, U.S. Department of Energy Global Energy Storage Database. Accessed: August 6 2023. [Online]. Available: <https://gesdb.sandia.gov/statistics.html>.
- [9] H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding, “Progress in electrical energy storage system: A critical review,” *Prog. Natural Sci.*, vol. 19, no. 3, pp. 291–312, Mar. 2009.
- [10] A. M. Dizqah, A. Maheri, K. Busawon, and P. Fritzon, “Standalone DC microgrids as complementarity dynamical systems: modeling and applications,” *Control Engineering Practice*, vol. 35, pp. 102–112, 2015.
- [11] T. Alnejaiili, S. Drid, D. Mehdi, L. Chrifi-Alaoui, and H. Sahraoui, “Sliding mode control of a multi-source renewable power system,” in *Proc. of the 3rd Intl. Conf. on Control Engineering and Information Technology – CEIT 2015*, Tlemcen, Algeria, May 2015, pp. 1–6.
- [12] M. Rajabzadeh, S. M. T. Bathaee, and M. A. Golkar, “Dynamic modeling and nonlinear control of fuel cell vehicles with different hybrid power sources,” *International Journal of Hydrogen Energy*, vol. 41, no. 4, pp. 3185–3198, 2016.
- [13] A. Kuperman, and I. Aharon, “Battery/ultracapacitor hybrids for pulsed current loads: a review,” *Renewable and Sustainable Energy Reviews*, vol. 15, pp. 981–992, 2011.
- [14] D. Iannuzzi, “Use of supercapacitors, fuel cells and electrochemical batteries for electric road vehicles: a control strategy,” in *Proc. of the 33rd Annual Conference of the IEEE Industrial Electronics Society – IECON 2007*, Taipei, Taiwan, Nov. 2007, pp. 539–544.
- [15] J. M. Guerrero, M. Chandorkar, V. Lee, and P. C. Loh, “Advanced control architectures for intelligent microgrids – Part I: Decentralized and hierarchical control,” *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1254–1262, 2013.
- [16] J. J. Justo, F. Mwasilu, J. Lee, and J. W. Jung, “AC-microgrids versus DC-microgrids with distributed energy resources: a review,” *Renew. Sustain. Energy Rev.*, vol. 24, pp. 387–405, 2013.
- [17] S. Schuler, D. Schlipf, P. W. Cheng, and F. Allgöwer, “ $\mathcal{L}_1$ -optimal control of large wind turbines,” *IEEE Trans. Control Syst. Technol.*, vol. 21, no. 4, 2013, pp. 1079–1089, 2013.
- [18] S. Xie, H. He, and J. Peng, “An energy management strategy based on stochastic model predictive control for plug-in hybrid electric buses,” *Appl. Energy*, vol. 196, pp. 279–288, 2017.
- [19] M. R. B. Khan, R. Jidin, and J. Pasupuleti, “Multi-agent based distributed control architecture for microgrid energy management and optimization,” *Energy Conv. Manag.*, vol. 112, pp. 288–307, 2016.
- [20] F. Martel, S. Kelouwani, Y. Dubé, and K. Agbossou, “Optimal economy-based battery degradation management dynamics for fuel-cell plug-in hybrid electric vehicles,” *J. of Power Sources*, vol. 274, pp. 367–381, 2015.
- [21] X. Xiandong, H. Jia, D. Wang, D.C. Yu, and H.-D. Chiang, “Hierarchical energy management system for multi-source multi-product microgrids,” *Renew. Energy*, vol. 78, pp. 621–630, 2015.
- [22] A. Castaigns, W. Lhomme, R. Trigui, and A. Bouscayrol, “Decomposed energy management of a multi-source fuel cell vehicle using energetic macroscopic representation,” in *Proc. of 2016 IEEE Vehicle Power and Propulsion Conference – VPPC 2016*, Hangzhou, China, Oct. 2016, pp. 1–6.
- [23] M. A. Silva, J. P. Trovao, P. G. Pereirinha, and H. M. Jorge, “Application of a decoupling method based on online filtering technique for multi-source electric vehicles,” in *Proc. of 2013 15th European Conference on Power Electronics and Applications – EPE 2013*, Lille, France, Sep. 2013, pp. 1–10.
- [24] A. Florescu, S. Bacha, I. Munteanu, A. I. Bratcu, and A. Rumeau, “Adaptive frequency-separation-based energy management system for electric vehicles,” *J. of Power Sources*, vol. 280, 410–421, 2015.
- [25] A. Florescu, A. I. Bratcu, I. Munteanu, A. Rumeau, and S. Bacha, “LQG optimal control applied to on-board energy management system of all-electric vehicles,” *IEEE Trans. Control Syst. Technol.*, vol. 23, no. 4, pp. 1427–1439, 2015.
- [26] W. Nwesaty, A. I. Bratcu, and O. Sename, “Power sources coordination through multivariable LPV/ $\mathcal{H}_\infty$  control with application to multi-source electric vehicles,” *IET Control Theory Appl.*, vol. 10, no. 16, pp. 2049–2059, 2016.
- [27] J.-M. W. Nwesaty, A. I. Bratcu, A. Ravey, D. Bouquain, and O. Sename, “Robust energy management system for multi-source DC energy systems – real-time setup and validation,” *IEEE Trans. Control Syst. Technol.*, vol. 28, no. 6, pp. 2591–2599, 2020.
- [28] L. Lublin, S. Grocott, and M. Athans, “ $\mathcal{H}_2$  (LQG) and  $\mathcal{H}_\infty$  control,” in *The Control Handbook*, vol. III (Control system advanced methods), W. Levine, Ed., Boca Raton: CRC Press, 2011.
- [29] H. Hanselmann, “Hardware-in-the loop simulation as a standard approach for development, customization, and production test of ECU’s,” in *Proc. of International Pacific Conference On Automotive Engineering*, SAE Technical Paper 931953, 1993.
- [30] F. Gao, B. Blunier, M. G. Simoes, and A. Miraoui, “PEM fuel cell stack modeling for real-time emulation in hardware-in-the-loop applications,” *IEEE Trans. Energy Conversion*, vol. 26, no. 1, pp. 184–194, 2011.
- [31] W. Nwesaty, A. I. Bratcu, and O. Sename, “Reduced-order LPV controller for coordination of power sources within multi-source energy systems,” in *Proc. of the 8th IFAC Symposium on Robust Control Design – ROCOND 2015*, Bratislava, Slovakia, July 8–11 2015. IFAC-PapersOnLine, vol. 48, no. 14, pp. 132–137.
- [32] K-INF – fusion of electrical sources. Accessed: August 13 2023. [Online]. Available: <https://www.k-inf.fr>.