# 1

# Issues in Electrical Energy Storage



## 1.1. Difficulties of storing electrical energy

The electrical energy vector has been highly developed over the past 150 years, as it is extremely practical to use, is not pollutant during use and can generate very little pollution if produced from renewable energies. Its transport over long distances at very high voltage is possible due to transformers, which make it possible to adjust the amplitude of voltage and current waves at will. This possibility offered by transformers goes a long way toward explaining why electrical grids have been developed using alternating voltages and currents.

The weak point of the electricity vector is that electrical currents cannot be stored directly. It is possible to store electrostatic energy (in capacitors) or magnetic energy (in superconducting coils), but the storage capacities of these solutions are quite limited. In order to obtain substantial storage capacities, electrical energy must be transformed into another form of energy. Storage in the form of potential energy by means of turbine pumping stations enables large quantities of energy to be stored, but these stations must be located in regions able to provide significant differences in height between two hydraulic storage tanks. Electrochemical storage using lead batteries has long been used for onboard applications and emergency power supplies, while the storage of kinetic energy by means of flywheels has been used for several decades for fixed applications such as emergency power supplies and some onboard applications, including satellites.

Electrochemical batteries make it possible to store electrical energy in continuous form. Inertial energy storage is used in machines that are required to operate at variable speed, that is, variable frequency. With electrical grids supplying electricity in the form of alternating voltage and currents at fixed frequencies, the implementation of these storage technologies remained complicated until the advent of electronic power, which was introduced in the 1960s, and is currently used to transform the form and characteristics of currents and voltages at will.

The difficulty of storing electrical energy explains why the management of electrical grids has been designed according to the principle of direct consumption of the electrical energy produced, even when the distance between production and consumption is several hundred kilometers. This approach has evolved slightly in France, with the development of nuclear facilities ideally able to produce constant power, favoring the development of hydraulic storage.

The direct consumption of energy has the advantage of a higher overall energetic yield. In fact, the energetic conversion required for storage causes very different losses depending on the storage technologies used. These losses can range from 10% to 50%, or even more. However, this notion of yield can be put into perspective if the stored energy comes from a source for which the non-stored energy would be lost anyway, as is the case with energy that is wind or photovoltaic in origin.

Finally, note, that electrical energy can be stored and subsequently used in another energetic form. This is the case with hot-water tanks in domestic grids, whose final use is thermal energy and the production of hydrogen via electrolysis. Some loads have a storage capacity enabling the control of the power supply from the electrical grid, as with cold storage in supermarket refrigerators, or storage in the batteries of electrical vehicles.

## 1.2. Why store electrical energy?

The management of electrical grids is based principally on the direct consumption of the electrical energy produced. As consumption is variable, this approach requires the constant adaptation of production to this consumption. Figures 1.1 and 1.2 show typical domestic and commercial consumer profiles, illustrating the variable character of consumption depending on the time of day, season and type of load.

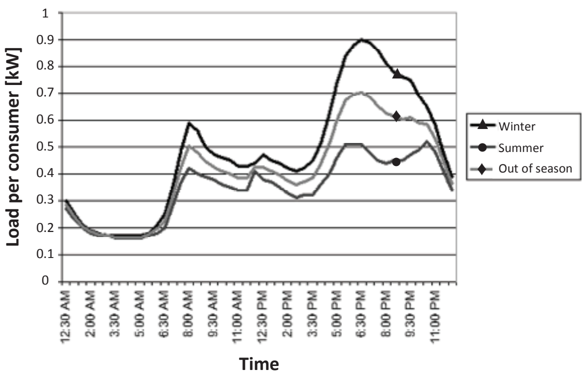


**Figure 1.1.** *Typical profiles of domestic consumers, not including electrical heating (RTE)*

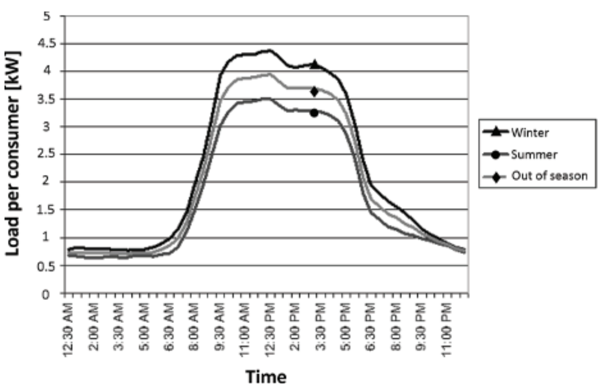


**Figure 1.2.** *Typical profiles of tertiary and artisanal consumers (RTE)*

Since the development of renewable energy sources, electrical grids have been forced to face the accommodation of highly intermittent production, as is the case for wind, photovoltaic and marine energies, as well as small hydraulic run-of-the-river energies [ROB 12c]. Figure 1.3 illustrates a wind turbine's production of 300 kW more than 5 min. Apart from high variability, fluctuations of 100 kW in 3 s have been recorded. Figure 1.4 illustrates the production of a photovoltaic facility in the span of a day; the presence of clouds induces a high variability of this production.

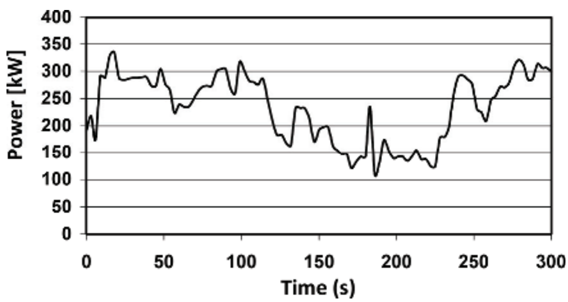


**Figure 1.3.** *Example of power generated by a fixed speed wind turbine of 300 kW*

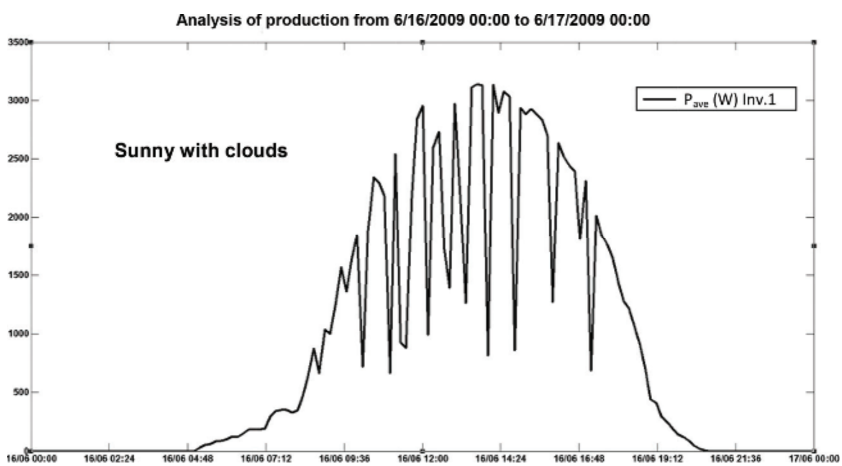


**Figure 1.4.** *Profile of a sunny day with clouds (source: Auchan)*

Hydraulic resources also show significant fluctuations. For example, ocean waves are an abundant resource, but with large and rapid variations, as shown in Figure 1.5. The flow of a river is also subject to significant fluctuations over months and years, as shown in Figure 1.6, even hours in case of flooding following heavy rainfall. Small run-of-the-river hydraulic facilities, which are not equipped with upstream dams or spillways, will therefore produce uncontrolled variable power when subjected to these fluctuations [ROB 12c].

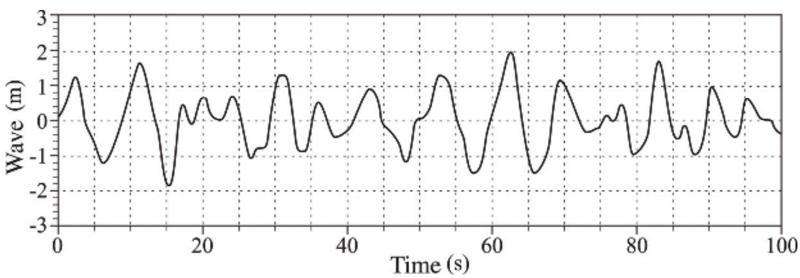


**Figure 1.5.** *Variation in wave height [MOU 08]*

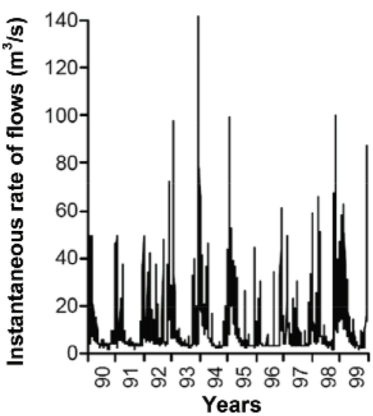


**Figure 1.6.** *Variations in output of the Oise river over 10 years [ROB 12c]*

These examples show that the balance between production and consumption does not occur naturally, and has been complicated by the increasing development of high-variability renewable energies. Storage of the electrical energy produced by these renewable sources makes it possible to smooth their production, and thus to facilitate their adaptation to consumption.

Conversely, sources such as nuclear power plants ideally produce at constant power. In this case, storage of overproduction during the night makes it possible to compensate for underproduction during the peak hours of the day.

The infrastructures of transport systems such as railways, metros and trams also call grid for fluctuating power on electrical grids due to the starts and stops of traction units, and to fluctuations in traffic at different times of the day [ROB 15].

Finally, the onboard systems of various modes of transport (rail, naval, aeronautical, aerospace, road vehicle, robot, etc.) incorporate electrical storage systems to power backup systems and local electrical grids, recover energy while braking and ensure vehicle propulsion. The development of electric vehicles in particular will significantly increase the need for high-performance onboard electrical storage in order to provide the vehicles with as much autonomy as possible in complete safety [ROB 15].

## 1.3. Value enhancement of storage in electrical grids

Energy storage systems are costly, and the additional cost they incur in a system of production or consumption can be prohibitive to their installation. It is necessary then to make sure that the economic enhancement of storage over its lifespan will at least compensate for the investment and maintenance costs. The cost of storage varies greatly depending on the technologies and the maturity level of these technologies, which are the subject of a great deal of research and development work. The value enhancement of storage in electrical grids will be dependent on the various services it can provide, which will depend on its positioning in the grid.

Two approaches to the development of storage in electrical grids can be distinguished:

– associated with large intermittent production units (e.g. hydraulic storage associated with wind power connected to the transportation grid);

– diffuse, that is, distributed within the distribution grid, for example.

To make storage profitable, one approach consists of mutualizing the services that a storage system can contribute among various actors (managers, producers and consumers) [DEL 09]. These services consist of:

– local precise and dynamic voltage control;

– support of grid in degraded operation;

– return of voltage in network parts;

– reactive compensation for grid managers (and customers);

– reduction of transport losses;

– power quality;

– energy postponement and support to the production units;

– primary frequency control and frequency stability of insular grids;

– solving of congestion;

– support for participation in ancillary services;

– erasure recovery;

– guarantee of a production profile;

– peak smoothing;

– consumption postponement;

– supply quality/continuity.

The developments presented in this book will illustrate the implementation of several of these services.

The mutualization of services can be associated with a corresponding mutualization of actors; multiple production resources of different types (renewable, difficult to predict and foreseeable, fossil, etc.), multiple consumers and multiple storage systems using different technologies, all with different and complementary characteristics (power, energy and dynamics). Therefore, these are known as multisource, multiload and multistorage systems.

For more than a century, grid management has been based on a centralized approach with limited means of communication, particularly in distribution grids. The implementation and use of new communication technologies along with advanced management resources will increase the intelligence level of grids and contribute to a safe increase in the penetration rate of random productions, while also increasing the energy efficiency of these intelligent grids (Figure 1.7). In this evolution toward smart grids, the storage of electrical energy will play an important role in favoring the development of renewable energies and contributing to the stability of electrical grids, as well as favoring self-consumption in the residential sector, industry and transportation systems. As part of this evolution, the large-scale development of electric vehicles may lead these vehicles to play a particular role, as they represent a significant storage capacity that could contribute to the efficiency and stability of a grid by controlling its load, or even occasionally generating energy on this grid.

The mechanisms of the electricity market also influence the profitability of storage systems. These mechanisms differ from one country to another and, in a competitive environment, evolve with time to favor the development of renewable energies generated on a grid or self-consumed, some loads such as electric vehicles, and energy storage. This storage, connected to an electrical grid, may be seen by this grid as a load or a source depending on whether it stores or generates electricity, which can result in having to pay twice the cost of the grid connection for this device, as a consumer and again as a producer.

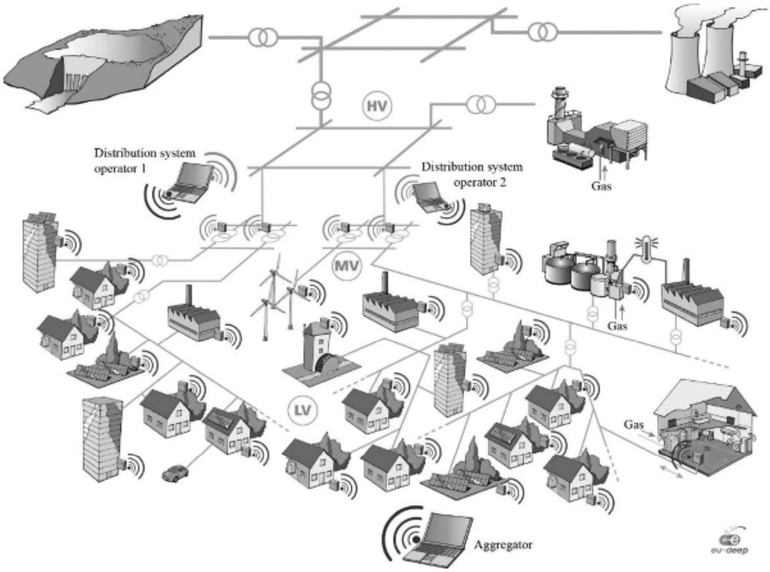


**Figure 1.7.** *Intelligent grid with communication via internet (source: European eu-deep project)*

The development of energy storage must contribute to sustainable development; therefore, it is important to consider the contribution of these systems to the reduction of $CO_2$ emissions, not forgetting the gray energy consumed by the construction of the storage system itself. One current trend is the conducting of a lifecycle analysis (LCA) on storage systems.

## 1.4. Storage management

The management of storage systems in electrical grids must respond to several challenges:

– the development of methods for the supervision of electrical systems whose state or behavior is not well known (random), in which the time horizon to be incorporated may be short (real time when reacting to dynamic stresses) or long (one year, e.g., in order to take into account the seasonal character of renewable sources). These strategies must adapt to an energy policy favoring the expansion of low-power generators dispersed throughout an area, in contrast to the current situation, which is based on the operation of a small number of very high-power production plants (mainly nuclear in France);

– the development of multistorage approaches;

– the development of multiobjective supervision strategies and the pooling of services.

Various time horizons may be put forth in the development of an energy storage system management strategy (Figure 1.8):

– long-term supervision corresponding to a timescale of 1 day;

– medium-term supervision corresponding to a timescale of between 30 min and 1 h;

– real-time supervision, corresponding to the smallest timescale needed to ensure system operation that is sufficient for its stability, the achievement of its objectives, the taking into account of hazards, etc. This timescale can range from a few dozen microseconds to several minutes.

The planning of more long-term storage (several days, weeks, months or years) may also be necessary for the effective management of storage and its economic profitability.

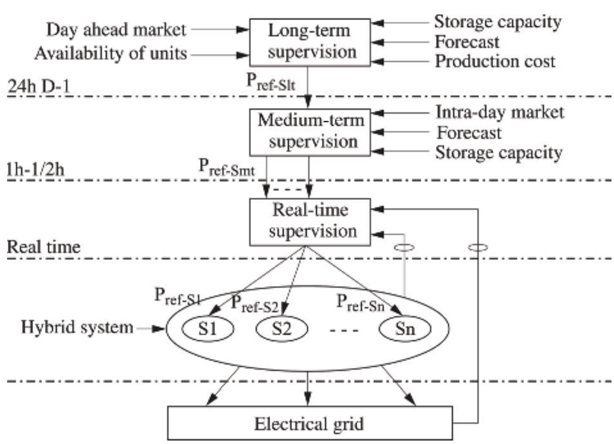


**Figure 1.8.** *Different time horizons to consider for the management of a hybrid system incorporating one or more sources, storage and possibly controllable loads*

Energy storage management is a significant challenge given the complexity of the problems to be addressed, the economic and ecological objectives and the fact that there is more than one solution that will enable these goals to be met [NEH 11, ROB 12a, ROB 13a, ROB 13b]. Three groups of tools are proposed in the literature to supervise hybrid systems incorporating storage:

– *causal formalization tools* [ALL 10, FAK 11, ZHO 11, DEL 12]. This approach consists of identifying power flows whose inversion can be used to determine reference powers. It requires a detailed mathematical model of the sources and storage systems as well as a good real-time understanding of these different flows and the associated losses;

– *explicit optimization tools* with objective functions [ROB 12b, SAR 13]. This approach is necessary to ensure optimum choice, which guarantees the maximization, for example, of energy produced from a renewable source. The minimization of a well-formulated cost function is difficult to implement, particularly in real time;

– *implicit optimization tools* with, for example, fuzzy logic [CHE 00, LEC 03, LAG 09, COU 10, ZHA 10, MAR 11, MAR 12, ROB 13a, ROB 13b]. This type of tool is well adapted to the management of "complex" systems dependent on the values or states that are difficult to predict and are not well known in real time (wind, sunshine, frequency and states of grid, variation of consumption, etc.).

Different approaches can be considered and combined to ensure storage management: filters, correctors and artificial intelligence technologies.

A design methodology of supervisors dedicated to the management of hybrid energy production systems incorporating storage is developed in this book [ROB 13a, ROB 13b]. This method is an extension of methods widely used in the design of industrial process controls: Petri grids [ZUR 94, LU 10] and Grafcets [GUI 99]. The latter are used to build system controls graphically and step by step in such a way as to facilitate analysis and implementation. They are particularly well adapted to sequential logic systems. However, in the case of hybrid production units that include random variables and continuous states, this type of tool reaches its limits of use. The method proposed is therefore an extension of this graphic approach to include fuzzy values that are not precisely known.

This methodology does not require mathematical models, since it is based on a system assessment represented by fuzzy rules. Inputs can be random and supervision may target multiple objectives simultaneously. Transitions are progressive between operating modes, as they are determined by fuzzy variables. Finally, this methodology enables storage management via convergence toward a state of charge (SOC) and a limitation of complexity with a view to real-time processing.

It can be broken down into eight steps assisting in supervisor design:

– determination of system specifications: the objectives, constrains and means of action must be clearly laid out;

– development of the structure of the supervisor: the necessary supervisor inputs and outputs are determined;

– determination of operational modes by means of functional graphs: a graphic representation of the operating modes is developed based on the knowledge of the system;

– definition of the membership functions of fuzzy variables;

– determination of fuzzy modes by means of operational graphs;

– extraction of fuzzy rules, fuzzy supervisor characteristics and operational graphs;

– definition of indicators used to evaluate the achievement of objectives. These may be, for example, indicators of power, energy, voltage quality, yield or they may be of an economic or environmental nature;

– optimization of supervisor parameters by means of experimental designs and/or genetic algorithms, for example.

This methodology will be progressively developed in this book by considering various applications involving energy storage, based on one technology or a combination of technologies, with renewable wind-power sources and classic sources considered in Chapters 4–7. These examples are readily transferable to the case of photovoltaic sources.

## 1.5. Bibliography


[ALL 10] ALLÈGRE A.L., BOUSCAYROL A., DELARUE P. *et al.*, "Energy storage system with supercapacitor for an innovative subway", *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, pp. 4001–4012, December 2010.

[CHE 00] CHEDID R.B., KRAKI S.H., EL-CHAMALI C., "Adaptive fuzzy control for wind – diesel weak power systems", *IEEE Transactions on Energy Conversion*, vol. 15, no. 1, pp. 71–78, 2000.

[COU 10] COURTECUISSE V., SPROOTEN J., ROBYNS B. *et al.*, "Methodology to build fuzzy logic based supervision of hybrid renewable energy systems", *Mathematics and Computers in Simulation*, vol. 81, pp. 208–224, October 2010.

[DEL 09] DELILLE G., FRANÇOIS B., MALARANGE G., "Construction d'une offre de services du stockage pour les réseaux de distribution dans un contexte réglementaire dérégulé", *European Journal of Electrical Engineering*, vol. 12, nos. 5–6, pp. 733–762, 2009.

[DEL 12] DELILLE G., FRANÇOIS B., MALARANGE G., "Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system's inertia", *IEEE Transactions on Sustainable Energy*, vol. 3, no. 4, pp. 931–939, October, 2012.

[FAK 11] FAKHAM H., LU D., FRANÇOIS B., "Power control design of a battery charger in a hybrid active pv generator for load-following applications", *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 85–94, January 2011.

[GUI 99] GUILLEMAUD L., GUGUEN H., "Extending grafcet for the specification of control of hybrid systems", *IEEE International Conference on Systems, Man, and Cybernetics*, Tokyo, pp. 171–175, 1999.

[KAN 11] KANCHEV H., LU D., COLAS F. *et al.*, "Energy management and operational planning of a microgrid with a pv-based active generator for smart grid applications", *IEEE Transactions on Industrial Electronics*, vol. 58, no. 10, pp. 4583–4592, October 2011.

[LAG 09] LAGORSE J., SIMOES G.M., MIRAOUI A., "A multiagent fuzzy-logic-based energy management of hybrid systems", *IEEE Transactions on Industry Applications*, vol. 45, no. 6, pp. 2123–2129, November–December 2009.

[LEC 03] LECLERCQ L., ROBYNS B., GRAVE J.M., "Control based on fuzzy logic of a flywheel energy storage system associated with wind and diesel generators", *Mathematics and Computers in Simulation*, vol. 63, pp. 271–280, 2003.

[LU 10] LU D., FAKHAM H., ZHOU T. *et al.*, "Application of Petri nets for the energy management of a photovoltaic based power station including storage units", *Renewable energy*, vol. 35, no. 6, pp. 1117–1124, June 2010.

[MAR 11] MARTINEZ J.S., HISSEL D., PERA M.C. *et al.*, "Practical control structure and energy management of a testbed hybrid electric vehicle", *IEEE Transactions on Vehicular Technology*, vol. 60, no. 9, pp. 4139–4152, November 2011.

[MAR 12] MARTINEZ J.S., JOHN R.I., HISSEL D. *et al.*, "A survey-based type-2 fuzzy logic system for energy management in hybrid electrical vehicles", *Information Sciences*, vol. 190, pp. 192–207, 2012.

[MOU 08] MOUSLIM H., BABARIT A., *SEAREV: système électrique autonome de récupération de l'énergie des vagues*, Techniques de l'Ingénieur, 2008.

[NEH 11] NEHIR M.H., WANG C., STRUNZ K., "A review of hybrid renewable/alternative energy systems for electric power generation: configurations, control, and applications", *IEEE Transactions on Sustainable Energy*, vol. 2, no. 4, pp. 392–403, October 2011.

[ROB 12a] ROBOAM X., *Systemic Design Methodologies for Electrical Energy Systems*, ISTE, London and John Wiley & Sons, New York, 2012.

[ROB 12b] ROBOAM X., *Integrated Design by Optimization of Electrical Energy Systems*, ISTE, London and John Wiley & Sons, New York, 2012.

[ROB 12c] ROBYNS B., DAVIGNY A., BRUNO F. *et al.*, *Electric power generation from renewable sources*, ISTE, London and John Wiley & Sons, New York, 2012.

[ROB 13a] ROBYNS B., DAVIGNY A., SAUDEMONT C., "Methodologies for supervision of hybrid energy sources based on storage systems – a survey", *Mathematics and Computers in Simulation*, vol. 91, pp. 52–71, May 2013.

[ROB 13b] ROBYNS B., DAVIGNY A., SAUDEMONT C., "Energy management of storage systems based power sources and loads", *Electromotion Journal*, vol. 20, nos. 1–4, pp. 25–35, 2013.

[ROB 15] ROBYNS B., SAUDEMONT C., HISSEL D. *et al.*, *Energy Storage in Transportation and Buildings*, ISTE, London and John Wiley & Sons, New York, forthcoming, 2015.

[SAR 13] SARARI S., KEFSI L., MERDASSI A. *et al.*, "Supervision of plug-in electric vehicles connected to the electric distribution grids", *International Journal of Electrical Energy*, vol. 1, no. 4, pp. 256–263, December 2013.

[ZHA 10] ZHANG H., MOLLET F., SAUDEMONT C. *et al.*, "Experimental validation of energy storage system management strategies for a local DC distribution system of more electric aircraft", *IEEE Transactions on Industrial Electronics*, vol. 57, no. 12, pp. 3905–3916, December 2010.

[ZHO 11] ZHOU T., FRANÇOIS B., "Energy management and power control of an hybrid active wind generator for distributed power generation and grid integration", *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 95–104, January 2011.

[ZUR 94] ZURAWSKI R., ZHOU M., "Petri net and industrial application: a tutorial", *IEEE Transactions on Industrial Electronics*, vol. 41, no. 6, pp. 567–583, 1994.

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