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Issues in Electrical Energy Storage for Transport Systems

1.1. Storage requirements for transport systems

For the past century, the difficulty of storing electrical energy in large quantities, within reasonable volume and weight limits, has been a major obstacle in the development of autonomous electric vehicles that are able to travel medium to long distances. This difficulty has been overcome in the case of guided vehicles, trains, trams or underground trains, which capture electrical energy from an overhead line or a third rail during their movement. This solution has also been applied to buses designed to cover only a well-determined route. This result was represented by the trolleybus, which captures electrical energy from an overhead line which is required to be double when there is no possible current return by the rails. With these applications, a stationary electrical energy storage system incorporated into the supply system makes it possible to recover the braking energy of vehicles and to regulate the power demand from the electric power grids prior to the supply with electricity, or to cover particular areas without power supply.

Vehicles that do not complete regular journeys or travel long distances, such as cars, vans, lorries and motor coaches, cannot benefit from the acquisition of energy in motion. In this case, it is therefore necessary to load the electrical energy in sufficient quantities to reach the final destination. An electric car should have 200 to 300 kg of Li-ion batteries on board for approximately 200 km of autonomy. In contrast, a liquid hydrocarbon makes it possible to store approximately 12 kWh of thermal energy in 1 kg; with approximately 50 kg of fuel, tank included, a car with a thermal engine can reach 1,000 km of autonomy.

Other onboard systems produce their electricity on-site: aircraft, vessels and diesel-electric locomotives. The tendency to use the electricity vector more frequently in these systems, for traction and/or auxiliary attachments, generates a growing demand for storing electrical energy to reduce operational risks and also to save the energy generated during the braking phases of engines and actuators.

The hybridization of vehicles and onboard systems using electrical energy and liquid or gaseous fuel of fossil or non-fossil origin is in the course of development, due to the fact that this solution represents an essential intermediate step towards introducing vehicles without fossil fuel consumption. In the case of guided modes of transport, hybridization makes it possible to optimize the energy consumption of trains that complete journeys using electrified and non-electrified lines. Noise pollution may also be reduced by using electricity for shunting locomotives, for example in urban areas.

Space satellites and vehicles are onboard systems that capture electrical energy using solar panels when they are facing the sun, and store the electrical energy to satisfy their energy requirement during movement in shadow.

The significant development of the electricity vector within the framework of transport systems is a consequence of the flexibility of electricity, as well as of its potentially non-polluting nature while being used. However, if electricity is produced from fossil energy, for example in thermal power stations, pollution, including CO_2 emissions, is not emitted at the level of the vehicle, but upstream during the production of electricity. To accomplish the objective of reducing polluting emissions, it is necessary to produce electrical energy from non-polluting renewable energy (or potentially nuclear energy, which does not emit CO_2, but generates radioactive pollution throughout its lifecycle), but also to reduce the use of energy from non-renewable energy sources and the overall amount of pollutant discharge during the construction and deconstruction phases.

With the purpose of reducing CO_2 emissions, as well as the consumption of non-renewable sources (fossil or from nuclear power), and using electricity produced from renewable energy sources, projects have been developed to combine the production of renewable energy and the power supply of trains or electric vehicles. The intermittent nature of these types of energy may require the use of storage systems, knowing that in the case of electric vehicles, the latter already incorporate this storage function (electrochemical batteries).

Storage systems, which in the future will be widely incorporated into electric vehicles, meet the requirements of these applications, but also provide the possibility of contributing assistance among other actors of the electric system. Due to the increased costs of storage systems, this could represent a way to enhance their financial value, including the obligation to control the aging of these systems. Studies have also been conducted to research the possibility of whether the storage capacity of electric vehicles, owing to the flexibility of their charge or discharge, can provide assistance to the electric power grid, or even directly to the buildings connected to the grid; reference is, thus, made to vehicle-to-grid or vehicle-to-home.

1.2. Difficulties of storing electrical energy

A weak point of the electricity vector is that the electrical energy cannot be stored directly and that conversion interfaces are required. It is possible to store electrostatic energy (in capacitors) or magnetic energy (in superconductive coils); however, the storage capacities of these solutions are very limited. To obtain substantial storage capacity, electrical energy must be transformed into another form of energy. Electrochemical storage by means of lead batteries has long been used for onboard applications, as they provide improved mass performance and emergency power supplies. Storage in the form 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 as a direct current voltage source. Inertial energy storage is based on electrical machines that are required to operate at variable speeds, namely variable frequency. With electric power grids supplying electricity in the form of alternating voltage and currents, the implementation of these storage technologies remained complicated until the advent of electronic power, which has been developed since the 1960s and is currently used to transform the form and characteristics of currents and voltages at will. A significant barrier has thus been overcome, allowing for a more extensive use of electrical energy storage today.

Ragone diagrams, which show power and specific energy, are often used in the field of onboard applications to compare technologies and illustrate their energy/power compromise [ROB 15]. Figure 1.1 shows a simplified example comparing several electrochemical technologies and supercapacitors [MUL 13].

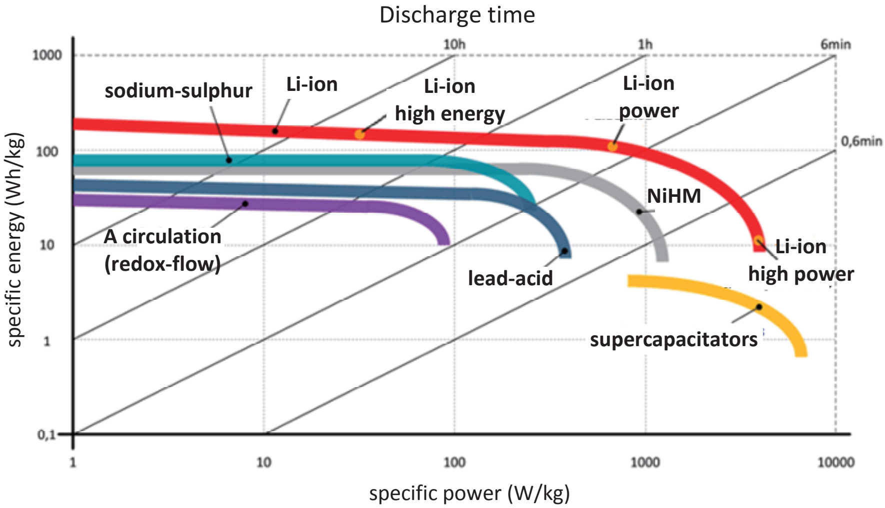

Figure 1.1. *Example of a Ragone diagram for electrochemical technologies and supercapacitors [MUL 13]*

The development of Li-ion technology in the last two decades represents a significant progress for onboard systems, that provides vehicles with a level of autonomy compatible with an increasing number of applications. Figure 1.2 shows the evolution of the energy density of lead, nickel-cadmium, nickel-metal-hydride and lithium-ion batteries over the past 40 years.

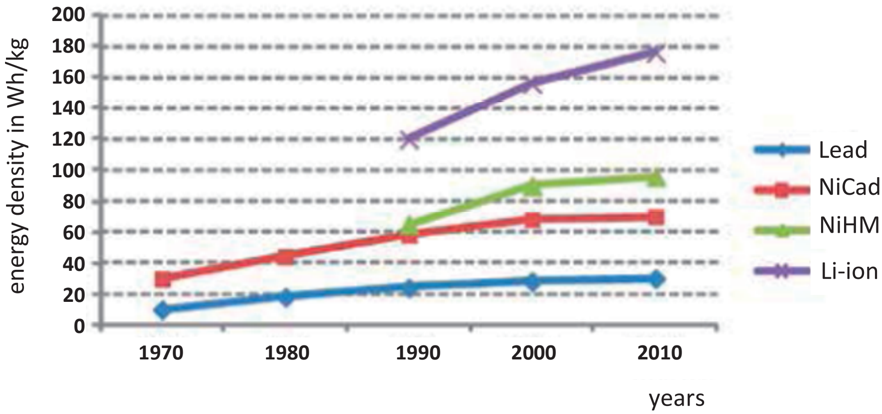

Figure 1.2. *Evolution of the energy density of lead (Lead), nickel-cadmium (NiCad), nickel-metal-hydride (NiMH) and lithium-ion (Li-ion) batteries [BAS 13]*

Lifetime remains a significant technological limitation in terms of lifecycle cost of these types of batteries. This is conditioned by the temperature of the battery, which should not be too high nor too low, the frequency of the charging/discharging cycles and the depth of discharge. Manufacturers estimate between 1,000 and 15,000 lifetime cycles for a maximum depth of discharge to be taken into account, and an operating temperature range. When considering a daily charging/discharging cycle, lifetime is estimated to be between 3 and 15 years. By reducing the depth of discharge, lifetime can be increased significantly. Some electric vehicle manufacturers propose to decrease the risk of premature failure for the operator by introducing rental of the vehicle battery pack.

The use of supercapacitors also contributes to the development of electrification in the case of onboard systems. Their energy capacity is clearly lower than that of batteries; on the contrary, they provide higher dynamics and a number of charging/discharging cycles for their lifecycle, which is 10 to 100 times higher, in the range of 10,000 to 100,000. Combining storage systems with supercapacitors and Li-ion batteries may thus be regarded as an interesting solution to obtain a global dynamic storage system with significant energy capacity, while ensuring satisfactory lifetime for various components. With such systems, supercapacitors generate rapid energy fluctuations, while batteries meet basic energy requirements gradually. For example, this type of solution is considered for trams and electric buses which can only be charged at station stopping times [URI 13].

The hydrogen vector is also considered to meet the requirements of onboard systems, particularly for motor vehicles, because this has a higher energy density than batteries (taking account of the tank and storage means). It makes it possible to generate electricity using a fuel cell, and it can be produced using electricity from an electrolyzer. The yield of the charging/discharging cycle is, however, relatively low, i.e. below 40%.

1.3. The electrical power supply of transport systems

The electrical energy used by transport systems can be produced locally or supplied by the electric power distribution grid. This solution does not apply to vessels and aircraft which require a different onboard source of energy, currently primarily of fossil or nuclear origin for some military vessels. The same applies to diesel-electric locomotives. Road vehicles are charged using a distribution grid. Guided electric modes of transport such as trams, underground trains or trolleybuses are also supplied by the grid.

In a scenario involving 2 million electric vehicles by 2025 and 5 million by 2030 in France, the grid consumption of electrical energy is forecast to increase significantly, for example if the vehicles are charged by their owners in the evening. This is illustrated by the dotted curve in Figure 1.3, as compared to the solid curve corresponding to the situation without electric vehicles. The dashed curve illustrates an intelligent management of an overnight charge of these vehicles, making it possible to regulate the power demand from the grids. Other charging strategies at other times of the day can, also be considered, for example the use of solar energy for charging purposes at work or at home.

Figure 1.4 illustrates the power demand profile of a power supply substation by urban trains over the course of one week. Subsequent power transmissions occur during morning and evening peak hours throughout the week.

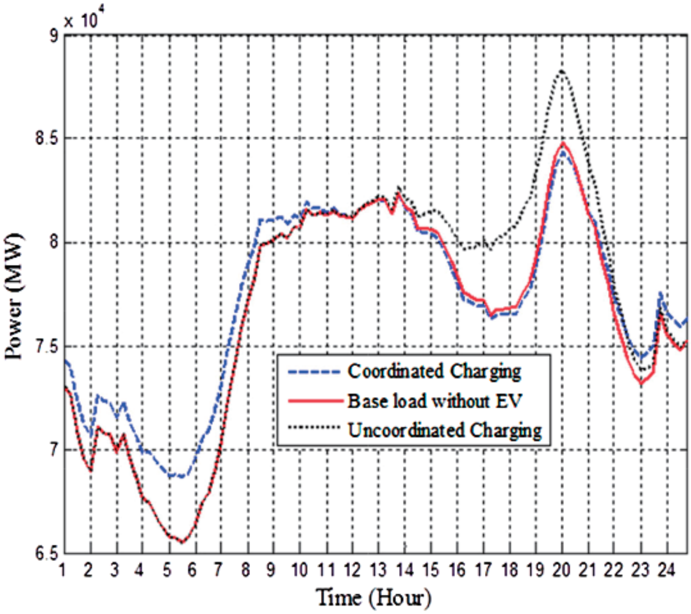

Figure 1.3. *Consumption profiles with or without electric vehicles over the course of one day for the French power system as a whole [SAR 13]*

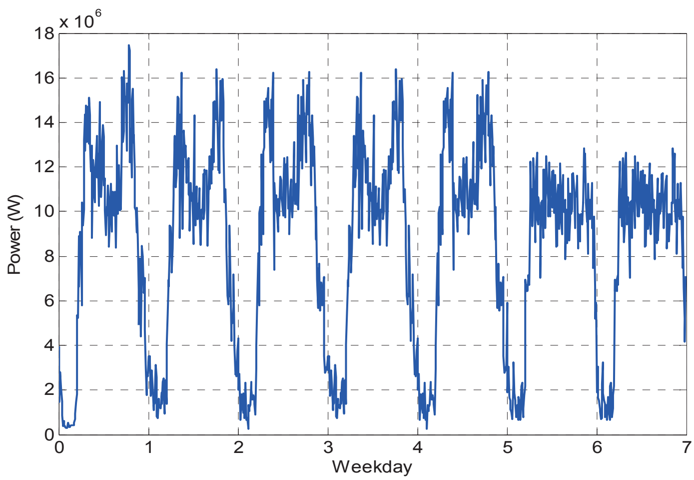

Figure 1.4. *Profile of power demand transmitted to a power supply substation by urban trains over the course of one week [PAN 13]*

These examples illustrate the variation of the power demand to the grid by different types of charge and the desire to regulate these variations, which is made possible by the storage capacities of these charges or the incorporated storage systems. The combination of fluctuating energies that are difficult to predict locally also justifies the use of storage systems. These storage capacities can also be enhanced by contributing complementary services to distribution or transport power grids, thus increasing their economic profitability [ROB 15].

The onboard systems of different modes of transport (rail, naval, air, aerospace, road vehicle, robot etc.) incorporate electrical storage systems to supply auxiliaries and local power grids and to ensure the recovery of braking energy and vehicle propulsion. Figure 1.5 illustrates the power transmitted to and generated in a local grid on board an aircraft supplying, for example, the flying controls.

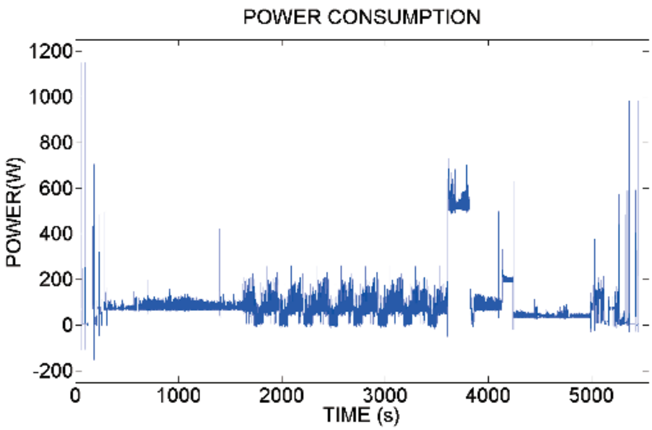

Figure 1.5. *Power transmitted to and generated in a local grid on board an aircraft supplying, for example, the flying controls at the wing level [SWI 12]*

1.4. Storage management

Various time horizons can be identified during the development of a management strategy for an energy storage system (Figure 1.6):

– long-term supervision which corresponds to a time scale of one day;

– medium-term supervision which corresponds to a time scale of approximately half an hour to one hour;

– real-time supervision which corresponds to the lowest time scale to be implemented to guarantee the proper functioning of the system so as to ensure its stability, achievement of objectives, consideration of hazards, etc. This time scale may range from a few microseconds to a few minutes.

Storage planning over a longer period of time (several days, weeks, months or years) may also be required for an efficient storage management and its economic profitability.

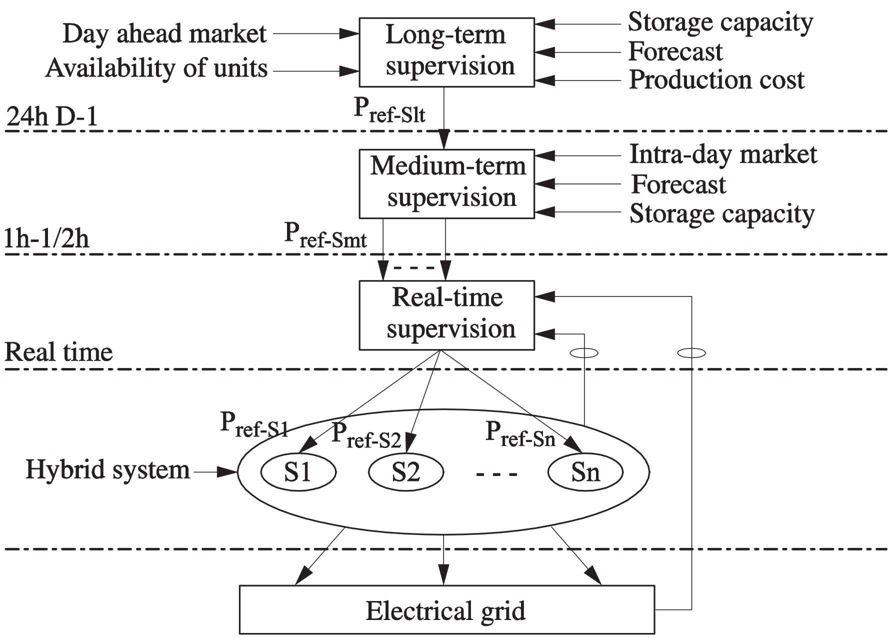

Figure 1.6. *Different time horizons to be considered for the management of a storage system*

The storage management of electrical energy is a major challenge owing to the complexity of the issues to be addressed, the variety of economic and environmental objectives, and the fact that there is more than one way to achieve these objectives [NER 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 designed to ensure the optimum choice which guarantees the maximization, for example, of energy produced from a renewable source. The minimization of a well-formulated cost function is, however, 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, LEG 15]. 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 not sufficiently 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 systems incorporating storage functions is developed in this book [ROB 13a, ROB 13b]. This method is an extension of the 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 so 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 tools reaches its usage limits. The method proposed is, therefore, an extension of this graphic approach so as to include fuzzy values that are not precisely known.

This methodology does not require mathematical models as it is based on a system assessment based on 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 towards a state of charge and a limitation of complexity with a view to real-time processing.

It is divided into eight steps for assisting in supervisor design. These steps are described in the following sections.

1.4.1. *Specifications*

The determination of system specifications clearly includes objectives, constraints and means of action, namely:

– the objectives of energy management, potentially with the implementation of one or several time horizons;

– the constraints of the system;

– the means of action, in particular devices that can be operated to achieve the objectives.

1.4.2. *Supervisor structure*

The input and output variables of the supervision module are deduced from the corresponding specifications of the system being considered. The input variables are selected to include the objectives and constraints of the system, while the output variables correspond to the means of action considered (Figure 1.7).

Figure 1.7. *Supervisor structure [BOU 15]*

1.4.3. *Functional graphs*

To facilitate the extraction of the fuzzy supervisor rules adapted to control a system, the supervision strategy can be defined graphically. The advantage consists of determining the linguistic rules of each operating mode, which makes it possible to restrict the complexity of the supervisor by determining the minimum number of significant rules for the analyzed problem. Graphs are, therefore, used to represent the transitions between the modes determined by the state of a certain number of system variables. If these states are described by fuzzy variables, the system can operate in several modes simultaneously, which facilitates smooth transitions between different modes. An example of a functional graph is represented in Figure 1.8. This graph includes:

– solid rounded rectangles to represent the operating modes;

– transitions between these modes to represent the states of the system.

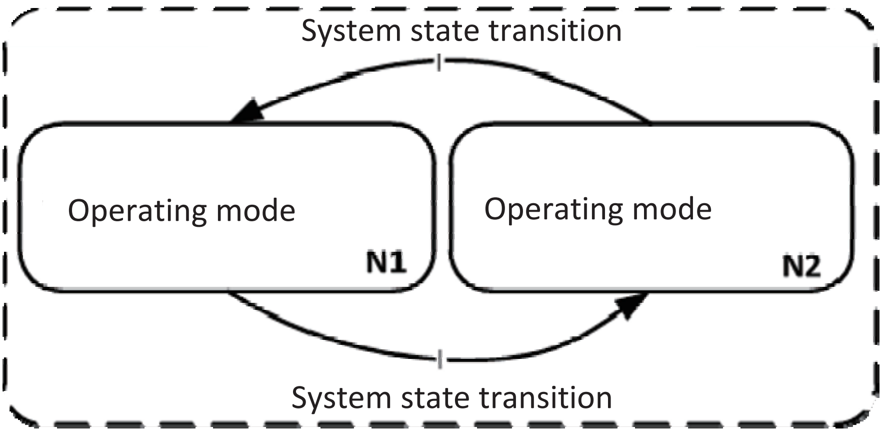

Figure 1.8. *Functional graph representing the operating modes [BUZ 15]*

1.4.4. *Membership functions*

The following step of the methodology consists of determining the membership functions that correspond to the input and output variables of the fuzzy supervisor. For a better understanding of this step, reference is made to certain notions related to fuzzy logic [ROB 15].

As opposed to the Boolean set defined by a characteristic function designated with the discrete values 0 and 1, the fuzzy set is defined by a membership function that can have values in the interval of [0,1]. In Figure 1.9, the set of values of the storage system state of charge (SOC) represents the universe of discourse of the "SOC" variable. "Small" is, therefore, a linguistic value of this variable. A state of charge of 15% is, therefore, considered to be "Small" with a degree of membership equal to 0.5; it can also be "Medium" with a degree of membership of 0.5. Finally, the third fuzzy set which is representative for the state of charge is the "Big" set. The type of set is generally defined so as to ensure that the sum of the degrees of membership is always equal to one.

Boolean logic constitutes a particular, more general, type of fuzzy logic. In Boolean logic, the "Small", "Medium" and "Big" sets shown in Figure 1.9 have a rectangular shape without any intersection between these sets. All the steps of the methodology presented in this chapter can also be applied in the case of Boolean logic.

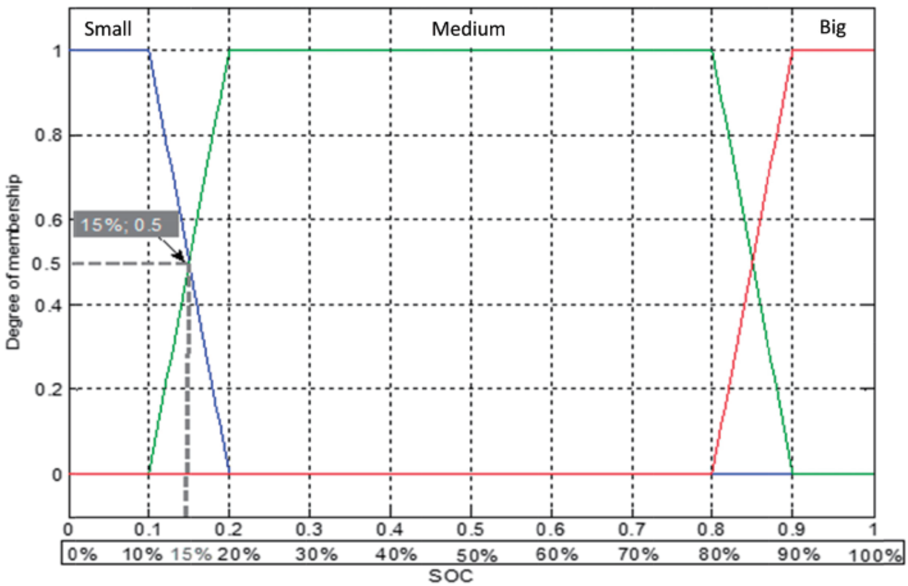

Figure 1.9. *Membership functions of a fuzzy function (SOC = storage state of charge) [BUZ 15]*

The following terms are used to define the steps of fuzzy reasoning [ROB 15]:

– *fuzzification*, which enables the transition from the real domain to the fuzzy domain (the degree of membership is, thus, determined by a value of a fuzzy set);

– *inference*, which is the logical operation by which we accept a proposition by virtue of its connection to other accepted propositions. In the first phase, this mechanism utilizes logical operators (e.g. min) to determine the degree of activation of each rule and the conclusion; then the fuzzy set of output variables is obtained by means of aggregation of the previously determined findings (by applying the max operator);

– *defuzzification* consists of converting the resulting fuzzy set obtained during the interference phase into a real value. The center of gravity method is one of the most widely used methods to ensure this conversion [ROB 15].

These steps can be preceded by a phase of formatting the input variables by means of normalization, followed by a phase of setting the output values to full scale by means of denormalization. During the operation of normalization, the values lose their physical unit and are expressed in per units (p.u.).

Due to the fact that the number of fuzzy rules is directly dependent on the membership functions, it is important to keep the number of fuzzy sets to a minimum.

1.4.5. *Functional graphs*

To extract fuzzy rules naturally for the purpose of energy supervision, the following step involves the translation of "functional graphs" by means of a graphic representation of the fuzzy operating modes, referred to as "operational graphs". The transitions between the operating modes are described, starting with the membership functions of the previously defined input variables and the activation of the operating modes by the fuzzy sets of the output variables. In Figure 1.10, the principle of the operational graph is illustrated using the example of the storage state of charge. In this case, the output variable is the storage reference power $P_{stock\_ref\_ct}$. The fuzzy sets of this variable are, for example, Negative Big (NB) and Positive Big (PB).

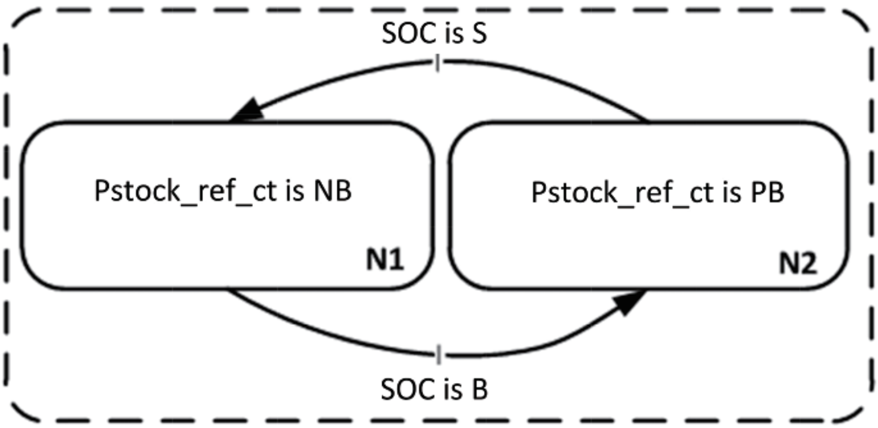

Figure 1.10. *Membership functions of a fuzzy function (SOC = storage state of charge, S = Small, B= Big) [BUZ 15]*

1.4.6. *Rules*

Once the diagram of all operating modes has been established, the associated fuzzy rules can be easily established. For example, in Figure 1.10, the corresponding fuzzy rules can always be formulated as follows:

– if SOC is Small (other possible conditions), then $P_{stock\_ref\_ct}$ is Negative Big;

– if SOC is Big (other possible conditions), then $P_{stock\_ref\_ct}$ is Positive Big.

1.4.7. *Indicators*

Performance evaluation, namely the achievement of the objectives of the energy management strategy, requires that all performance indicators be defined. These may be, for example, indicators of power, energy, voltage quality, efficiency or they may be of an economic or environmental nature, etc. At least one indicator must correspond to each objective. An objective may be evaluated using several complementary indicators.

1.4.8. *Optimization of supervisor parameters*

As the first step, the parameter set of the supervision system (membership functions, gains, etc.) can be determined empirically depending upon the developer's expertise. The selection of the characteristic points of membership functions may be a complex task. Figure 1.11 illustrates this principle by showing a set of shapes that could be assumed by the membership functions in the universe of discourse. The characteristic parameters of these membership functions may also be determined by means of an optimization tool and the indicators defined previously.

Genetic algorithms are well adapted to adjust the parameters of the fuzzy systems. The purpose of this optimization is to minimize/maximize an objective function that is not different from the predefined performance indicator. It should be noted that this optimization phase is carried out "offline" based on the charging or production profiles, for example, by interfering with the system input. On the basis of the obtained result, the supervisor is then used in other case studies for management in real time to test its robustness. The implementation of the experimental design method prior to the optimization phase makes it possible to identify the influential system parameters and to limit the number of parameters to be optimized.

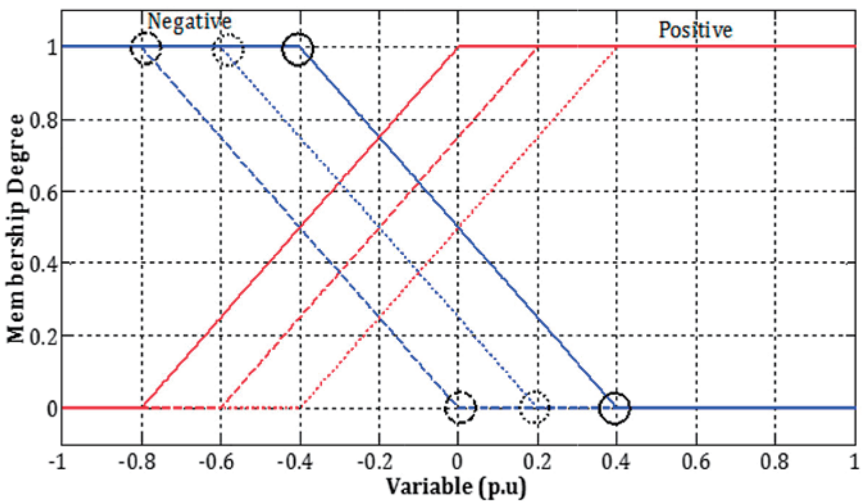

Figure 1.11. *Examples of shapes of membership functions for the same variable [BOU 15]*

1.4.9. *Type-2 fuzzy logic*

An extension of the fuzzy set, referred to as type-2 fuzzy logic, makes it possible to take into account the uncertainty generated by an empirical determination of the membership functions. This is achieved by considering not only one membership function, but a set of membership functions for a fuzzy subset (or linguistic variable), as illustrated in Figure 1.12 [MAR 12].

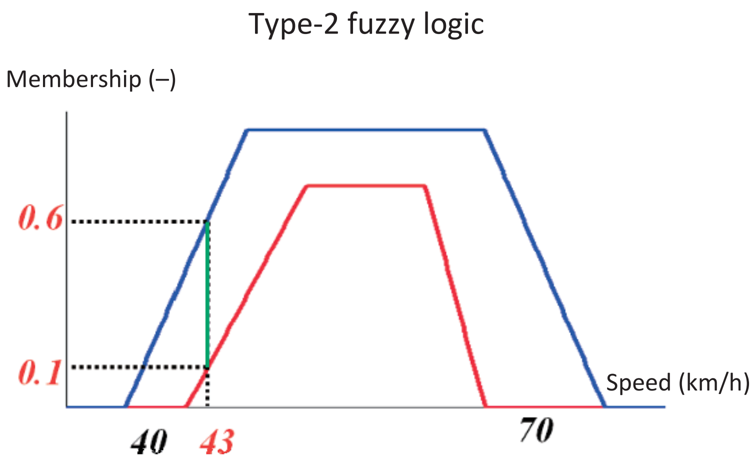

Figure 1.12. *Examples of membership functions in a type-2 fuzzy logic [MAR 12]*

1.4.10. *Methodologies for the development of energy management in a storage system*

Several methodologies for developing the management of a storage system are gradually implemented in this book, based on a technology or a combination of storage technologies associated with different transport systems (air, road and rail vehicles and infrastructures). Table 1.1 summarizes the different types of methods for designing an energy management system, as illustrated throughout this book.

Chapter – subject	*Methodologies and tools for the development of energy management*
2. Onboard aircraft grids	Fuzzy logic with optimization by means of experimental design and genetic algorithm
3.3. Integration of electric vehicles into the electric power grid	Fuzzy logic with optimization by means of genetic algorithm
3.7. Hybrid vehicles	Type-2 fuzzy logic
4. Hybrid locomotives	Digital filtering and explicit optimization
5. Hybrid railway power substations	Fuzzy logic with optimization by means of experimental design and genetic algorithm

Table 1.1. *Different methods for designing an energy management system, as illustrated throughout this book*