Management and evaluation of the advanced adiabatic CAES integrated in the power system considering the contribution to system service

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ABSTRACT. *This paper[1] proposes a methodology of real-time supervision which allows maximizing ancillary services and contributing to the profitability of the Advanced Adiabatic Compressed Air Energy Storage (CAES). A real-time multi-objectives supervisor based on fuzzy logic is developed in order to maximize the economic gain of the storage, taking into account the buy/sell action and ancillary services (imperative and additional) of the storage, such as frequency control, congestion management and covering renewable energy production. The proposed supervisor is tested on the IEEE 14 bus test system. The results of the simulation show a significant economic gain of the storage when participating in ancillary services and in others additional services which need a real-time management.*

RÉSUMÉ. *Cet article propose une méthodologie de supervision temps réel permettant de maximiser les services rendus et de contribuer à la rentabilité d’un stockage CAES adiabatique. Un superviseur temps réel multi-objectifs basé sur la logique floue est développé pour maximiser le gain économique du stockage en prenant en compte l’action achat/vente et les services (obligatoires et supplémentaires) du stockage comme le réglage de fréquence, la gestion des congestions et la garantie de la production renouvelable. Le superviseur proposé est testé sur un réseau de test IEEE 14 nœuds. Les résultats de simulation montrent un gain économique du stockage significativement plus intéressant s’il participe aux services système et à des services supplémentaires nécessitant une gestion temps réel.*

KEYWORDS: *adiabatic compressed Air energy storage, ancillary services, transmission network, energy supervision.*

MOTS-CLÉS : *stockage CAES adiabatique, services système, réseau de transport, supervision énergétique.*

DOI:10.3166/EJEE.18.215-241

1. Article accepté dans le cadre du dossier SGE 2014 (*EJEE*, vol. 17, n° 5-6)

1. Introduction

The technique of electric power storage under compressed air in underground cavern in France nowadays is considered as one of the few credible alternatives, in the range of several hundred MW, together with pumped-storage hydroelectricity installed in mountainous areas, which has almost been exploited (Geth *et al*., 2015). However, this technique requires a large investment while the energy efficiency is under 50% Zhao *et al.*, 2016; Chen *et al*., 2016)

The objective of this study, integrated in the ANR SACRE project (Stockage par Air Comprimé pour le Réseau Electrique), is to analyse the economic valuation and the benefit of these storage devices to the power system (Calaminus, 2007; Jakiel *et al*., 2007; Liu et Wang, 2016). Figure 1 illustrates the principal of this type of storage. A thermal storage stage is added in order to recover the thermal energy liberated at the air compression; this energy is being reused to heat the air at the entrance of the turbine. The energy efficiency is then increased up to 65%.

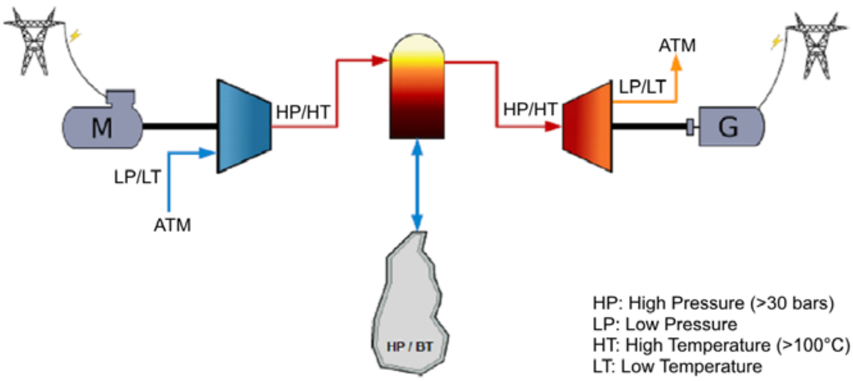

Figure 1. Adiabatic Compressed Air Energy Storage (Source: EDF)

The existing storage technologies are at the limit of profitability in the current electrical system, which takes into account only traditional valuations related to supply and demand. The maximization of ancillary services and the profitability will be obtained only through the optimal localization and sizing of the storage system in the power system and with the help of an optimal temporal management (Vergnol and Robyns, 2011; Robyns *et al.*, 2013a). This supervision is available on different time scales: long term (the day before for the next day), medium term (1 hour or 30 minutes in advance) and short term (real time).

This study focuses on the development of a supervision strategy in real-time in order to maximize ancillary services and the profitability of the storage, based on a pre-sizing and a pre-location. A construction method of the supervisor based on fuzzy logic is implemented (Sprooten *et al.*, 2009; Courtecuisse *et al*., 2010; Robyns *et al.*, 2013b). The IEEE 14 bus test system is chosen as an example to illustrate the application of the method. Three variants of the supervisor are compared: a supervisor limited to the traditional valuation based on supply and demand planned at the day ahead, the proposed real-time supervisor based on fuzzy logic and a Boolean variant of this supervisor. The results of the simulation show a significant economic gain of the storage when participating in ancillary services and in others additional services which need a real-time management.

2. Services provided by the storage

2.1. Planning of the storage

An initial valuation of the storage will be performed based on the electricity market with the buy/sell mechanism for the day ahead.

In order to increase the economic valuation of the storage, many additional services can be offered to players in the electrical system. In this study, only imperative services and additional services that have an important economic benefit are considered: the frequency control service, the congestion management service and the support service for renewable energy.

2.2. Frequency control

The frequency control consists of 3 levels: primary control, secondary control and tertiary control, but only the first two levels are imperative (Robyns *et al.*, 2012).

In case of the primary control, if the output power of the production unit is greater than 40 MW, it must be able to maintain a minimum reserve capacity of 2.5% of the installed power.

In addition, the total liberation of this reserve must be done in less than 30s and this service must be maintained for at least 15 minutes when the frequency variation is between 49.8 and 50.2 Hz. This control is accomplished by means of a straight droop between the power and the frequency (Robyns *et al.*, 2012).

Regarding the secondary control of the frequency, this service is required for the installation with a rate power higher than 120MW and the reserve must be at least 4.5% of the rated power. The deployment of the service must start within 30s after the incident and finish before 7 minutes, and in case of significant variation in frequency this service must be maintained as long as necessary.

2.3. Congestion management

The congestion management consists of relieving the transmission line overloaded by the power flow. Storage devices, due to their reversibility, are interesting tools for resolving congestions.

The treatment of long-term congestion implies that the TSO (Transmission System Operator) reinforces the network by building additional power lines. However, the construction cost is very high and may take up to ten years or more, in this context the establishment of a storage by the TSO may postpone costly investments and accelerate the strengthening of the network (Vergnol *et al*., 2009; Vergnol *et al*., 2011).

2.4. Covering renewable energy

A strong insertion of renewable generation in the power system may cause rapid reversals of power flows due to the random nature of the primary source. This phenomenon appears already at the interconnection lines between Germany and its neighboring countries, due to the high concentration of wind power in northern Germany (Ackermann, 2005).

The error in wind power forecasting at a regional scale ranges from 3% for a forecast at 1-hour-scale and 7% at 72-hour-scale which is entirely satisfying for the control of the supply/demand balance. However, this error is about 15% for a single wind farm with a significant disparity in terms of the local topography (Ackermann, 2005).

Currently, additional reserves to overcome these uncertainties are supported by conventional groups. But due to the fast development of unpredictable sources, the manager of random renewable power plants will have to respect a profile of daily power production defined at the day ahead, like conventional power plants.

The storage could then provide to this producer a service of covering their production, the principle is that the storage should ensure the production of the missing power and store the power produced in excess compare to the forecast. Renewable producers can then avoid penalties. This economic benefit could be shared with the owner of the storage system through a service fee, which remains lower than the cost of penalties.

3. Supervision strategy

3.1. Methodology

The integration of decentralized sources and loads in the future smart grid requires the development of energy storage valuation by a pooling of services, and a multi-objectives supervision adapted to the integration of multi-source and multi-load systems. A challenge for the development of such supervision strategies is the random behavior of the systems whose time horizons could be very short (dynamic loading) or very long (seasonal characteristic of renewable sources). Conventional optimization methods (or explicit) are difficult to implement in real time, and are not easily exploitable when the time horizon of study must extend over a year and when it is necessary to consider systems whose state depends on the time, such as the storage.

However, implicit methods with artificial intelligence tools such as fuzzy logic are well adapted to the management of "complex" systems dependent on variables or states that are difficult to predict such as wind, solar, network status, consumption… A methodology for construction of supervisors based on fuzzy logic for the management of hybrid systems of energy production is proposed in (Sprooten *et al*., 2009; Courtecuisse *et al.,* 2010; Robyns *et al*., 2013b). This methodology does not require mathematical models, because it is based on the expertise of the system represented by fuzzy rules. Inputs could be random and the supervision may have several objectives simultaneously. Transitions are progressive between modes of operation, as they are determined by fuzzy variables. Finally, this methodology allows a management of the storage by convergence to a charge level and a mastering of the complexity for the real-time processing.

The construction of the fuzzy supervisor is developed based on the methodology presented in (Sprooten *et al.*, 2009), (Courtecuisse *et al.*, 2010; Robyns *et al*., 2013b), and is organized in eight steps:

– Determination of system specifications; objectives, constraints and means of action are identified.

– Structure of the supervisor; the inputs and the required outputs of the supervisor are determined.

– Determination of “functional graphs”; a graphical representation of operating modes is provided. This representation is based on the knowledge of the system.

– Determination of membership functions of the fuzzy supervisor.

– Determination of “operational graphs”; a graphical representation of fuzzy operation modes is proposed.

– Extraction of fuzzy rules, characteristics of fuzzy supervisor, “operational graphs”.

– Determination of indicators to assess the achievement of objectives.

– Optimization of parameters of the fuzzy supervisor by the design of experiments and genetic algorithm, for example.

This study implements the development methodology of fuzzy supervisors which is proposed in these previous works. However, the context of application is different.

While the previous works focus on the hybrid renewable energy systems (may be with the presence of storage but attached to a renewable source (Robyns *et al.*, 2013b; Foley *et al.*, 2015)), this study considers the case that the storage system is connected independently to the power system. Therefore, the objectives of the multi-objectives fuzzy supervisor are totally different compare to previous works.

3.2. Objectives, constraints and means of action

The structure of the supervisor will be organized to achieve the three main objectives defined in the Table 1. The constraints of supervision are also presented.

The long-term supervisor is supposed to have defined at the day ahead a power planning for the storage, taking into account the electricity market and the network planning. The objectives of the multi-objectives fuzzy supervisor could be classified into three groups: economic objective, imperative services and additional services.

Table 1. Objectives, constraints and means of action

Objectives	Constraints	Means of action
– Maximizing the economic benefit while respecting the planning curve – Ensure the primary frequency control – Provide additional services to the system – Ensure the availability of storage	– The limitation of the storage – The capacity of transmission line – The fluctuation of wind power	– The power control instruction of the storage

3.3. Structure of the supervisor

Each objective corresponds with an input of supervisor. The structure of the supervisor is shown in Figure 2. Four inputs are identified:

– To ensure the availability of storage for the frequency control and other services, the state of charge of the storage should be considered an input (SoC).

– The second input is the instruction of non-imperative or additional services $P_{service}$, which is the sum of the service of congestion management $P_{congestion}$ (Vergnol *et al.*, 2009; 2011) and the service of covering renewable generation $P_{covering}$.

– The third input of the supervisor will be the planning power of the storage P_{plan}. The storage planning is made a day before the considered day, based on the price curve and network needs.

– The frequency control requires a direct action on storage due to the dynamic and the imperative of the service. Therefore, it is injected directly on the instruction at the output of the fuzzy supervisor to generate the final instruction: $P_{instruction}$.

In Figure 2, K1, K2, K3 and K4 are adaptive coefficients in per unit of input and output variables.

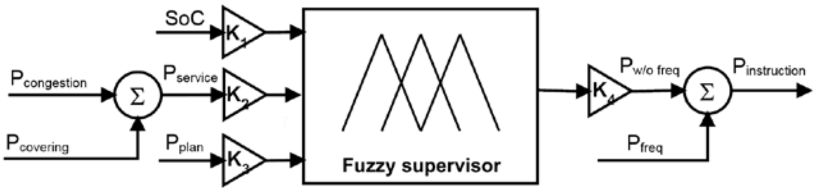

Figure 2. Inputs and output of the real-time supervisor

3.4. Determination of functional graphs

The operating modes are shown in Figure 3 by rounded rectangles and the system states by the transitions between these modes.

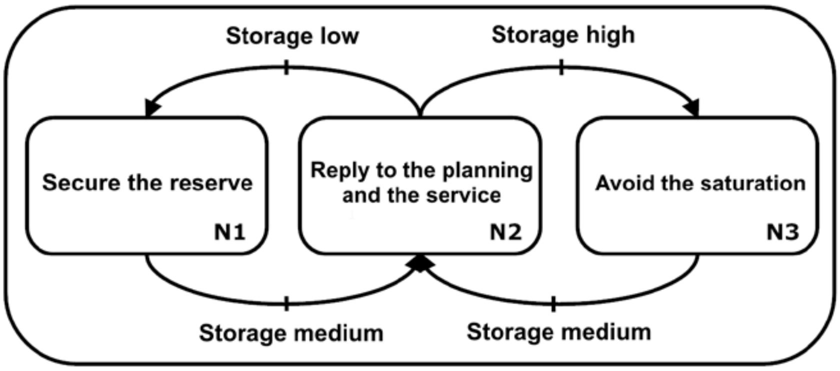

Figure 3. Functional graph of the fuzzy logic based supervisor

Based on the level of the storage, the operation of the storage system can be divided into three operating modes. Transitions from one mode to another are defined by the state of the storage system. A negative power instruction corresponds to a charge storage, and conversely, a positive instruction corresponds to a discharge of the storage.

N1 (Figure 4): if the level of the storage system is low, the storage cannot discharge in order to preserve energy required for the frequency control. If the storage is requested to charge, the process of charge will be accelerated.

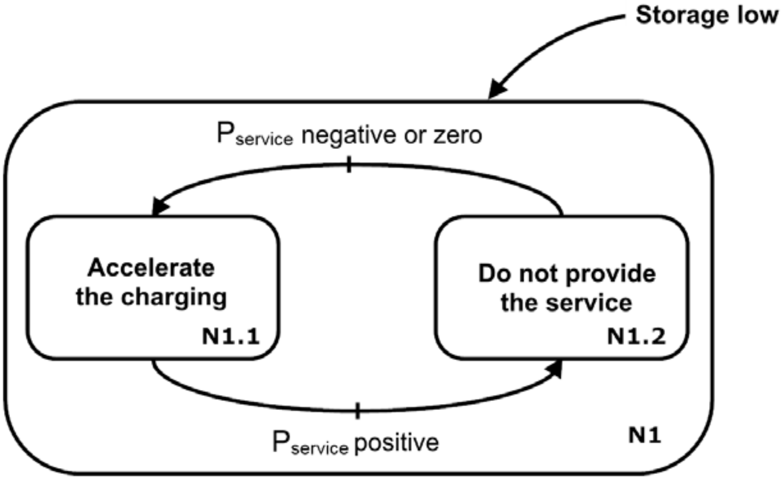

Figure 4. Functional graph of mode N1

N2 (Figure 5): if the level of the storage system is medium, it could follow the instruction of additional services. If no instruction is given, the storage will respect the planning made at the day ahead to maximize the economic gain.

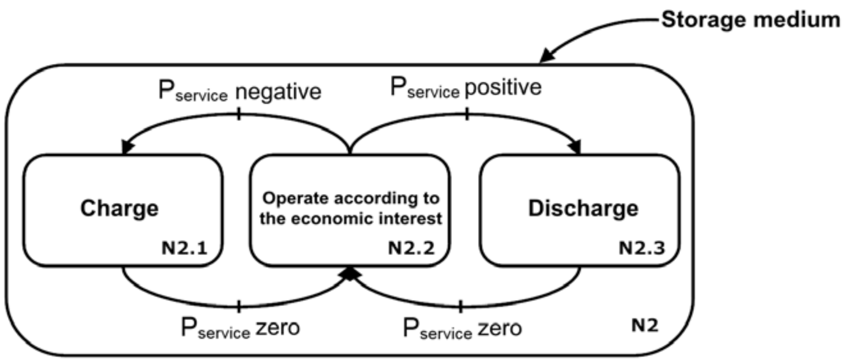

Figure 5. Functional graph of mode N2

N3 (Figure 6): if the level of the storage system is high, the storage cannot be charged to avoid the saturation. If the storage is requested to discharge, the process of discharge will be accelerated.

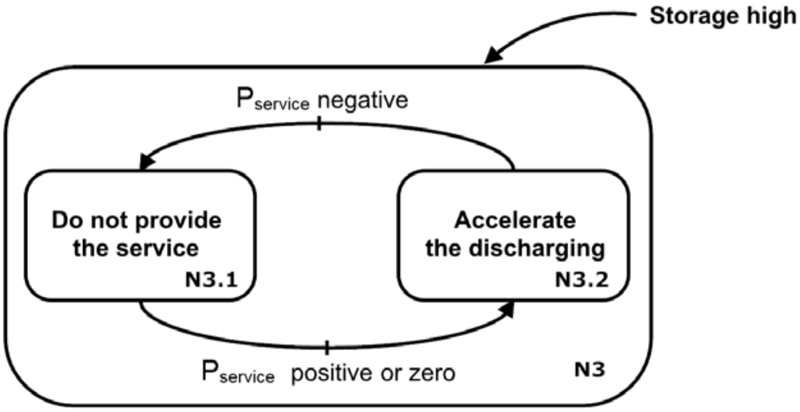

Figure 6. Functional graph of mode N3

For the mode N1.2 and N3.1, a fuzzy law could be established directly for each block. They are independent of the last entry: the planning curve. For the rest, the more detailed functional graphs must be presented.

N1.1 (Figure 7): the storage is low and the power required by the services is negative or zero. To promote the charging of the storage, the supervisor gives an instruction to charge at maximum rate whenever the planning curve of the storage is less than or equal to zero. Alternatively, when the planning output power is greater than zero, the instruction seeks to satisfy the power demanded by the services.

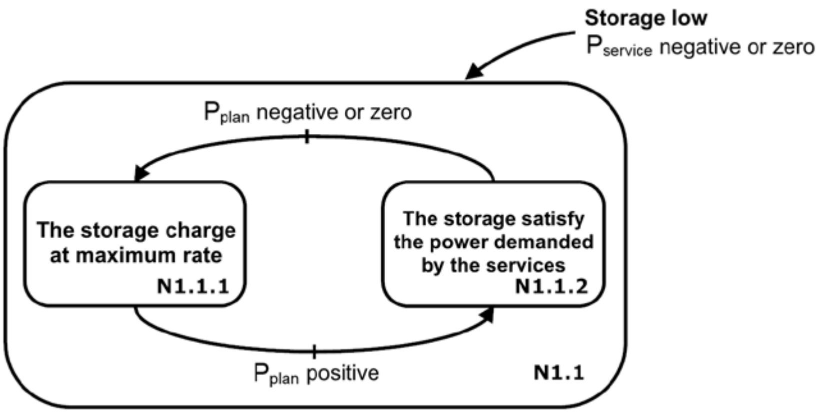

Figure 7. Functional graph of mode N1.1

N2.1 (Figure 8): the level of the storage is medium and the power required by the services is negative. In this mode, the supervisor gives the instruction to charge at maximum rate whenever the planning curve of the storage is negative. Otherwise, it gives an instruction to reply the demand for services.

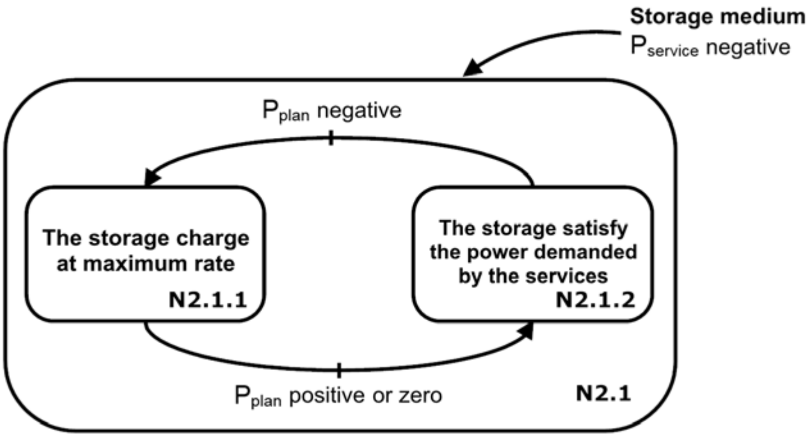

Figure 8. Functional graph of mode N2.1

N2.2 (Figure 9): the storage is medium and the power required by the services is zero. In this mode, the supervisor gives an instruction following the economic interest, determined by the planning curve: if the planning power is negative, storage charges at maximum rate, if the planning power is positive, storage discharges at maximum rate, otherwise, if the planning power is zero, the storage will be put in standby mode.

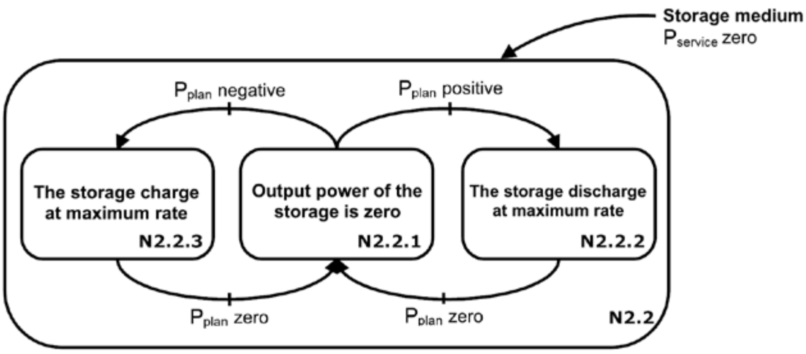

Figure 9. Functional graph of mode N2.2

N2.3 (Figure 10): the storage is medium and the power required by the services is positive. In this mode, the supervisor gives an instruction to discharge at maximum rate whenever the planning power is positive. Otherwise, it gives an instruction to reply the demand for services.

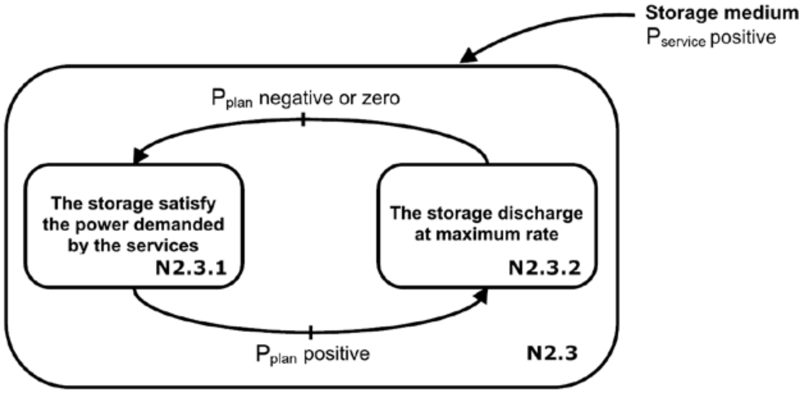

Figure 10. Functional graph of mode N2.3

N3.2 (Figure 11): the storage is high and the power required by the services is positive or zero. To promote the discharge of the storage, the supervisor gives an instruction to discharge the storage at maximum rate whenever the planning power is higher than or equal to zero. Alternatively, when the planning power is negative, the supervisor seeks to satisfy the power demanded by the services.

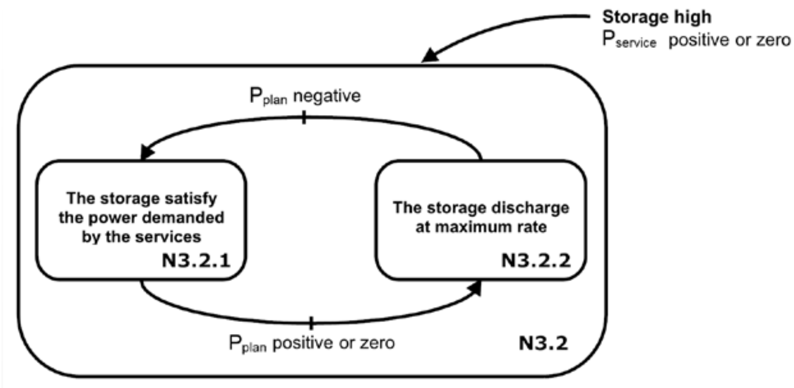

Figure 11. Functional graph of mode N3.2

The set of all operating modes is shown in the functional graph in Figure 12.

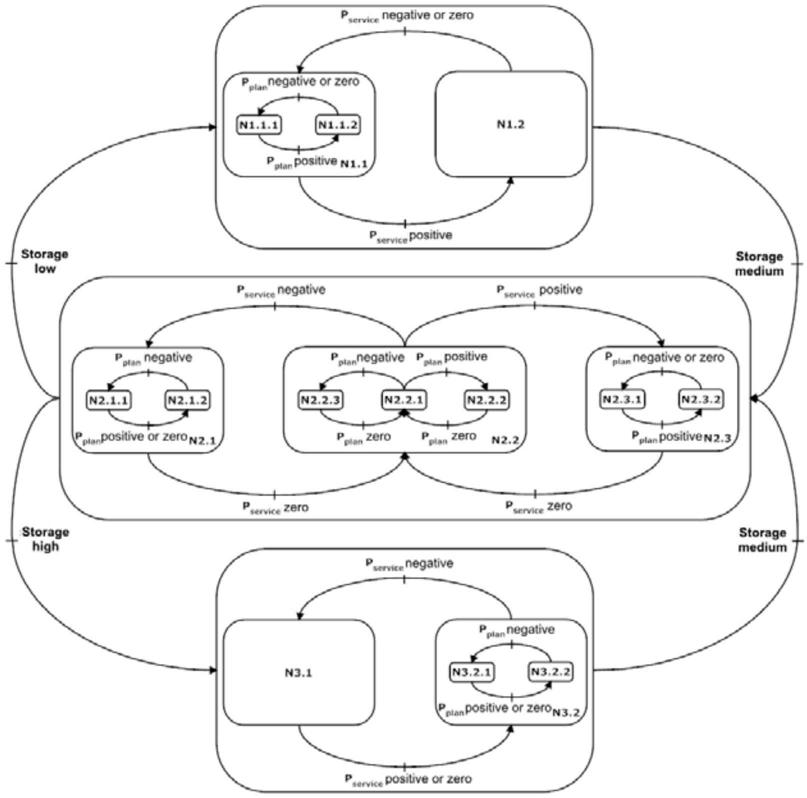

Figure 12. Functional graph with all operating modes

3.5. Determination of membership functions

The membership functions of the input variables determine the transitions between different operating modes and the value of the instruction.

The membership functions related to the state of charge consists of three levels (Figure 13) based on the three operating modes (N1, N2, N3) from the previous graph.

– The set “S” and “L”, respectively for “Small” and “Large”, provide the energy reserve necessary for the contribution of the storage to the frequency control.

– The set “M” for “Medium” assures the other goals.

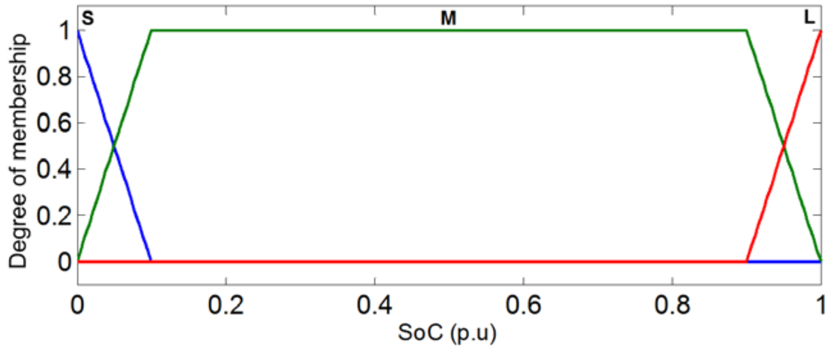

Figure 13. The membership functions related to the state of charge

The membership functions related to the power required by the services consist of 3 levels (Figure 14):

– The set “Z” for “Zero”, in the triangular form, is the mode where the storage is not asked to provide additional services.

– The set “BN” and “BP”, respectively for “Big Negative” and “Big Positive” representing the power required by additional services. A "Negative" demand means that the storage charge or reduce its discharge power and vice versa.

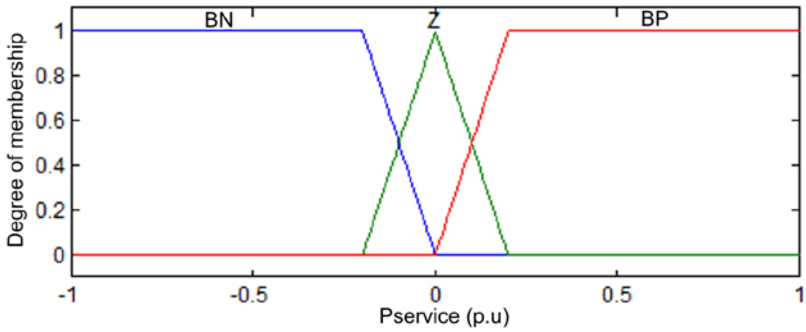

Figure 14. The membership functions related to the power required by the services

The membership functions related to the planning of the storage consist also of 3 levels (Figure 15):

– The set “Z” for “Zero”, in the triangular form, is the “pending” mode of the storage. In this mode, the sell/purchase price is not favorable for charging or discharging.

– The set “BN” and “BP”, respectively for “Big Negative” and “Big Positive”.

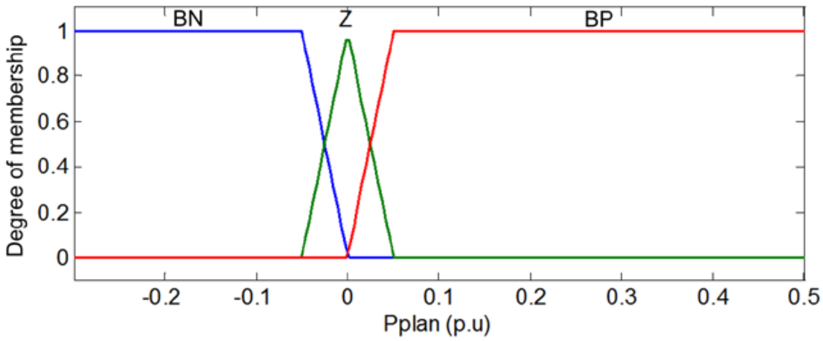

Figure 15. The membership functions related to the planning of the storage

For membership functions related to the output (Figure 16), the instruction of storage power, five sets are considered to achieve a compromise between the accuracy of the generated power and complexity of the supervisor. The sets are referred to as "BN" ("Big Negative"), "MN" ("Middle Negative"), "Z", "MP" ("Middle Positive") and "BP" ("Big Positive").

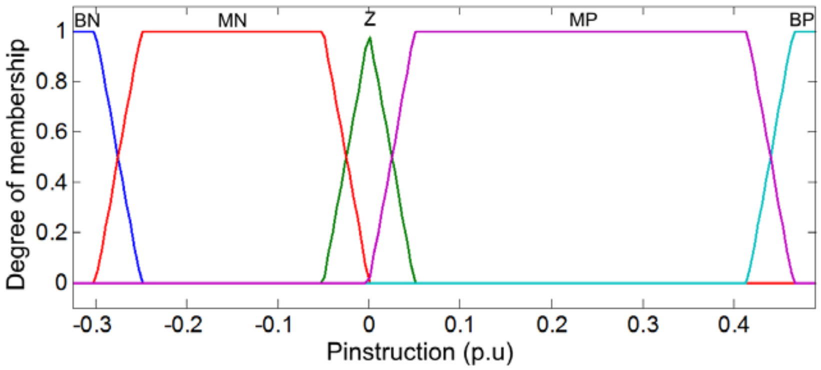

Figure 16. The membership functions related to the output

The membership functions related to the instruction of storage power are asymmetric due to the fact that the maximum charge and discharge power of the storage are not identical.

3.6. Determination of "operational graphs"

The number of fuzzy rules associated with each output variable is determined by multiplying together the fuzzy set numbers of each input variable is 3×3×3=27. Traditionally, these laws are determined using tables. The table associated with each output variable will be three-dimensional. The proposed methodology with associated graphic representation has a double advantage: facilitate the writing of fuzzy laws by avoiding the use of tables and only extract the most relevant laws for the overall operation of the system. To determine the fuzzy laws, it is necessary to convert the “functional graphs” into “operational graphs” in which involved the membership functions defined above. The transitions between operational modes will be described by the membership functions of the input variables. Figure 17 shows all operational graphs.

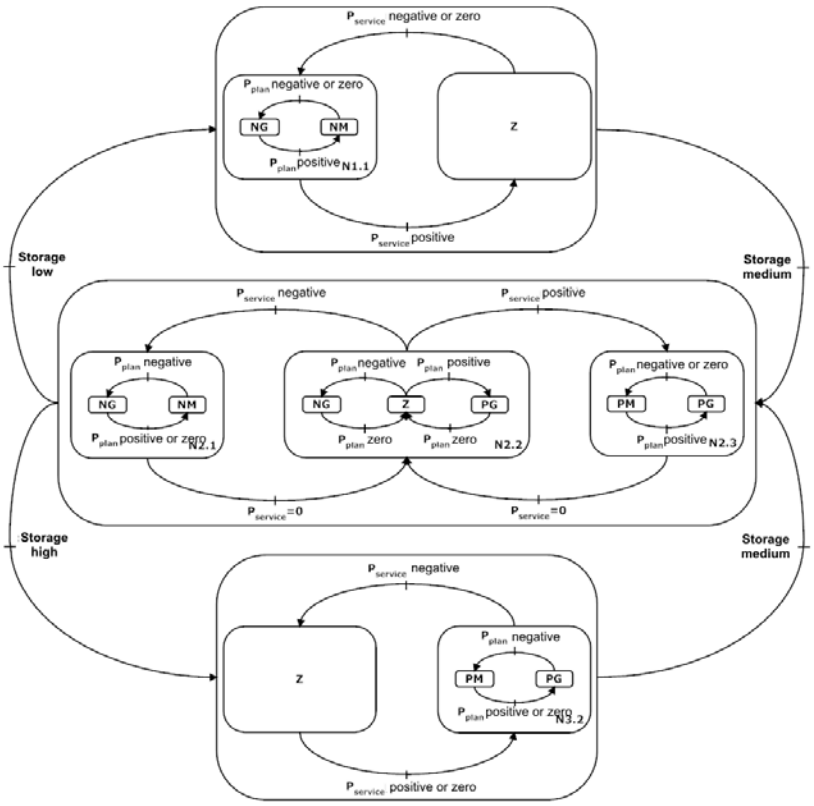

Figure 17. Operational graph

3.7. Extraction of fuzzy rules

Fuzzy laws are extracted directly from the operational graph in Figure 17. They are shown in Table 2. With the proposed methodology, only 13 fuzzy laws are considered instead of the 27 possible laws.

Table 2. Fuzzy laws of the supervisor

SoC	$P_{service}$	P_{plan}	$P_{consigne}$
S	BP	BP, BN or Z	Z
S	BN or Z	BP	MN
S	BN or Z	BN or Z	BN
M	Z	BN	BN
M	Z	Z	Z
M	Z	BP	BP
M	BN	BN	BN
M	BN	BP or Z	MN
M	BP	BP	BP
M	BP	BN or Z	MP
L	BP or Z	BN	MP
L	BP or Z	BP or Z	BP
L	BN	BP, BN or Z	Z

3.8. Indicators

In order to assess the achievement of objectives in Table 1, it is necessary to develop adequate indicators. The objectives for the power planning of the storage and the imperative and additional services must provide a financial gain; the corresponding indicators therefore measure in €uro. The goal on the availability of storage will be the indicator corresponds to the storage level (SOC for State of Charge).

4. Economic value of services

The economic interests of the storage can be obtained from three main sources:

– The buy/sell action: buy electricity when the price is cheap and sell at a higher price.

– Provide imperative service system (frequency control)

– Provide additional services to the network operator (congestion management) and renewable producers (covering renewable energy production)

The details of the pricing of these services are presented in this section.

4.1. The buy/sell action

The billing for the purchase and the sale is based on the electricity price curve. When the storage is charging, the manager buys electricity, and the sale of electricity corresponds to the discharge phase of the storage. In this study, a price curve will be selected with a period of low price at night and two consumption peaks, one in the morning and one at night.

The electricity price considered as an example in this study is shown in Figure 18. This data is taken from the website of RTE-France on 11/06/2015 (RTE, 2013). It's the price bidding on the electric market which varies every day. In this research, we simplified this variation by 3 price step: 15 €/MWh in the night, 40€/MWh in peak hours and 30 €/MWh for the rest of time.

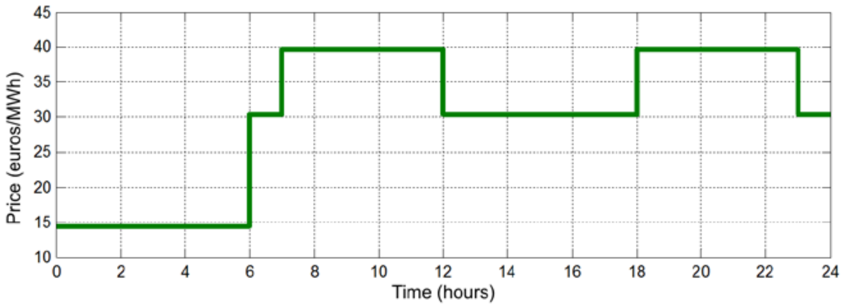

Figure 18. Electricity price curve in the day

4.2. The billing for frequency control

According to (RTE, 2013), the remuneration for the primary frequency control is of 8.04€/MW with increment of half an hour. The remuneration for the secondary frequency control is composed of two terms. The first is to maintain the reserve, which is equal to 8.04 €/MW with increment of half an hour. The second is the use of the reserve, which is equal to 9.30 €/MWh.

4.3. The billing for additional services

Additional services will be charged according to the contract signed between the parties. In this study, a price of 25€/MWh is chosen. Approximately, it is the difference between the higher price (~40€/MWh) and the low price (~15€/MWh). This price is the amount that storage vendor can receive more (excluding the cost of purchase/sale) for each MWh that provides more or does not provide compare to the planned production-storage curve. As the storage tries to follow the demand of services, it must be paid at least the same amount as the gain realized on a buy/sell normal (40-15=25€/MWh) between peak hours and off-peak hours.

5. Application

5.1. The test system

The IEEE 14 bus test system consists of two different levels of voltage (33kV and 132kV). The structure of the network is shown in Figure 19.

The network consists of 11 loads with a total consumption of 259MW and 73.5MVAr. The generator connected to bus 1 (132kV) is separated into two for the N-1 security of the power system. The power of each of the generators is 160 MW. The generator at bus 2 has a capacity of 60MW. Three synchronous compensators are respectively connected to bus 3, 6 and 8. Three wind farms are added to the bus 12, 13 and 14 (33kV) with the installed capacity of 20, 50 and 70MW respectively (Do, 2012).

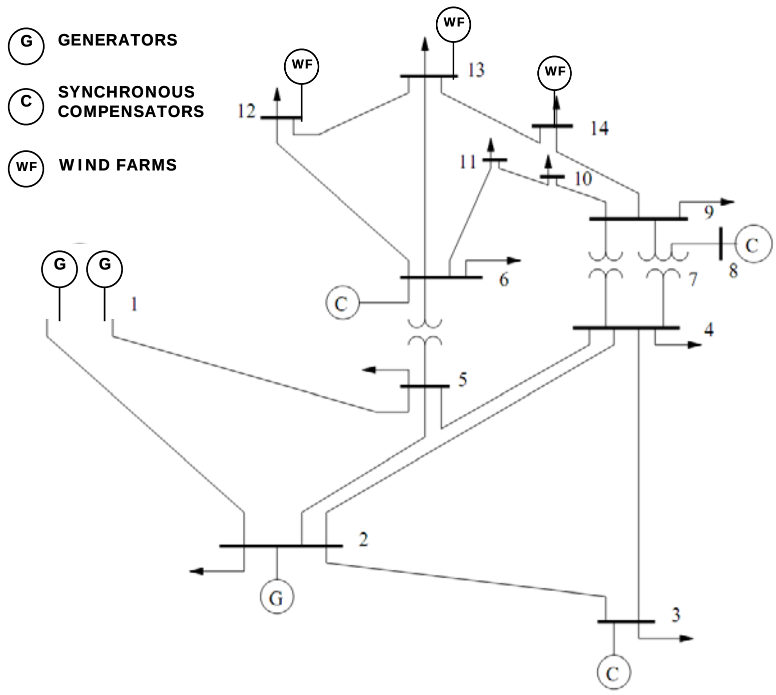

Figure 19. IEEE 14 bus test system

The compressed air storage is installed bus 6 with the maximal discharge power of 50MW and the maximal charge power of 30MW. Its storage capacity is 500 MWh. The performance of charge and discharge are estimated at 80% giving an overall efficiency of charge-discharge cycle of 64%. The full discharge time of the storage is 10hours. The cavity storing air is assumed a volume of 160,000m^3 with a maximum pressure of 30 bar and a minimum pressure of 20bar. The maximum flow rate of the air is 50kg/s in the phase of charge and 120kg/s in the phase of discharge.

Figure 20 shows the load curve for a day in per unit (p.u) with a time step of 1 hour (RTE, 2012). Loads profiles were inspired by a typical daily variation. The off-peak during the night and two consumption peaks, one in the morning and evening, are clearly visible.

The same wind profile is considered for all wind farms (Figure 21). This wind profile varies imposing significant variations in the production of wind farms. A line congestion occurs at 18pm.

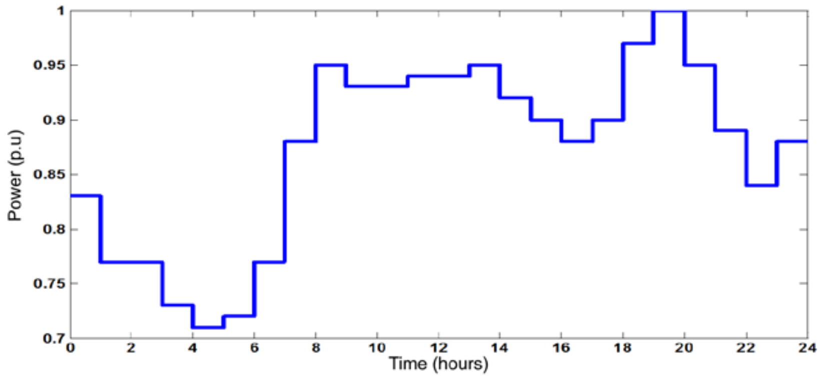

Figure 20. The daily consumption curve of the load

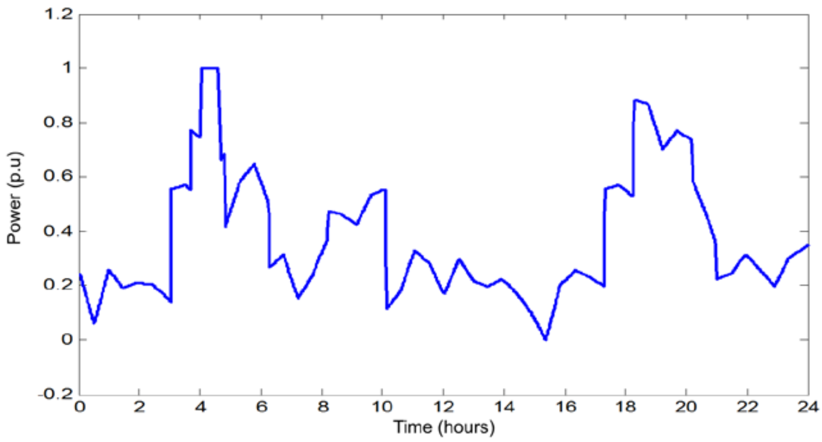

Figure 21. The typical profile of wind power in a day (Vergnol, 2010)

5.2. Interest of storage contribution to ancillary services

In this example, we will compare the economic gain obtained when the storage follows the planning only with that obtained by operating according to the set of real-time supervisor, integrating the planning.

Figure 22 shows the power curve of the storage planned the day ahead in dash lines, and that obtained with the fuzzy supervisor in solid line. We can see that without the participation to ancillary services, the reserve of storage for frequency control is not necessary; the storage can discharge at maximum power. The power curve of the storage with the instruction of the fuzzy supervisor is more fluctuating.

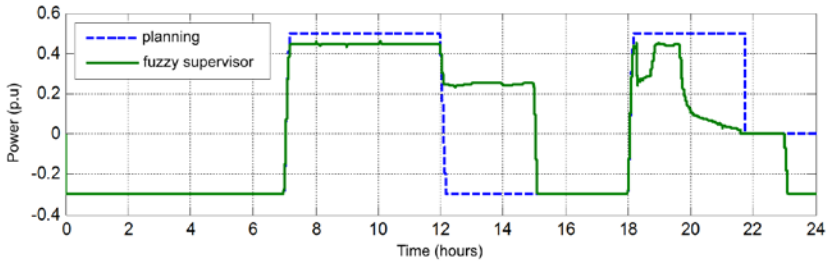

Figure 22. Planned power curve of the storage and that obtained with the real-time supervisor

Figure 23 shows the energy level in the storage with and without the real-time supervision. With the fuzzy supervisor, storage discharge more compare to the scenario where only the planning curve is considered because it must also participate in the ancillary services (in our case the service of covering renewable energy production is the most requested, and it asks the storage to discharge). At the end of the day, when the storage is almost empty and the electricity price is not too high, the fuzzy supervisor gives an instruction for the storage to charge. For this reason, the state of charge of the storage at the end of the day in the scenario with the fuzzy supervisor is higher compared to that obtained with the planning only. This difference is equal to 0.0536p.u, corresponding to an energy amount of 26.8MWh. The balance of energy storage in both scenarios is presented in Table 3.

In previous research, the storage has to maintain a balancing power at the end of the day because its mission is attached to the operation of a renewable source which cannot be forecasted precisely.

However, the storage in this research does not have this constraint. It can operate freely in order to maximize the profit while the electric price of tomorrow is almost forecasted, even informed. In fact, it has to maintain only a reserve of energy equal to 10% of its capacity in order to provide the frequency control.

At the end of the day, the storage try to discharge because the price is 40€, which is higher than the price it bought in the afternoon (30€) and almost 3 time the price it bought in the morning (15€). Moreover, reducing the SoC could avoid the loss due to auto discharging.

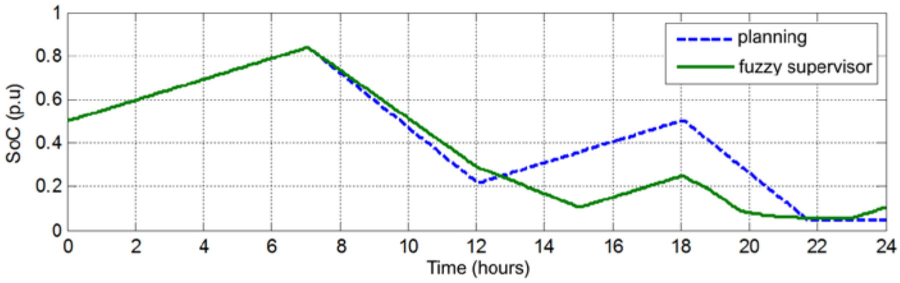

Figure 23. The state of charge of the storage obtained with the planning curve only and with the real-time supervisor

Table 3. Balance of energy storage obtained with the planning curve only and with the real-time supervisor

	Planning only	Real-time fuzzy supervisor
SoC initial	250MWh	250MWh
Charge	310.1MWh	262MWh
Discharge	535.1MWh	460.2MWh
SoC at the end of the day	25MWh	51.8MWh

Figure 24 shows the evolution of financial gain with the planning curve only and with the real-time supervisor. Table 4 presents the financial gains obtained over 24h by the service.

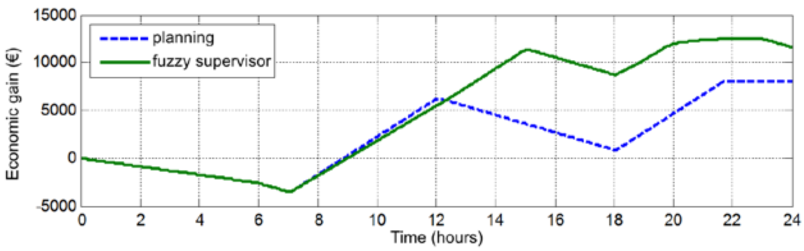

Figure 24. Evolution of financial gain with the planning curve only and with the real-time supervisor

Table 4. Financial gain with the planning curve only and with the real-time supervisor

	Planning only	Real-time fuzzy supervisor
Planning buy/sell	8080€	6840€
Frequency control	-	860€
Additional services	-	4000€
Total gain	8080€	11700€

The economic gain of the storage in the day is higher if it operates follow the instruction of the real-time supervisor. With the fuzzy supervisor, the storage manager can collect up to 11700 euros at the end of the day instead of 8080 euros with the planning curve only, which is 44.8% more gain.

The economic gain of the purchase/sale is 6840 euros with the fuzzy supervisor, lower than 8080 euros in the scenario where storage operates on the planning curve only. However, the level of the energy storage at the end of the day is 26.8MWh higher.

Although an imperative service storage, the contribution of frequency control service to the total economic gain is not high: only about 860 euros over the entire 11700 euros.

The economic gains made by the additional services are important in the total gain: 4000 euros. It's all the remuneration that the storage manager can receive for covering renewable energy production and congestion management.

It should be noted that in this example, it is not the absolute values of the gain that are important, but their comparative values between the two cases considered that highlight the necessity to evaluate the storage through multiple services.

5.3. Interest of the fuzzy supervisor compare to a Boolean supervisor

In this section, the fuzzy supervisor will be compared with a Boolean supervisor. This Boolean supervisor follows the same rules as the fuzzy supervisor but all the transitions between states of the input and output variables are Boolean as shown in Figure 25.

The power curves of the storage in the scenario with the Boolean supervisor and in the scenario with the fuzzy supervisor are presented in Figure 26. We can see a difference between the two curves during the interval between 18h and 24h.

At 18h, there is a congestion in a line. The network manager demands the storage to reduce the production in order to remove the congestion. With the fuzzy supervisor, the power curve of the storage is smoother. However, with the Boolean supervisor, this curve is very fluctuating. This can be explained by the fact that with the fuzzy supervisor, there is a transition zone between two states which stabilize the output. Figure 27 shows a zoom of the storage power between 18h and 19h.

At 20h, the state of charge of the storage is low, the energy stored in the storage is below 0.1p.u (Figure 28). With the fuzzy supervisor, the storage reduces its output power to slow down the discharge and conserve energy. This action can also be seen in Figure 28. The discharge of the storage with the Boolean supervisor is then deeper than that obtained with the fuzzy supervisor. The balance of energy storage in both scenarios is presented in Table 5.

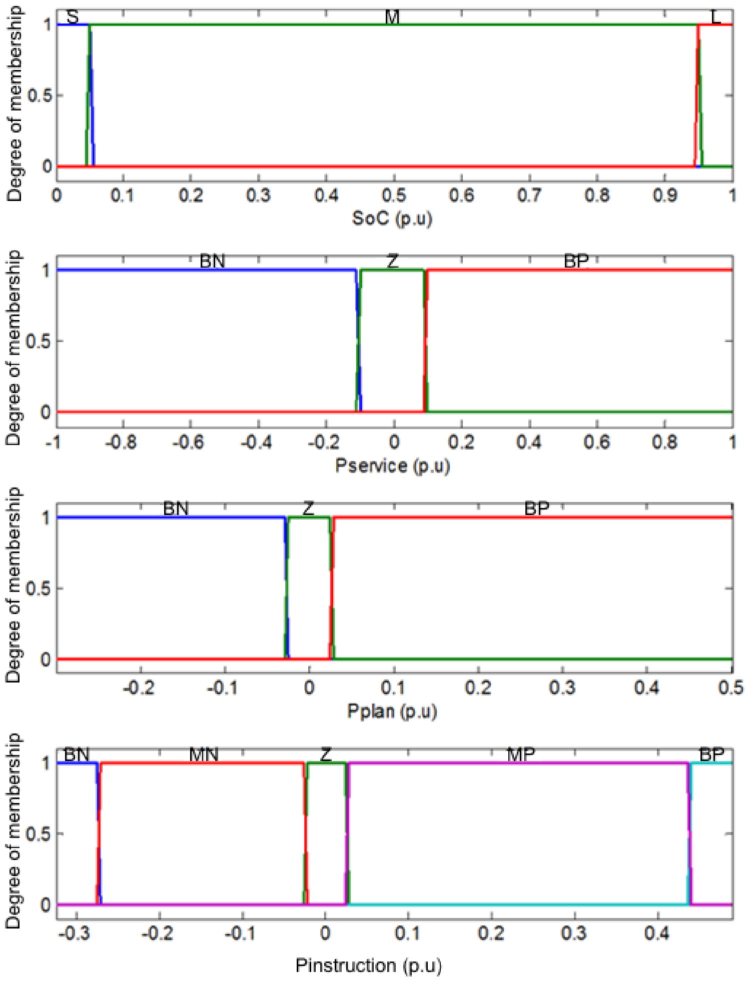

Figure 25. Membership function of Boolean supervisor

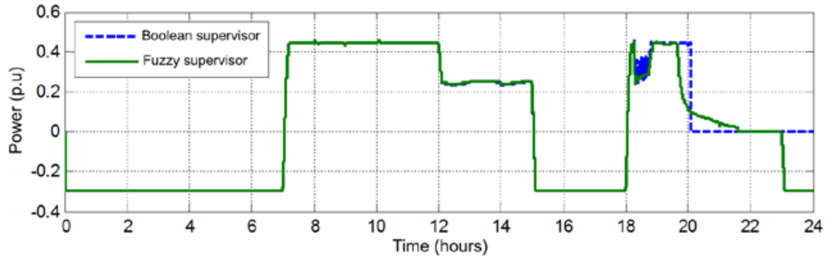

Figure 26. Power curve of the storage in the scenario with Boolean supervisor and fuzzy supervisor

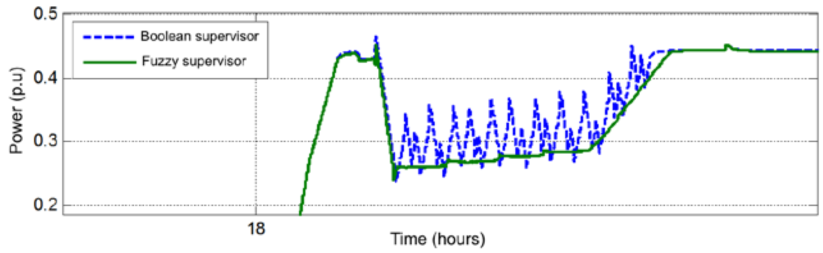

Figure 27. Zoom of the storage power between 18h and 19h

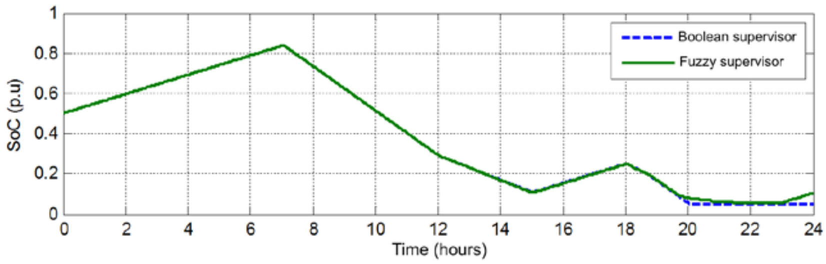

Figure 28. The state of charge of the storage in the Boolean supervisor scenario and in the fuzzy supervisor scenario

Table 5. Balance of energy storage in the Boolean supervisor scenario and in the fuzzy supervisor scenario

	Boolean supervisor	Fuzzy supervisor
SoC initial	250MWh	250MWh
Charge	239.5MWh	262MWh
Discharge	464.5MWh	460.2MWh
SoC at the end of the day	25MWh	51.8MWh

From the point of view of economic indicators, there is no significant difference between the two variants of real-time supervisors.

This shows the impact of the parameters of the membership functions determined empirically as a first step. These parameters can be further optimized to be sure to maximize the economic gains.

6. Conclusions

This paper proposes a methodology for real-time supervision allow to maximize the services and to contribute to the profitability of an adiabatic CAES storage. A multi-objective real-time supervisor based on fuzzy logic was developed to maximize the economic gain, taking into account the purchase/sale action and services (imperative and additional) of the storage as the frequency control, congestion management and covering renewable energy production.

The proposed supervisor was tested on an IEEE 14 bus test system over a period of 1 day. The simulation results showed an economic gain significantly more interesting if the storage participates in system service and additional services requiring a real-time management.

The proposed methodology helps the supervisor's design and reduces its complexity. It can obviously be applied to other storage technologies. The modularity of the method allows integrating easily other goals and constraints (other services, control of aging...).

Finally, the fuzzy logic, which is deterministic and not stochastic, generally has a good robustness towards uncertainties, particularly the uncertainties in forecasting of renewable energy. The supervisor constructed according to the proposed method has the ability to adapt its response to this type of randomness.

Acknowledgment

This study received funding from the ANR through the SACRE project whose partners are EDF, Géostock, Laboratories LMS, PROMES and L2EP.

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