Provision of frequency containment reserve through large industrial end-users pooling

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Abstract—This paper reports the recent work carried out to engage a pool of large industrial end-users in frequency control complying with the performance criteria of conventional generation. The pooling approach unites the benefits of continuous loads and staggered loads (discrete active power response). Based on a local measurement of the frequency, the primary control signal is dynamically reconstructed through a centrally managed automation infrastructure integrating the industrial constraints and the requirements of the Transmission System Operators (TSO). The regulation algorithm, minimizing the total number of up and down activations of the loads, as well as the regulation infrastructure, are presented and detailed. After a discussion of the practical implementation at three distant industrial sites, the response of the experimental installation of the pool is discussed through its performance measurements and assessment. From the industrial point of view, the overall regulation system is in operation, adding value to the power system and the end-users and is reported to be economically viable. The implemented entity has been certified by the French TSO RTE.

Index Terms—Ancillary Services, Primary Frequency Control, Frequency Containment Reserve, Demand Response, Load Aggregation, Pooling Strategy.

I. INTRODUCTION

The system frequency is the foremost indicator of an instantaneous power imbalance in transmission grids. One of the main tasks of *Transmission System Operators* (TSO) is to ensure the stability of the grid, and thus to organize and supervise the actions and mechanisms related to frequency control [1], [2]. There are generally three layers of frequency control required in large transmission grids from primary (local) to tertiary (global), to cope with deviations [3].

Now referred to as *Frequency Containment Reserve* (FCR), the *Primary Frequency Control* (PFC) is widely used in industrial applications. The FCR of a power system is predominantly provided by the droop capability of large generators [4]. The advent of *Demand Response* (DR) in the development of today's smart grids has made the demand side a new actor in the stability of an electrical grid [5]. Various incentives are implemented to reveal the potential contribution of end-users to ancillary services [6]–[8]. However, current initiatives are mainly focused on contingency reserve through the aggregation of multiple small loads and quite often with specific regulation arrangements [9]–[12]. Stand-alone loads

are difficult to be engaged on the established markets because of size, capability or performances [13], [14]. Aggregating loads still needs to find a proper balance between technical complexity, rigid TSO rules, and economic viability [15].

Strategies exist for small individual loads and for storage facilities to supply frequency-controlled reserves [16]–[19]. Pooling strategies (both optimal and sub-optimal) propose adaptive and self-tuning control approaches with either distributed or centralized implementation [20], [21]. Those strategies are based on robust control methods, artificial neural network as well as fuzzy logic or genetic algorithm [22]. In the end, being able to aggregate, in a pool, high energy consumers with a centralized infrastructure seems to be the most practical possibility currently to reach economic viability in a context of a limited FCR market [23].

In this paper, the contractual requirements of the TSO are summarized for the continental Europe synchronous area and then compared to the reality of end-users' process capabilities and constraints. Demand-side limitations are illustrated through two large end-user processes: *electrolysis* and *electric arc furnaces* (EAF). A pooling strategy is then proposed to resolve the problem. The principle of load aggregation for FCR is developed and implemented with a real-life aggregate of six large industrial loads for a rated power of more than 150 MW. A dedicated section depicts the technical implementation of the system with a multi-layer automation infrastructure. Finally, performance results are discussed, focusing on the analysis of the additional end-users' requests. Note that this whole process has been certified by the French TSO RTE as a multi-site DR entity and has been in operation for the past year, thus proving its robustness and its economic viability.

II. CONTEXT OF THE PROBLEM

A. Primary Frequency Control requirements

For main generators directly connected to the grid, the primary control represents the first reserve of power, activated within seconds, to reduce frequency deviation [24]. For the European synchronous area, the ENTSO-E defines the overall conditions on the *Primary Control Reserve* (PCR) shared with the 24 interconnected TSO [1], [25]. Primary control is intended to be provided continuously and symmetrically from 49.8 Hz to 50.2 Hz whatever the profile of the frequency signal. In case of a quasi-steady state deviation of ± 200 mHz, the reserve must be fully delivered and maintained for at least 15 min, which is the maximum expected relief time of the secondary reserve. From the dynamic point of view, 50 % of the requested power deviation must be deployed within 15 s, and 100 % within 30 s [3].

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TABLE I
MAIN CHARACTERISTICS FOR FCR OF THE USED INDUSTRIAL LOADS.

Characteristics	Electrolysis	EAF
Type of load	Continuous	Discrete
Process symmetry ¹	Full	Partial
PCR (% of rated power)	5 % to 15 %	15 % to 20 %
Elementary step response	100 kA/s	5 s
Time delay	<3 s	<5 s
Power resolution	Continuous	[~300;1200] kW
Frequency of discrete transitions	N/A	~25,000/year ²

¹ Centred range around the operating point of power variations.

² Highly dependent on tap-changer technology and process requests.

The French TSO RTE strictly applies the ENTSO-E requirements. Administrative entities providing primary control must be validated in one block in accordance with the previously mentioned conditions [26]. No distinction is made between generation and demand, albeit some other European TSO fragment the reserve, proposing asymmetrical products and under/over-frequency thresholds for end-users.

The governors of the generators follow a first order transfer function smoothing dynamics of the FCR response [4]. This characteristic is integrated in the TSO's performance controls and applies to consuming assets. The expected FCR response must be greater than the power set-point signal, filtered by a first order function with a time constant of 20 s [26]. The applied filter gives room to the process in terms of dynamics, which potentially alleviates the raw signal constraints.

B. Demand-side capabilities of industrial loads

Using the flexibility of loads in a smart grids perspective is commonly accepted to be of interest [27]. The associated services will depend on the characteristics of those loads [28], [29]. Industrial loads are by default not designed for ancillary services, since the power flexibility is tightly related to the characteristics of the process defined, for example, by the industrial production or intrinsic dead-band/inertia values. They are consequently restricted regarding their availability, operating ranges, dynamics and energy balance. The precise characterization of the potential power capacity is to be assessed statically and for multiple time horizons. This is the first step of asset enrollment of DR primary control services.

Recent research is being conducted to enable the flexibility of industrial loads, either directly, or using additional storage capacities to increase their possibilities [30], [31]. Providing flexibility to industrial loads requires the addition of optimization algorithms, once the communication infrastructure is operational. In this context, multiple ancillary services are available, using additional local production with PV panel [32], or being driven by time-based signals [33].

Load characteristics can be classified into three major types for control purposes: continuous, discrete, and bi-state loads. Their power responses generally follow the same categorization. This paper focuses on the enrollment of the first two types, making the most of their respective flexibilities to overlap their own constraints, in an industrial context. TABLE I provides a summary of their main characteristics.

C. Problem statement

The objective is to aggregate distant and constrained industrial processes with distinct characteristics (mainly through the control of continuous and steps of power). This is done without the help of additional storage or production capacities, with the industrial process being in operation at the same time. With a centralized practical pooling strategy, that aggregation of load proposes a flexibility to the grid in the form of short term frequency support. In addition, this regulation has been implemented and deployed on an industrial scale (targeting 10 MW of FCR with more than 150 MW of cumulated load power) for a year (which means it is economically viable). The lessons learned from that experiment are discussed in the results and conclusion, Section VI and Section VII.

Even if the service is provided, since each control action results in an effective and precise performance on the power, the reversibility of the response is tainted with signals specific to the industrial sites: low frequency on the baseline of the site, average frequency on the unexpected natural fluctuations of the site, and high frequency due to noise (metrological). The control method is a research and development subject in itself, the objective of which is to obtain a satisfactory level of statistical confidence.

III. CHARACTERISTICS OF THE INDUSTRIAL LOADS

A set of generators providing ancillary services has a direct connection to the contractual point of grid export. On the contrary, a set of loads providing FCR runs conjointly with other processes, introducing additional uncontrolled consumption. Depending on TSO rules, the performance control is carried out at the *delivery point* (DP) or at the load sub-metering points. In our application, the French TSO RTE requires a control at the contractual DP or an aggregation of DP [26]. In this case, the auxiliary consumption must not counteract the regulation effect and the local noise should not annihilate the signal. Fig. 1a and Fig. 1b provide an overview of the involved industrial loads, and what control signals are being transmitted to/from these resources. The proposed method was applied to the available industrial loads at the time, i.e. continuous and discrete load. The characteristics of the load are presented before the pooling strategy as they have a significant impact on it. Note that, though no bi-state load is considered in this paper, mathematically speaking, we can consider them as a set of discrete loads.

A. Electrolysis

The process of electrolysis is based on the management of DC current flowing through a line of cells. The chemical decomposition of the electrolyte is driven by the intensity set-point with the condition that the cell voltage is higher than the decomposition potential. DC is generated and controlled by high voltage rectifiers, producing 25 to 75 kA in our case. Although current regulation through the automation of the rectifiers is dynamically efficient, the expected active power consumed by a set of cells is subject to natural variations of voltage and the impedance of the line due to production plans,

Fig. 1. Principle of the primary control of the industrial loads of the pool.

electrolyte quality, thermal conditions, and overall infrastructure instabilities.

There are a few limitations regarding the commitment of electrolysis to frequency regulation, as stated in TABLE I. The first one is the PCR, i.e., the remaining power over the nominal functioning range of the process to be engaged. For large electrolysis (>10 MW), 5 to 15 % of the rated power can be typically enrolled as PCR, ensuring a continuous reserve from a low to a full industrial production plan. The overall response time of the rectifier infrastructure is the characteristic at the core of the dynamic performance. Special care might be taken with transient regimes to make sure that overshoots do not disturb the frequency regulation and if not, the need to be mitigated by the regulation. Finally, the capability of asymmetrical energy consumption over a moving time window is to be assessed, to accept a maximum time lag for energy imbalance (one year in this work).

B. Electric arc furnaces

Three phase AC EAF are commonly used in the electro-metallurgical and steel industries. Ores or metals are smelted through the supply of a massive quantity of energy from electric arcs with three electrodes of graphite [34]. Unlike steel, non-ferrous metal production is usually a continuous smelting process. The energy fed to the EAF is continuously controlled to ensure stable heating conditions of the matte and the slag. Two main variables are controlled to regulate the EAF power. The phase voltage will determine the furnace power set-point while a fine regulation around the set-point will be provided by the positioning of the electrodes.

In order to compensate for disturbances from the material feed rate, electrode consumption, and chaotic variations of the bath, the impedances and thus the arc lengths will be continuously adjusted through movements of the electrodes. The positioning of the electrodes is driven by actuators with slow ramping, managed by complex regulators that are not relevant for frequency regulation. On the other hand, the phase voltages are driven by on-load tap changers, which are controlled by the operators to adjust the production plan. Power regulation through tap changers is a good candidate for external regulation as long as the production of the matte and the maintenance of the tap changers are not disturbed. Tap

voltage set-point is also part of the electrode positioning regulation, which will always supersede any external regulation. Moving parts of the tap changers are particularly sensitive. Recurrent high voltage contacts require heavy maintenance following a threshold number of movements recommended by the manufacturer (typically 25 000 transitions per tap changer). Note that frequent maintenance costs and several days of factory shutdown are by far the main losses under consideration induced by the FCR participation.

IV. THE POOLING STRATEGY

Committed power, dynamic performance, and service continuity are the key conditions to provide a conforming FCR. The main challenge with the flexibilities of industrial loads is therefore to maximize the committed power (the PCR) under those conditions, through a smart arrangement of the available degrees of freedom of the targeted processes. The gathering of loads from multiple sites and various industrial sectors can maximize the engaged power, making the most of the characteristics of the load to respect or circumvent the end-users' constraints.

This section illustrates the effective pooling of continuous and discrete loads to generate a power signal image of the grid frequency. As a real application, the implemented pool is composed of two continuous loads (electrolysis) and four discrete loads (EAF), dispatched to three distant end-users.

A. Reconstruction of the frequency signal

The proposed approach is to build the FCR response via two contributions. The first one comes from blocks of power released from discrete loads (EAF) and the second one is covered by small continuous variations through more reactive and precise continuous loads (electrolysis). The introduction of large discrete loads allows considerably increasing the overall committed power, bringing potential and steep response time to the pool. Discrete loads could not comply with the performance criteria alone, they especially cannot afford a recurrent start-stop or comply with the expected accuracy. On the other hand, continuous loads bring an accurate response and continuous availability. These characteristics are particularly useful for feedback control, to manipulate small frequency deviations, and reduce uncertainties from discrete loads.

Fig. 2 depicts the principle of the aggregation scheme. For the sake of clarity, only one load of each type is represented. A hysteresis operation is introduced for the discrete loads with the aim of drastically reducing their number of activations. This will be detailed in Section IV-B. The aggregation entity is determined by a set of frequency thresholds, latching and releasing the staggered stages of the discrete load. Persistence values are associated to the latching thresholds, defining the set of release thresholds. Frequency deviation is a wide-sense stationary process, as the mean and auto-covariance are stable over time. Thus, the activated stage is expected to be more quickly released if the persistence value is low. The statistics of the occurrences of the activations and their durations can be assessed and compared with the load or process constraints. The change of the signal provokes an asymmetrical response

and alters the course of the continuous load. The collateral impact of this alteration also needs to be characterized, through monitoring in our case. The arrangement remains the same with several loads involved. More complexity is introduced, but without compromising the technical implementation.

B. Determination of the discrete load thresholds

The overall goal is to provide FCR response to support the grid by a smart dynamic adjustment of industrial loads consumption. From a given PCR commitment, the problem to be solved is to continuously cover the TSO rules with the existing flexibility of end-user's processes. The proposed approach is to enroll a set of discrete and continuous processes. The load composition of the FCR entity is done beforehand in compliance with the power and dynamic requirements summarized in Section II-A and documented in [25], [26]. As the grid frequency time-series cannot be realistically modeled, the resolution procedure is based on historical data.

The following mathematical formalism is described as an optimization problem to facilitate its expression. However, the approach cannot be regarded as a rigorous optimization problem, since the expected solution is not a unique optimum but rather a compromise solution complying with the referenced constraints. The method rather provides a satisfactory high confidence statistical response to the constraints instead of a theoretically optimal one, in the form of a sub-optimal control.

Each type of load of a predefined entity introduces specific process constraints to be arranged. As per Fig. 2, frequency thresholds of discrete loads appear to be structural as they fix the overall load arrangement. The positioning of the thresholds is directly related to the number of movements of the discrete loads which is one of the main industrial process indicator. Thus, the number of movements is the objective to be minimized in (1). The maximum and minimum activation times of discrete loads and statistics of energy neutralization over a year (i.e. at the end of the year, industrial production should be identical with or without solicitation for frequency support) are additional respected process constraints. They are successively tested according to inequalities (2)–(4).

In case of no solution, the composition of the PCR entity needs to be reviewed by adding new loads or decrease the committed power. The solution is indeed chosen to respect the constraints on discrete and continuous loads requests. It represents a mix of expertise in the controlled process and a problem formulation from the regulation point of view, as described in Subsection IV-B1. Note that the proposed solution is the best candidate to provide a good (but sub-optimal) estimate rapidly. Eq. 7 drastically reduces the possible number of combinations, hence reducing the solution space. A complete implementation to solve the problem is in progress. No time constraint is to consider, as the problem is solved for the upcoming full year.

1) *Expression of the problem:* The regulation is designed to “help the grid”, it means provide FCR provision while respecting the TSO rules for a financial benefit. The practical implementation targets 10 MW of FCR, with the associated dynamics, while minimizing the ON/OFF transitions of the

discrete loads (150 MW of cumulated power are aggregated in the pool of continuous and discrete loads). The dynamics are implicitly considered in the problem since the composition of the FCR entity is the preliminary input of the regulation. Because power and dynamic capabilities of loads are additive, the FCR entity can be initially set up in compliance with the TSO requirements with a fixed number of loads. The viability of the entity against frequency signal is then checked through the process minimizing the solicitation of the discrete loads under constraints. The minimization is part of the regulation, to be set-up once for the up-coming year on historical data and concerns the transitions of the discrete loads.

The fixed input parameters are: the number of total stages from discrete loads n_d , and $i \in [1; n_d]$ the stage index; the power echelons of load stages $\{P(i)\} = \{P(l, s)\}$ with l the discrete load index and s the load stage index, each i is linked to a unique combination of (l, s) ; n_c the number of continuous loads; C_m the maximum amount of discrete load transitions for the considered time period, and K_{reg} (MW/Hz) the primary control gain targeted by the entity. The index s is taken between $n_{s<0}^l$, number of negative stages, and $n_{s>0}^l$, number of positive stages, of load l . The time period T , the data sampling interval T_s , and the number of samples $N = T/T_s$, are initial parameters for the data analysis.

Considering a fixed initial configuration of discrete and continuous loads to respond to the service, the pool ensemble is fully determined by a set of frequency thresholds applied to the discrete loads. The input of the pooling model is a series of pairs $\{F_b(i)\} = \{f_{latch}(i); p(i)\}$ with $p(i) = |f_{latch}(i) - f_{release}(i)|$ a frequency delta, always positive, called the *persistence*. The parameter p introduces hysteresis into the regulation as a Schmitt Trigger function. f_{latch} and $f_{release}$ are defined as frequency deviations from 50 Hz, represented in Fig. 2 with the persistence p .

The challenge is therefore to find a set of pairs $\{F_b\}$ which properly fit the service requirements and process constraints. The complete series can be expressed as $\{F_b\} = \{\{F_b(1)\}, \{F_b(2)\}, \dots, \{F_b(i)\}, \dots, \{F_b(n_d)\}\}$.

The overall number of transitions over the period is defined here as the objective to minimize. The ultimate objective of the problem solution is to ensure a primary control response with a minimum of discrete movements, remaining at least below the maximum target C_m , represented in Fig. 2. Multiple datasets are involved in the determination of a satisfactory solution, defined $\forall n \in [1; N]$:

- $\{\Delta f(n)\}$ is the historical frequency deviations over T ;
- $\{\delta(n)\}$ is the signed stage transitions of discrete loads;
- $\{P_d(n)\}$ is the power requests from the discrete load;
- $\{P_a(n)\} = K_{reg}\{\Delta f(n)\} - \{P_d(n)\}$ is the power requests from the continuous loads;
- $\{d_i(k)\}, \forall k \in [1; K]$ is the duration of load stage activation for each pair $\{F_b(i)\}$. K is the number of times a stage is activated for one pair $\{F_b(i)\}$ over T .

We consider the function $C : \mathbb{R}^{n_d} \times \mathbb{R}^{n_d} \mapsto \mathbb{N}$ as the objective function to minimize, subject to constraints (2)–(4). C represents the total number of ON/OFF transitions of

Fig. 2. Arrangement of the discrete and continuous loads – Primary control signal reconstruction.

discrete loads.

$$\min C(\{F_b\}) = \min \left(\sum_{n=1}^N |\delta(n)| \right) \quad (1)$$

$$C(\{F_b\}) \leq C_m \quad (2)$$

$$\max(\{d_i\}) \leq d_i^{max} \quad (3)$$

$$\min(\{d_i\}) \geq d_i^{min} \quad (4)$$

Where d_i^{max} is the maximum acceptable time of a stage's activation; d_i^{min} is the minimum time of a stage's activation. Also, the distribution of the aggregated requested power from discrete and continuous loads, $\{P_d\}$ and $\{P_a\}$, should present an “acceptable” energy balance over a moving time window, i.e. centered, and with a standard deviation and maximum range within the limits agreed on with each end-user. The series are also checked against the stand-alone response (refer to Fig. 5 for illustration).

Note that $\{\delta(n)\} = 0$ is not a relevant solution as it would limit the FCR to the continuous loads only, representing a potential of 4MW, when the target is 10MW. Combining discrete and continuous loads is then necessary, or the power from the discrete loads would not be released at all whereas it is an initial condition of PCR power commitment.

2) *Procedure*: The search for a satisfactory set of $\{F_b\}$ is carried out through an sub-optimal procedure, presented in Fig. 3. Each set of $\{F_b\}$ for a given combination of available loads is called a “scenario”.

To find an initial set of transitions $\{\delta(n)\}_0$, an initial $\{F_b\}^{in}$ is defined as the exact provision of power when requested by the regulation rule: $\Delta P = K_{reg} \times \Delta f$, with a persistence equal to zero. $\{F_b\}^{in}$ is the aggregation of $\{F_b(i)\}_{(l,s)}^{in}$ for all discrete loads l and stage indices s . The constraints are then

successively checked to adjust the initial parameters according to predefined rules for $f_{latch}(i)$ or $p(i)$.

$$\begin{aligned} \{F_b(i)\}_{(l,s)}^{in} &= \{f_{latch}(i) = f_{latch}(l, s); p(i) = 0\}, \text{ with} \\ \left\{ \begin{aligned} \forall s \in [1; n_s^l < 0], f_{latch}(l, s) &= \sum_{m=1}^s P_{(l,-m)} / K_{reg} \\ \forall s \in [1; n_s^l > 0], f_{latch}(l, s) &= \sum_{m=1}^s P_{(l,m)} / K_{reg} \end{aligned} \right. \quad (5) \end{aligned}$$

First, the number of overall movements is computed and compared to the maximal target C_m , to satisfy $C(\{F_b\}) = C_m - \varepsilon$. The choice of the error parameter ε , based on internal expertise, is a technical and economic compromise between load flexibilities, overall costs, and ease of problem solving. In this research, $\varepsilon = 10\,000$. If the number of transitions pass that threshold, the persistence value is adjusted (though kept constant per load stages in this work).

Then the durations of the activated stages are checked. Indeed, too short and too long durations of stage activation are likely to disturb the nominal production set-point. Finally, quality checks are conducted to characterize the global service request of the discrete and continuous loads in terms of effective power. The energy balance is checked over a pre-defined time moving window. The global energy request of the process must remain within a given tolerance, defined by the end-user. The bias and skewness are also checked to ensure an overall equilibrium of the energy with an acceptable variance.

The additivity property of the hysteresis relays is widely used in the compilation of the series. The overall staged response of the discrete loads is broken up into elementary relays. The number of overall transitions from one discrete load at different stages equals the sum of the transitions from

Fig. 3. Assessment procedure, $\forall i \in [1; n_d]$, $\forall k \in [1; K]$ and $\forall n \in [1; N]$.

each stage (or relay) whatever the frequency threshold and the associated persistence are, as expressed in (6).

$$C(\{F_b\}) = \sum_{i=1}^{n_d} C(f_{latch}(i); p(i)) = \sum_{i=1}^{n_d} \sum_{n=1}^N |\delta_i(n)| \quad (6)$$

When the elementary relays are physically linked to a single load, the different stages are necessarily staggered. A stage cannot be released before the one at the upper level. The staggered activation must respect the additional inequality of (7). This condition drastically reduces the range of possibilities.

$$\begin{aligned} \forall i \in [1, n_d - 1], f_{latch}(i) - \text{sign}(f_{latch}(i)) \times p(i) \\ \leq f_{latch}(i+1) - \text{sign}(f_{latch}(i+1)) \times p(i+1) \end{aligned} \quad (7)$$

Fig. 4 is constructed to quickly assess the number of transitions (up or down) from a stage of a discrete load. Given the stage settings f_{latch} and p , one can obtain the associated number of transitions over one year of frequency deviations. Thanks to the additivity property, it is also particularly helpful to explore an ensemble of multiple stages and obtain, by summation, the overall number of transitions. A set of frequency

deviation thresholds with persistences can be freely positioned on the chart. The chart has been processed from one year of frequency deviations with $T_s = 10$ s.

As an example, the red dots in Fig. 4 indicate the response of each staggered relay of a discrete load engaging 6 MW on a DR entity of $K_{reg}=50$ MW/Hz, respecting $K_{reg} \times [f_{latch}(i+1) - f_{latch}(i)] = 1$ MW, with a single persistence of $p(i)=40$ mHz. The result is 85 354 transitions, which is below the maximum target of 10^5 movements (dark red ceiling line in Fig. 4).

The inequalities (3) and (4) are checked using the same type of diagram, plotting the minimum and maximum values of $d_i(k)$ per pair $\{f_{latch}(i); p(i)\}$. Those extrema must remain within the area delimited by d_i^{min} and d_i^{max} , $\forall i \in [1; n_d]$.

The resulting power requests $\{P_d\}$ and $\{P_a\}$, are computed and checked for consistency regarding their “acceptable” distribution. The skewness and kurtosis of the distribution are compared against end-user degrees of freedom, energy balance being one of the main constraints. Fig. 5 shows the distributions of mean power per moving average time lag. It provides a statistical overview of how the power is balanced over a time window, which provides a normalized indicator of energy imbalance. The aim is to obtain a quick convergence to a centered, symmetrical, and narrow power distribution. In the presented implementation, following the end-users’ specifications, after half an hour, 95 % of the mean power variations must be confined to within $\pm 10\%$ of the power reserve commitment.

In comparison with the overall energy demand without pooling (represented in blue in Fig. 5), the introduction of discrete load activations considerably reduces the spread of the continuous load energy balance, without losing symmetry. The mean power quickly falls into the tolerance limits of $\pm 10\%$ of power volatility. The discrete load supports a much higher variability. However, the service request is likely to be distributed over several loads and anyway still remains below the reference without pooling arrangement.

Finally, note that the process of the client is at the core of the control. If no solution is found for the considered configuration (i.e. too much solicitation of the discrete loads is needed), the process of the client is not solicited at all (configuration not used). It means, in that case, that it is not possible to propose the full capacity for frequency support on the market.

V. CONTROL ARCHITECTURE AND APPLICATION

A. Regulation algorithm

The control architecture involves multiple functional blocks to provide an efficient service to the grid. The main functions are marked in Fig. 6. The principal intelligence resides in the regulation and coordination of the different types of continuous and discrete loads with the central supervision. The mixed DR regulator, gathering continuous and discrete flexibilities, is illustrated in Fig. 7. The core input to the regulator is the real-time measurement of the frequency deviation carried out locally, ensuring the real-time regulation autonomy of each site. A significant part of the complexity is to integrate and aggregate industrial processes of this size with their own operational issues that are otherwise quite remote from FCR

Fig. 4. Diagram of relay movements per pair $\{f_{latch}(i); p(i)\}$.

Fig. 5. Energy balance requests. Mean power per 10 s. Interval over a moving time window (IQR is used for interquartile range).

issues. Thus, in addition to the technical complexity of the proposed approach, a significant organizational challenge to support such a pool has to be overcome.

The additivity property of the hysteresis relays is used to fragment the regulator operation. Each stage of a discrete load can be considered as a unique relay. An elementary relay i is characterized by a latching frequency $f_{latch}(i)$ and a persistence $p(i)$. The superimposition of the relays gives the series $\{F_b(i)\}$ for one discrete load, within the condition of staggered stage, as expressed in (7). Families of $\{F_b(i)\}$ per scenarios are hard-coded within the local *Programmable Logic Controller* (PLC). They could be dynamically computed and pushed to the local regulation PLC as well.

The distributors of discrete and continuous loads (denoted by DL and CL in Fig. 7) respectively activate the loads

Fig. 6. Functional overview of the FCR pooling implementation.

or discrete stages according to predefined logical rules. DL outputs a binary activation of the elementary relays, while the CL outputs a percentage of FCR response to be applied to each of the continuous loads. In particular, the logic includes the loss of availability of an asset caused by technical fault, manual withdrawal, or scheduled roll-out of load. The central instructions also act on the distributors to manage the completeness and performance of the pool.

B. Regulation infrastructure

The technical implementation of the overall regulation algorithm is constituted by several layers, executing either local algorithms close to the asset or central supervision. The infrastructure is based on industrial tools, meshed sensors, PLC, and a *Supervisory Control And Data Acquisition* (SCADA) system,

Fig. 7. Mixed DR PFC regulator, simplified block diagram.

Fig. 8. Overview of the automation regulation infrastructure.

as depicted in Fig. 8. The sub-optimal decision is set-up based on a whole year historical data, but the regulation has a reactive layer. The regulation is then responsible for adapting the output to the required performances once the first compliant set of usages of the loads has been computed. Energy imbalance due to asymmetrical frequency signal is insignificant (≈ 2.63 MWh in 2018 with a 10 MW commitment). In case the pooling aggregation specifically induces a drift of consumed energy, the energy imbalance is reduced by a readjustment of the production plan in order to avoid additional electricity cost and variation of products.

At each site, one dedicated PLC collects the data from transducers installed in the TSO DP. The PLC manages the load regulation from the different operational inputs based on local asset automation and remote supervisor instructions. As output, a pre-processed dynamic set-point is transmitted to the load automation, and instantaneously added to the current process set-point. Each load is independently regulated according to predetermined scenarios. The central regulation supervisor, based on a SCADA technology, acts as a continuous performance control and centralized regulator. According to the current state of the pool, it generates events to instantaneously correct departures from the expected performance, sending extra correction set-point to the continuous loads. The central supervisor also acts as the pool organizer: any

fault detection or operational change (e.g., asset availability) reorganizes the load according to preset rules.

The overall reconfiguration time of a new scenario or the reduction of a momentary departure from a site to another through the central supervisor is less than 5 s and usually close to 2 s. This event-based response time does not disturb the expected response time of the primary frequency control. Instantaneous power data is continuously provided to the TSO for surveillance and performance control.

VI. PERFORMANCE RESULTS

A. Case study

The period of investigation T is one year of frequency deviations, in order to grab representative seasonal extreme events. The sample interval T_s is 10 s, which is the standard time interval considered by the French TSO for performance control.

The first DR entity consists of eight high-power assets, six of which are included in the regulation: four EAF and two lines of electrolysis (with a total rated power of ~ 150 MW). The four committed EAF are equally distributed in two geographically distant sites, and the pairs of furnaces have the same design in terms of power stages. This arrangement reduces the number of combinations and sets of $\{F_b(i)\}$ to be determined prior the operation. The minimum asset combination to comply with the 10 MW of continuous power commitment is two lines of electrolysis and two EAF. The size of the pool is limited in the practical implementation by the availability of high energy loads and the client willingness to provide access to their industrial processes, with in mind an insured capacity to meet the FCR commitments agreed with the TSO. Other practical development issues have also to be solved regarding the scalability of the solution in terms of telecommunication protocol, cybersecurity, hardware deployment, etc. The size of the pool is in the end relevant for economic viability at the same time as for scalability.

During nominal operation, the two EAF sites are available. The execution of power instructions follows a simple priority rule, alternatively requesting from a site to be activated as the first stage and then interlocking the sites' latching thresholds. Priority turnover is done at staff shifts, to balance the sites' requests. At the site level, the selection of the EAF is left to the plant operator, since the tap-changer design is similar. In the case of the unavailability of a site, the completion of stage instructions is carried out by the remaining site, provided that the two on-site EAF are available. This gives a total of four simple combinations for which a set of $\{F_b\}$ is defined. The parameters for the inequality are collected at each site and tested according to the regulation described in Section IV.

B. Primary control performance

The performance of the control of the pool response to the FCR is based on the rules of the national TSO where the entity is registered. In France, registration is made of a set of certification tests: a sequence of 15 min steps (± 15 mHz, ± 50 mHz, ± 200 mHz) controlling the dynamics and stability of the response, and a continuous regulation test of eight hours.

Fig. 9. Pool response to +200 mHz step (a) and -200 mHz step (b).

An example of a power response is shown in Fig. 9, extracted from the most restrictive test: steps of ± 200 mHz (i.e., ± 10 MW). The response must reach 50% of PCR within 15 s and 95% of PCR within 30 s including a 10 mHz tolerance.

Active power data is collected at 1 s intervals from each DP. The data is locally synchronized, timestamped, and centrally aggregated. The control performance has been assessed during the implementation and the validation of the method. The time delay is minimum as the implementation is done as close as possible to the loads and the control is implemented in an asynchronous manner. In addition, all response times (data acquisition, actuators and process) have been validated by the TSO method. As seen in Fig. 9, the active power of the entity fulfills the TSO dynamic requirements. The dynamic performance is compliant no matter what the configuration of the pool is, as long as at least two of the EAF and two of the electrolysis lines are available for regulation.

In the presented entity, no direct inter-dependence of regulated and non-regulated processes has been observed. However, the remaining consumption introduces noise into the overall FCR response: close to 3 % of the pooling power. This estimate is to be compared with $\simeq 5$ % of the total entity of the PCR. Moreover, unlike generators, the set of aggregate power has natural fluctuations with no relation to the regulated power. The assessment of the performance of the FCR requires estimating the consumption baseline. Filtering methods are usually implemented to discriminate the FCR response from the baseline fluctuations and auxiliary noise. If the consumption baseline presents a low cut-off frequency, the auxiliary noise spectrum is spread, and overlaps the PCR spectrum, which makes the control more difficult.

The French TSO carries out an *ex-post* performance control through a proprietary algorithm based on real-time telemeasurements. The complex and precise control of the TSO is not presented here, but a statistical analysis is proposed to get a visual assessment of the performance. In the following, K_{reg} refers to the committed gain in MW/Hz and $\hat{K}_{reg}$ to the estimate of K_{reg} from a dataset. The method is based on a LOESS nonparametric regression [35], a locally weighted regression smoothing the baseline. The residuals of the fitted baseline are extracted and linearly regressed with the coordinated frequency deviations. The slope of the regression assesses the regulating energy $\hat{K}_{reg}$ of the pool.

(a) Assessed gain $\hat{K}_{reg}$ with LOESS (b) LOESS residuals vs. TSO frequency baseline smoothing.

Fig. 10. Performance assessment of the pooling strategy.

Fig. 11. Performance analysis of the real FCR response with LOESS baseline smoothing (time window of 4 h).

LOESS regression introduces a span parameter defining the dataset length of the moving window for which the local weighted regression is carried out. The span is defined as the ratio between the length of the window dataset and the length of the total dataset. A set of spans has been tested with the dataset to find the best coefficient of determination giving an indication of the best fit. The obtained span is 0.15, which corresponds to a 36 min window. A tri-cubic relation is applied within that window [35]. The assessment of $\hat{K}_{reg}$ finally gives a value of 50.9 MW/Hz with a coefficient of determination R^2 of 0.58, as shown in Fig. 10. The quality of the K_{reg} estimate ($\hat{K}_{reg}$) fully depends on the baseline determination and natural fluctuations. A correlation coefficient higher than 0.6 is a good estimate with consideration to the complexity of the multi-site configuration. In our case, $\hat{K}_{reg}$ remains stable over time. In rare events, $\hat{K}_{reg}$ can drift because of technical issues or process reconfigurations, e.g. removal or adjunction of electrolysis cells. Informative mechanisms (default alerting, production planning) are in place to require adjustment of the response or re-declaration of a new gain to the TSO.

The LOESS regression provides an initial statistical assessment of the performance analysis of the real FCR response, visually illustrated in Fig. 11 with a time length of 4 h. The method avoids a negative impact of a phase difference and is robust to a FCR response delay. However special care must be taken when the frequency signal is not locally stationary and steep gradients of consumed power occurs, for instance, due to electrode breaches or changes in the processes' set-points.

C. Certification and viability

From the industrial processes point of view, changes in the production occur as we act on processes (either discrete or continuous ones). The implemented constraint that the overall yearly production should remain constant makes that action acceptable for industry. It is undoubtedly a selling point for potential flexible clients as, on a yearly basis, there are possible additional revenues selling flexibility to an aggregator in the form of a constant yearly forfeit. Indeed, the global constraint for the industrial process to have the same production over a year insures that, whatever use of the process for frequency support, the industrial process enabling its flexibility can only benefit from this regulation.

The complex pooling of three large end-users involving six regulating assets has become the first multi-site entity ever certified in France and constitutes a breakthrough in provisioning a primary frequency reserve to the grid, currently in operation (to the best of our knowledge, it is a first worldwide as well). From the point of view of the aggregator, this service is proven to be economically viable and functional for industrialization, being in operation since more than a year. On the end-user side, this innovative and effective pooling strategy brings new incentives to industrial consumers. In 2017, France joined the shared call for tender for FCR provision and the bidding platform "Regelleistung." The gain expectancy observed over 2018 for a French entity is 12.6 €/MW/h (min: 7.2 €; max: 23.1 €), thus offering new revenues to end-users.

Finally, the French TSO RTE has carried out a performance control with respect to its internal standards and certified the entity in accordance with ENTSO-E policy [3]

VII. CONCLUSION

This paper presents a pooling strategy for discrete and continuous industrial loads to provide *frequency containment reserve*. The method produces satisfactory solutions in compliance with the end-user flexibilities with regards to dynamic requests and energy balance. The characterization of end-user limits is crucial, although it presents a major challenge.

The concrete realization of a pool made of end-users releasing 10 MW of PCR based on a 150 MW of cumulated flexible continuous and discrete loads has demonstrated that a smart arrangement of demand-side flexibilities can simultaneously fulfill the grid requirements and comply with industrial process constraints. This brings high value to modern power systems, particularly those affected by the recent penetration of renewable generation, adding new built-in sources of primary reserve. As the first FCR multi-site entity ever certified in France (and in the world to the best of our knowledge), this achievement takes part in the development of smart grids, initiating a new equilibrium of energy markets.

Further work will first address the sub-optimal solution chosen to regulate the solicitation of the flexible loads. Moving to an optimal solution through a complete modeling of the problem is a major research effort, currently in progress. A next step is to be conducted to scale up the pool: increase the number and the type of loads, diversify the technologies,

and introduce different time frames for the process requests, without putting aside the cybersecurity of the infrastructure. A specific insight is to be studied to carry out a dynamic optimization of FCR potential and scheduling coupled with real-time regulation, seeking to dynamically set the pool of loads, in particular via an artificial intelligence implementation. New challenges will also come with the volume expansion, for instance, the characterization and mitigation of multiple sources of noise and uncertainty, dynamic portfolio management and forecasting, as well as a scalable and robust regulation infrastructure.

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