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Energy Limits in Primary Frequency Control with Short-Term Frequency-Band Allocation

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***Abstract*—Frequency stability of large power systems requires the use of very fast flexible resources to contain frequency excursions. Potential candidates able to provide such flexibility are demand response and storage. However, capacity and energy constraints on these resources usually restrict their use to exceptional and rare events. Recently, some interesting works have been trying to integrate energy constraints in power system operations. In this paper, we discuss one of them : short-term frequency-band allocation. Periodically, the system operator may change dead-band zones and saturation levels of resources proportional controllers and thereby manage the energy constraints in a dynamical way. The paper presents the model and shows some first results highlighting its interest : the integration of capacity limits, energy limits and storage direction preferences. Finally, some limits of the approach are discussed : the inability to recover efficiently past delivered energy.**

***Index Terms*—Demand response, Energy Storage, Power System Control, Automatic frequency control**

I. Energy management insights from literature

Primary frequency control is one of the most important part of power system frequency stability. Its main role is to provide damping to system frequency deviations and maintain system frequency close to its nominal value f_0 (i.e. 50Hz in ENTSO-E). A proportional control is used in which Generation units (resp. flexible Consumers) will adapt their power output (resp. power consumption) proportionally to frequency deviations.

In power systems, some power capacity (MW) must be available whole year long and follow frequency changes as fast as possible to prevent large frequency excursions and limit frequency oscillations. This **power capacity requirement** is justified for exceptional events (e.g. loss of large power unit,...). Therefore, a reserve purchasing process is performed regularly by the different transmission system operators (TSOs). Each TSO may purchase reserve on different time periods from years up to a week ahead of operations. All TSOs of a certain synchronous interconnection will have to reserve a predefined amount of capacity. It will have to be completely deployed when system frequency reaches the extreme steady-state limits (i.e. ±200mHz in ENTSO-e CE). The total requirement is defined by a reference event [1]. This events corresponds to the loss of the two biggest units in the synchronous zone (i.e. 3000MW in CE).

In addition to this security-related constraint, there also exists a less explicit **energy capacity requirement**. As the frequency deviations are mostly unpredictable, all participants never know for **how long** they will have to provide the committed reserve capacity. This suggests that the final energy injected to (resp. withdrawn from) the grid is unpredictable. As some participants could face limits in the total amount of **energy** they could provide in excess of/below their **initial schedule**, this becomes rapidly a problem.

Two additional comments are necessary to understand the **energy requirement** issue. On the one hand, *Synchronous Time Control* provides a theoretical limit to the cumulative energy that must be provided in the long-run. The natural frequency is a reference for time counters and clocks. *Time control* in power systems insures that the integral of frequency deviations stay within a certain number of cycles [2]. This prevents clocks time references to drift away from UTC time. As a side effect, it thereby maintains the long-run energy requirement of primary control around zero.

On the other hand, *Time control* observes the output of the frequency control loop. Exclusively resources providing loss-less and purely symmetric flexibility for positive and negative frequency deviations would reach the zero-sum energy level. However, this ideal case is unrealistic. Time delays in units dynamics, non-linearity in storage (i.e. storage losses,...), demand response (asymmetric behavior) and in the system itself (non-constant power system parameters as natural load frequency dependence changes with time) as well as the dead-band of the power frequency curve (see figure 3) imply that the energy required to zero frequency deviations integral will come from different sources at different time of the day in a non-controllable way. It would therefore not guarantee resources to be able to deliver the exact same amount of energy (with opposite sign) than what was spent in previous reactions.

However, Primary frequency control could be organized in some ways to circumvent the energy requirement problem. Some interesting ideas are detailed below.

1) Frequency band allocation: As shown in figure 1, the power-frequency curve must be filled in by the partic-

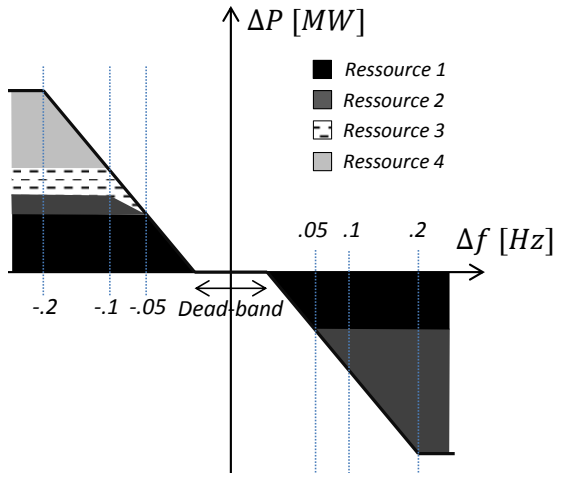


Figure 1. Frequency band allocation. Resource 1 offers a symmetrical service around zero Hz. Resource 2 offers a much larger service for downward regulation (positive frequency deviation) than for upward regulation (negative frequency deviations). Both resources 3 and 4 offer upward regulation.

ipating units in a very precise way. Limited-energy units (e.g. resource 4 on fig. 1) are deployed during extreme events where large frequency deviations are observed (i.e. $|\Delta f| > 100mHz$). Table I illustrates for the year 2012 the different utilization rate of flexibility when activated within precise system frequency bands. We may observe that year-long asymmetrical participation in the extreme event bands requires a single half-hour of storage relatively to the provided capacity.

2) Offset Scheduling: The energy provided by limited-energy units to primary control may be compensated by offset scheduling strategies [3]. Resources use a base-point offset to recover the energy consumed in excess (or not-consumed) in the past. For instance, resources that had to deliver $+1MWh$ in past reactions could offset their initial schedule of $-1MW$ during 1 hour. This offset will tend to change the steady-state system frequency. Consequently, secondary control and the system itself (i.e. natural dependency of loads) will react and thereby provide the required energy. Both primary and secondary control need to be over-sized and the energy storage capacity must have some minimal values [4].

3) Filters and Centralized control: The high-frequency component of system frequency deviations are extracted by a high-pass filter and control fast and limited-energy units. Slower variations will be controlled by slower units. This allow the limited-energy units to alternate more often around their economic base-point and limits the long-term energy they have to provide. An adjustment mechanism is still required to insure zero-sum activation. This is also performed by some form of offset scheduling coordinated with slow units economic base-point change. An existing example can be found in the PJM interconnection (see *DReg signal* in [5]).

4) Short-Term frequency band allocation: The object of this paper. At each market period (i.e. quarter of hour in UCTE), the power-frequency curve is redefined by the TSO. This process restrict the use of resources in the different bands depending on their energy state, power capacity limits and costs. More details are given below.

A. Motivations of the study

Short-Term Frequency Band Allocation (SFBA) is a way for primary control to profit from the different characteristics of flexible assets.

Limited-energy resources will thereby be able to share the energy burden imposed by primary control as optimally as possible. There exists periods of time where frequency deviations are biased, and when the system frequency stays on average below (resp. above) f_0. During these times, all resources will be progressively discharged (resp. charged). When limited energy resources are used in combination with non-limited ones, the SFBA process will limit the energy storage capacity required to continuously provide service.

As presented above, different strategies have been developed for limited-energy resources to rely on secondary control and other adjustment mechanism to recover past delivered energy. We would like to test how different **primary control** participants could share among themselves the energy burden without **any impact** on the external system. In particular, limited impact is foreseen on total primary control reaction and on secondary control. We therefore intend to capture interdependence between secondary and primary control. The results of the study do not highlight this particular feature but it is left for future research.

Moreover, we would like to enforce certain constraints as the limited capacity of certain resources or the asymmetric energy storage capacity. Indeed, some demand response resources are only able to consume less at first, and then recover the missing energy by consuming more. We further would like to adapt allocation to take advantage of the different cost components of all participants.

This paper has a threefold objective. Firstly, the paper highlights the potential benefits of short-term allocation frequency-band. Namely : integration of capacity and energy limits into primary control dispatch. Secondly, it shows by two extreme cases the improvement potential of the discussed model. Finally, it highlights the limits of the model. Particularly, some non-limited energy resources must be part of primary control in order to limit the needs to over-size reserves.

The paper is organized as follows. Section II describes the system model used in simulations. Section III explains the linear discrete approach chosen to integrate non-linear characteristics. Section IV provides test cases. Finally, we discuss the results.

II. Model description

The objective of the model is to minimize total costs of providing primary control (related to frequency deviations) by using storage and demand response. We start by optimally construct a reference power-frequency curve.

Table I
ILLUSTRATIVE ENERGY VOLUMES AND POWER CAPACITY IN EACH FREQUENCY BAND - BELGIUM 2012. SOURCE : ELIA SYSTEM OPERATOR. THE FIGURES ARE NOT COMPLETELY PRECISE DUE TO LIMITED TIME RESOLUTION OF THE MEASUREMENT SIGNAL (10 SECONDS)

Frequency Band [Hz]	[-0.2 ;-0.1[	[-0.1;-0.05[	[-0.05 ;-0.01[	]0.01 ;0.05]	]0.05 ;0.1]	]0.1 ;0.2]
Available capacity [MW]	47.5	23.75	23.75	-23.75	-23.75	-47.5
Annual energy [MWh]	25	963	34546	-34758	-767	-9
Use [% of time]	0.005%	0.46%	16.56%	16.66%	0.37%	0.002%
Quarter hour values						
Minimum Qh energy [MWh]	-	-	-	-6	-6	-2
Maximum Qh energy [MWh]	6	5	6	-	-	-
Minimum Qh energy [%]	-	-	-	100%	100%	17%
Maximum Qh energy [%]	51%	79%	100%	-	-	-

Let us define a set $\mathcal{I}$ of flexible assets. Each asset may be controlled by external signals and will respond with known dynamics. We suppose that all assets follows first-order dynamics with some technical limits (see Table II).

Table II
TECHICAL LIMITS OF PARTICIPANT i ($\forall i \in \mathcal{I}$)

Name	Unit	Description
T_i	s	Response Time
$\overline{\Delta P}_i$	MW	available upward-regulation capacity
$\underline{\Delta P}_i$	MW	available downward-regulation capacity
$\overline{E}_i$	MWh	maximum upward energy contribution
$\underline{E}_i$	MWh	minimum downward energy contribution

The asset i primary control reaction on time t is denoted $R_{i,t}$. For convenience, the reaction is divided into positive $R^+_{i,t}$ and negative $R^-_{i,t}$ components. The dead-band zone of the asset i is defined by two threshold values of the frequency deviation $\Delta f^+_{i,db} < \Delta f^-_{i,db}$. Positive reaction is zero when $\Delta f^+_{i,db} < \Delta f_t$ as well as negative reaction when $Delta f_t < \Delta f^-_{i,db}$. For any value of the frequency deviation below (resp. above) the threshold $\Delta f^+_{i,sat}$ (resp. $\Delta f^-_{i,sat}$), each asset must insure full deployment of the committed positive (resp. negative) capacity. This implies saturation of the control for large deviations.

A. System model

The evolution of the system frequency is described by equation (1), similarly to [6].

$$\frac{d}{dt}\Delta f_t = \frac{1}{M}(ACE^{ol}_t + ACE^{cl,ext}_t + \sum_{i\in\mathcal{I}} R_{i,t} + R^{ext}_t - L\Delta f_t + S_t) \quad (1)$$

It corresponds to a single bus system were control reactions in one particular zone are highlighted, as shown by figure 2. The left hand side is the rate of change of frequency (ROCOF) and is equal to the instantaneous imbalance between power generation and demand [MW], divided by the rotating masses angular momentum ($M = I_n\omega_0 = 4.10^6[kg \cdot m^2/s]$). The initial imbalance (in brackets) is composed by the open-loop Area Control Error (ACE) in the highlighted zone (ACE^{ol}_t) and the closed loop Area Control Error of all external zones connected in the same interconnection ($ACE^{cl,ext}_t$). The natural frequency dependence of all loads in the interconnection provides some damping to the evolution of the frequency ($L\Delta f$). In the zone of interest, the open-loop ACE is diminished by all negative feedback reactions and control actions : the secondary control reaction (S_t) and the sum of all assets primary control reactions ($\sum_{i\in\mathcal{I}} R_{i,t}$). All manually activated reserves (e.g. tertiary control) are included in the open-loop area control error.

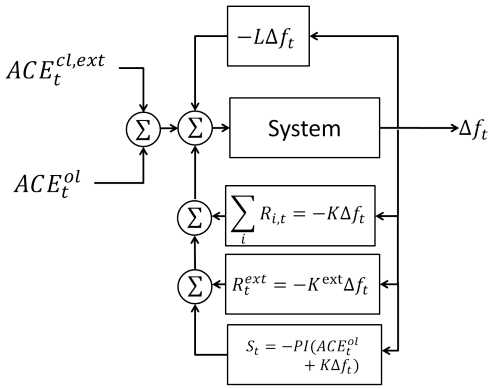


Figure 2. Illustration of the considered system

Primary control Dynamics ($\forall t$ and $\forall i \in \mathcal{I}$)

$$\frac{d}{dt}R_{i,t} = \frac{1}{T_i}(\Delta P^+_i(\Delta f_t) + \Delta P^-_i(\Delta f_t) - R_{i,t}) \quad (2)$$

The dynamics expressed in (2) are non-linear. The next subsection explains how the set-points ΔP^+_i and ΔP^-_i may be formulated through a mixed-integer approach.

Secondary control Dynamics ($\forall t$ and $\forall i \in \mathcal{I}$)

$$\frac{d}{dt}S_t = \frac{1}{T_M}(-a_m ACE^{cl}_t - b_m \int_{\tau=0}^{t} ACE^{cl}_\tau d\tau - S_t) \quad (3)$$

Secondary control is a proportional-integral controller that tries to counteract the closed loop ACE : $ACE^{cl}_t = ACE^{ol}_t + S_t + K\Delta f_t$. **Note :** In the simulations performed, as mentioned above, secondary control is simulated for the zone of interest (i.e. Belgium in our case). We also need to consider some *saturation* level. Indeed, secondary control is rather often (25% of time in 2012) deployed at its maximum or minimum available capacity in the Belgian system. In order to keep the linearity of equation (3), we simply pre-process the ACE.

Capacity limits : ($\forall t$ and $\forall i \in \mathcal{I}$)

$$\underline{P}_i \le R_{i,t} \le \overline{P}_i \quad (4)$$

Energy limits : ($\forall t$ and $\forall i \in \mathcal{I}$)

$$\underline{E}_i \le E_{i,0} + \int_0^t R_{i,\tau}\, d\tau \le \overline{E}_i \quad (5)$$

The energy and capacity limits could be relaxed in the cost function. Nevertheless, the worst case scenario must be considered to assess the extreme values of $R_{i,t}$ and its integral over time.

III. Primary control : Mixed integer linear approach

The evolution of primary control reaction is expressed through a non-linear equation.

We use a discrete allocation of the power frequency curve. Let us define the total droop K of the zone, and $\mathcal{F}$ frequency intervals such that $\forall \phi \in \mathcal{F} : \Delta f \in]f_{\phi-1}; f_\phi]$. Figure 3 illustrates the concept. We also define two frequency intervals $\mathcal{F}^+$ and $\mathcal{F}^-$ respectively related to upward and downward regulation (resp. negative and positive Δf).

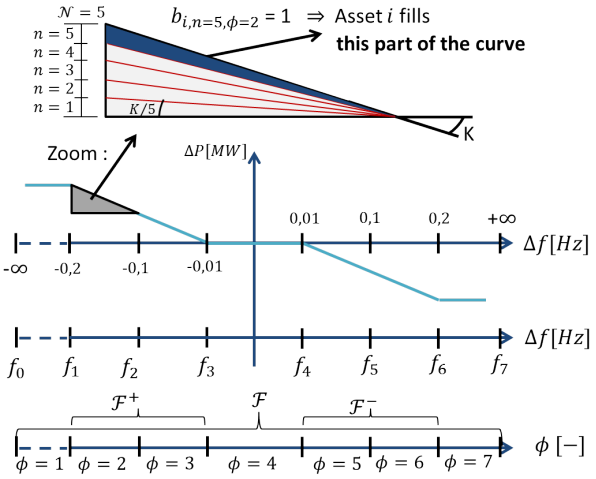


Figure 3. Illustration of the discrete approach.

In each of these frequency interval, the derivative of the *power frequency curve* w.r.t. Δf is equal either to 0 (constant or no flexible power) or to $-K$ (constant negative feedback droop). Therefore, optimization must decide which of the flexible assets ($i \in [1..\mathcal{I}]$) should deliver some of the required droop. Let us assume that $\mathcal{N}$ equal portions of the required droop can be shared in each frequency interval. We denote $n \in [1...\mathcal{N}]$ as the index of each portion.

Thanks to this discrete approach, attributing to each asset i, a portion n of the droop in interval ϕ, consists in setting a binary value $b_{i,n,\phi}$ to 1.

Power frequency curve ($\forall \phi \in [\mathcal{F}^-, \mathcal{F}^+]$)

$$\sum_{i=1}^{\mathcal{I}} \sum_{n=1}^{\mathcal{N}} b_{i,n,\phi} = \mathcal{N} \quad (6)$$

Equation (6) imposes that the droop in each discrete frequency interval outside of the saturation/dead bands is exactly equal to $-K$.

Capacity limits : ($\forall i \in \mathcal{I}$)

$$\sum_{\phi \in \mathcal{F}^+} \sum_{n=1}^{\mathcal{N}} b_{i,n,\phi} \frac{K}{N} (f_\phi - f_{\phi-1}) \leq \overline{\Delta P_i} \quad (7)$$

$$\sum_{\phi \in \mathcal{F}^-} \sum_{n=1}^{\mathcal{N}} b_{i,n,\phi} \frac{K}{N} (f_{\phi-1} - f_\phi) \geq \underline{\Delta P_i} \quad (8)$$

For each asset, the maximum (resp. minimum negative) positive power capacity that may be called at some point in time must stay below or equal of the asset's capacity limits. Therefore, the cumulative sum in all negative (resp. positive) frequency band is constrained by those limits.

We denote below by the term *active* the frequency band in which the deviation Δf_t can be found on time t.

As can be perceived from Figures 1 and 3, the individual reactions in the active band on time t can be decomposed in a *continuous reaction* and a *saturated reaction*. The first reaction corresponds to the part of the desired primary control reaction that changes continuously with Δf_t in the active band with the negative feedback $-K\Delta f_t$. The second is the sum of all reactions situated in the bands that are closer to zero than the active band. For the saturation part, complete deployment of the committed capacity in the saturated bands is required.

The set-points of the different assets are computed below. We firstly need to treat efficiently the information on continuous and staurated part of the reactions.

Time evolution of system frequency ($\forall \phi \in \mathcal{F}, t$)

$$u_{\phi,t} \leq 1 + \frac{f_\phi - \Delta f_t}{B_1} \quad (9)$$

$$u_{\phi,t} \leq 1 + \frac{\Delta f_t - f_{\phi-1}}{B_1} \quad (10)$$

One single interval is active ($\forall t$)

$$\sum_{\phi \in \mathcal{F}} u_{\phi,t} = 1 \quad (11)$$

A second set of binary variables $u_{\phi,t}$ indicates whether or not the frequency deviation Δf_t is in the interval $]f_{\phi-1}; f_\phi]$ at any time t. B_1 is a sufficiently large constant that always guarantee the left hand side to be positive.

Selection of continuous reactions ($\forall i, n, \phi \in \mathcal{F}, t$)

$$\alpha_{i,n,\phi,t} \leq b_{i,n,\phi} \quad (12)$$

$$\alpha_{i,n,\phi,t} \leq u_{\phi,t} \quad (13)$$

$$b_{i,n,\phi} + u_{\phi,t} - 1 \leq \alpha_{i,n,\phi,t} \quad (14)$$

A third set of binary variables $\alpha_{i,n,\phi,t}$ is the product ($b_{i,n,\phi} * u_{\phi,t}$) and indicates whether or not the asset i contributes to the portion of droop n in the active interval on time t, and therefore the the *continuous part* of the primary control reaction.

Continuous part of the deviation on time t

$(\forall i, n, \phi \in \mathcal{F}^+, t)$

$$-B_2(1-\alpha_{i,n,\phi,t}) + (f_\phi - \Delta f_t) \leq \Delta^+ f_{i,n,\phi,t} \quad (15)$$

$$\Delta^+ f_{i,n,\phi,t} \leq (f_\phi - \Delta f_t) + B_2(1-\alpha_{i,n,\phi,t}) \quad (16)$$

$$0 \leq \Delta^+ f_{i,n,\phi,t} \leq B_2 \alpha_{i,n,\phi,t} \quad (17)$$

$(\forall i, n, \phi \in \mathcal{F}^-, t)$

$$-B_3(1-\alpha_{i,n,\phi,t}) + (f_{\phi-1} - \Delta f_t) \leq \Delta^- f_{i,n,\phi,t} \quad (18)$$

$$\Delta^- f_{i,n,\phi,t} \leq (f_{\phi-1} - \Delta f_t) + B_3(1-\alpha_{i,n,\phi,t}) \quad (19)$$

$$-B_3 \alpha_{i,n,\phi,t} \leq \Delta^- f_{i,n,\phi,t} \leq 0 \quad (20)$$

A continuous variable $\Delta f_{i,n,\phi,t}$ is constrained to be equal to the *continuous part* of Δf_t on time t. The continuous part of the frequency deviations is the difference between Δf_t and the deviation at the edge of the active interval that is the closest to zero. This only holds when asset i is active in interval ϕ for portion n of the droop ($\alpha_{i,n,\phi,t} = 1$). It must otherwise be zero. We choose B_2 and B_3 such that we have $B_2 >= |f_{\phi-1} - \Delta f_t|$ and $B_3 >= |\Delta f_t - f_\phi|$ on each time t.

Saturated activation

$(\forall i, \phi \in \mathcal{F}^+, t)$

$$-B_4(1 - \sum_{\varphi=1}^{\phi-1} u_{\varphi,t}) + \sum_{n=1}^{\mathcal{N}} b_{i,n,\phi} \leq A^+_{i,\phi,t} \quad (21)$$

$$A^+_{i,\phi,t} \leq \sum_{n=1}^{\mathcal{N}} b_{i,n,\phi} + B_4(1 - \sum_{\varphi=1}^{\phi-1} u_{\varphi,t}) \quad (22)$$

$$0 \leq A^+_{i,\phi,t} \leq B_4 \sum_{\varphi=1}^{\phi-1} u_{\varphi,t} \quad (23)$$

$(\forall i, \phi \in \mathcal{F}^-, t)$

$$-B_5(1 - \sum_{\varphi=\phi+1}^{\phi_{max}} u_{\varphi,t}) + \sum_{n=1}^{\mathcal{N}} b_{i,n,\phi} \leq A^-_{i,\phi,t} \quad (24)$$

$$A^-_{i,\phi,t} \leq \sum_{n=1}^{\mathcal{N}} b_{i,n,\phi} + B_5(1 - \sum_{\varphi=\phi+1}^{\phi_{max}} u_{\varphi,t}) \quad (25)$$

$$0 \leq A^-_{i,\phi,t} \leq B_5 \sum_{\varphi=\phi+1}^{\mathcal{F}} u_{\varphi,t} \quad (26)$$

A final set of discrete variable expresses the *saturated part* of the individual reaction. It sums up all reactions that are saturated, as they have been deployed in bands that are closer to zero than the active band. B_4 and B_5 are large enough constants.

Reaction Set-Point

$$\Delta P^+_{i,t} = \sum_{\phi in \mathcal{F}^+} \sum_{n=1}^{\mathcal{N}} \frac{K}{\mathcal{N}} \Big(\Delta f_{i,n,\phi,t} + (f_\phi - f_{\phi-1}) A^+_{i,n,\phi,t} \Big) \quad (27)$$

$$\Delta P^-_{i,t} = \sum_{\phi in \mathcal{F}^-} \sum_{n=1}^{\mathcal{N}} \frac{K}{\mathcal{N}} \Big(\Delta f_{i,n,\phi,t} - (f_\phi - f_{\phi-1}) A^-_{i,n,\phi,t} \Big) \quad (28)$$

The reaction set point is the sum of the continuous and saturated part of the reaction. The expressions found for $\Delta P^+_{i,t}$ and $\Delta P^-_{i,t}$ can now be injected in equation (2) in order to capture the dynamics of primary control.

The cost function and Energy limits depends on the test case considered, and are detailed below.

IV. Test Cases

As mentioned above, short-term adjustments of the power-frequency curve can help to manage the energy limits of certain flexible assets. We propose different test cases to illustrate potential benefits.

The energy storage capacity of the different assets is denoted by the Energy to Power ratios $r^+_i = \overline{\Delta E_i}/\overline{\Delta P_i}$ and $r^-_i = \underline{\Delta E_i}/\underline{\Delta P_i}$ expressed in hours.

Comparison criteria are used to highlight what SFBA process could bring to system operator.

$$Oversizing : < P^{max}_{rel,i}, P^{min}_{rel,i} >$$

Maximal and minimal relative power capacity required to provide continuous service on a monthly basis for asset i are used to assess the over-sizing.

$$P^{max}_{rel,i} = \frac{\overline{\Delta P_i}}{0.2\,K} \quad (29)$$

Relative power capacity refers to the ratio between the necessary installed power capacity of the limited-energy resource with the committed capacity for primary control. The sum of all required capacity

A. Ideal symmetrical allocation

Time control limits the theoretical cumulative frequency deviations to ±6000 frequency cycles in extreme cases.

$$P^{max}_{rel,i} \geq 2 \frac{6000[-]}{0.2[Hz]\,3600[s/h]\,r_i[h]} \quad (30)$$

Table III shows criteria values for limited-energy resources with different Energy to Power ratio. The values are valid for ideal and loss-less symmetric participation in primary control. The factor 2 suggests that storage capacity would need to be charged at half of its maximal capacity to provide symmetric service.

Table III
Maximal and minimal oversizing

r_i	$P^{max}_{rel,i}$	$P^{min}_{rel,i}$
0.25	66	-66
0.5	33	-33
1	16.7	-16.7
2	8.3	-8.3

B. The Week test case

The week test case simulates the first week of the year 2012 in the Belgian system. The purpose is to get results with realistic order of magnitude. We present in figure 6 a comparison of two runs of the model.

In both cases, the model is run in a rolling horizon process (see figure 5). For each market period MP in the horizon h, the model must respect all the capacity and energy limits, but also must completely fill in the power-frequency curve.

In this case, we suppose that each asset i is characterized by its Energy to Power ratios (r^+_i,r^-_i). The maximum/minimum capacity is a variable and its sum (in

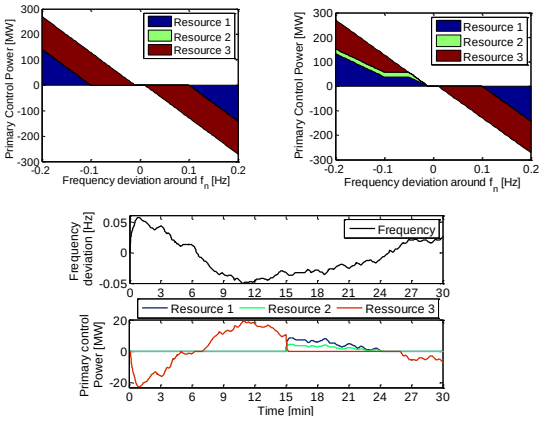


Figure 4. Result of a half hour simulation.

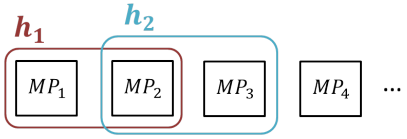


Figure 5. Rolling horizon principle. In this example, the horizon considers two market periods (e.g. two successive periods of 15 minutes each).

absolute terms) is minimized in the objective function of the model.

$$\underset{horizon}{\textbf{minimize}} \quad \sum_{i\in\mathcal{I}} (\overline{\Delta P}_i - \underline{\Delta P}_i) \tag{31}$$

Therefore, the energy limit constraint (5) is reformulated as below. $E_{i,h}$ is the energy state at the beginning of the horizon, and T_h the starting time of the horizon.

$$r_i^- \underline{\Delta P}_i \leq E_{i,h} + \int_{T_h}^{t} R_{i,\tau}\, d\tau \leq r_i^+ \overline{\Delta P}_i \tag{32}$$

Equation (32) requires some knowledge about the asset reaction and the time evolution of its integral. Therefore, as this knowledge is not available in practice, we consider two cases.

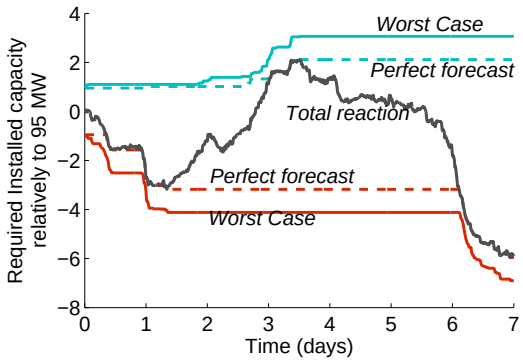


Figure 6. Result of the optimization for Worst Case and perfect forecast SFBA. They are 3 identical participants. The chart represents the oversize maximum and minimum capacity that the participants must dispose of to be able to provide the service. Blue lines represents $P^{max}_{rel,i}$. Red lines are for $P^{min}_{rel,i}$. In all cases, $r_i^+ = 0.25h = r_i^-$.

The first set of runs is a SFBA under *perfect forecast*. Therefore the integral is perfectly known. The second set of runs is a SFBA under *worst case*. For each band in the power-frequency curve, the worst case consists in a constant activation of the total offered flexibility in the band. The first message of the study is represented in figure 6.

Figure 6 shows the oversize criteria evolution The Total reaction corresponds to the integral of the total primary control response : $\sum_{i\in\mathcal{I}} \int R_{i,t} dt$. As mentioned in the symmetric case, the total reaction would lead oversize criteria to be very high (up to 66 times of the initial needs). Figure 6 shows clearly that, if exclusively limited-energy resources are performing primary control, the oversize criteria would at least be higher than the one presented in Table III.

C. Combination with non-limited resources

A final test case is considered in which a power generation plant may provide $\pm 20MW$ of flexibility. These $20MW$ can not fully fill the first

1) Comparison with previous case: to be filled in

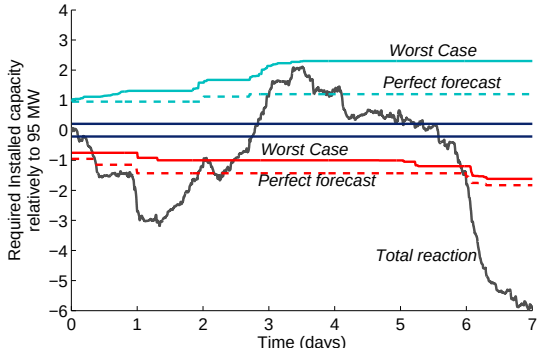


Figure 7. Result of the optimization for Worst Case and Perfect forecast SFBA, with the use of . Blue lines represents $P^{max}_{rel,i}$. Red lines are for $P^{min}_{rel,i}$. In all cases, $r_i^+ = 0.25h = r_i^-$.

2) Asymmetric storage: Some limited-energy resources can be considered as a *positive* (resp. *negative*) *asymmetric storage* when they need to be charged (resp. discharge) before they can discharge (resp. charge) the same amount of energy. This is the case of some demand response, which must decrease power demand before increasing it to recover the shifted energy.

V. Conclusion

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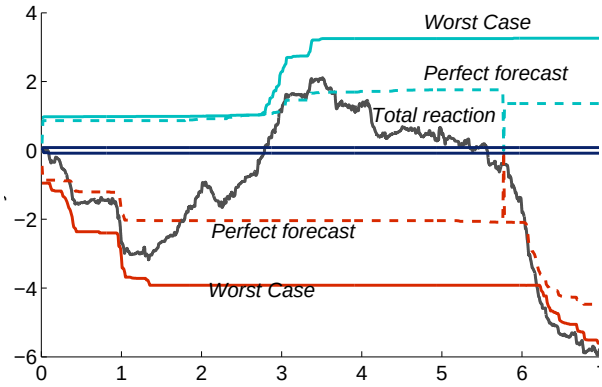


Figure 8. Results of the case with asymmetric storage : $r_i^+ = [0.25\ 0\ \infty]$ and $r_i^- = [0\ 0.25\ \infty]$. The large dip is due to a problem during one of the runs (all constraints could not be respected). The two plain lines around zero show the $\pm 20MW$ limits of the non-limited resource. **Note :** the dynamics of the limited-energy resources and non-limited one are different : $T_i = [3\ 3\ 6]$.

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