DISTRIBUTED AND COORDINATED DEMAND RESPONSE FOR THE SUPPLY OF FREQUENCY CONTAINMENT RESERVE (FCR)

Gaspard LEBEL
Raphaël CAIRE
Nouredine HADJSAID
Univ. Grenoble Alpes, G2Elab
CNRS, G2Elab
F-38000 Grenoble, France
gaspard.lebel@g2elab.grenoble-inp.fr

Karel KUYPERS
Dep. of Electrical Engineering
Technische Universitet Eindhoven
Eindhoven, the Nederland
k.kuypers@student.tue.nl

Stéphane BEDIOU
Alain GLATIGNY
Energy Division,
Schneider Electric Industries
F-38000 Grenoble, France
stéphane.bediou@schneider-electric.com

ABSTRACT

The availability of frequency-controlled reserves is essential for any Utility to secure the power system in both interconnected and microgrid contexts. This paper presents a concept of coordinated Distributed Energy Resources (DER), load modulation willing to supply frequency-controlled reserves. These reserves, compliant with both Frequency Containment Reserves (FCR) and Under Frequency Load Shedding (UFLS) requirements, are provided through a structure of Virtual Power Plant (VPP). Physical demonstrations have already been performed on an off-grid system. HVAC variable speed motors and resistive loads control tests are now depending at the European scale within Dream FP7 project.

INTRODUCTION

European Utilities are currently facing up to large Electrical Renewable Energy Resources (RES-E) spreading. This occurs in a parallel context of bulk generation units decommissioning driven by climate and energy policies. Such trend is willing to deprive these Utilities of part of their historic frequency-controlled reserves suppliers. It is then willing to challenge the system security since RES-E generators can show less robustness face to large frequency excursions as observed during 2003 Italian blackout [1]. Such paradigm is topical in both interconnected and microgrid contexts.

It appears so the opportunity – that could perhaps even become a necessity – to distribute the frequency-controlled reserves over the network at any voltage level. These reserves could be supplied by either controlling Distributed Generation (DG) units or by performing load control through Demand Response (DR) solutions. The ability to distribute these frequency-controlled reserves over the network is technically enabled by the large diffusion of Information and Communication Technologies (ICT) close to any kind of dispatchable loads. The control of loads on a minute or even second basis used definitely not be doable in the past.

This paper presents so a patented ICT-based application, designed for the supply of frequency-controlled reserves to the power system. The solution developed within Dream[1] FP7 project is based on a coordinated shedding of distributed loads. The frequency range of operation targeted by the solution would encroach upon either the FCR or the Under Frequency Load Shedding (UFLS) range (Fig. 1). By doing so, the solution enables first to support the FCR in period of lack of bulk reserve. It could then pre-empt partly the blind tripping of UFLS relays face to major frequency excursions. Thus it could avoid to affect vital loads and save from disconnection the distributed generators whose availability is essential at any time for the system stability. The solution would comply as well with down regulation process thanks to the shedding of Distributed Generation (DG).

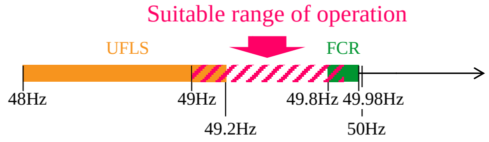

Figure 1: Suitable operation frequency range of smoother UFLS (data applied in ENTSO-E's Regional Group Continental Europe)

The first part of the paper presents the concept and its principle of operation. A second part is devoted to a presentation of the advances provided by the method proposed. A third part challenges finally the acceptability of the innovation by the Utilities and the DER owners involved in the VPP designed.

CONCEPT

The fast frequency regulation proposed by Grenoble INP, TU/e and Schneider Electric leads on a pool of Customer Energy Management Services' devices (CEMS). These CEMSs control the power supply of dispatchable loads, depending on the system frequency. To do so, each of these CEMSs embed frequency-based relays with remotely programmable thresholds. At the top of the CEMSs, a coordination platform is in charge of computing the frequency shedding and reconnection thresholds respected by each relay. The thresholds are defined in order to reproduce by aggregation at the system scale a targeted power-frequency characteristic.

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[1] Dream is a project funded by the European Commission under FP7 grant agreement 609359

This coordination enables finally to reproduce virtually the behavior of bulk generation units, as usually targeted by any Virtual Power Plant (VPP) structure.
The present structure constitutes an autonomous system able to provide frequency-controlled reserves, compliant with either the Frequency Containment Reserve (FCR) or Under Frequency Load Shedding schemes (UFLS).

Architecture

The system can be deployed locally at the scale of a secondary substation, a primary substation or even at a larger scale, not correlated with the network topology thanks to a cloud-oriented architecture. In topology-dependent architectures, the coordination platform which is a software, is embeded in the substation Remote Terminal Unit (RTU). Being an autonomous system, it is finally replicable autonomously from one substation to others or from one cloud-portfolio to others.

The CEMS itself is composed of a power meter, a frequency sensor, a communication channel and a microcontroller. These components can be either independent the one from another and linked by a local ICT bus or be an all-in-one component. The all-in-one component can be directly embed in a utility power meter in a "regulated world" or being an proprietary device located down the meter in a "deregulated world". The CEMS can embed as many triplets of {power meter, relay, comparator} as numbers of dispatchable loads willing to be driven independantly from one another.

Fig. 2 presents an architecture designed at the scale of the secondary substation, where the coordination platform is embed by the substation's RTU. Fig. 3(a) and 3(b) presents then examples of CEMS architectures. Fig. 3(a) presents an all-in-one CEMS, adapted to the domestic world. Fig. 3(b) presents a split architecture, willing to be deployed on an industrial site. It presents an HVAC system, with variable speed motors. In Fig. 3(b), the functions of each device are highlighted in green.

The selection of the architecture would be mainly driven by the wholesale and ancillary services market framework:

- Regulated
- Deregulated

and by the communication channels available at the devices location:

- Power Line Communication (PLC) available to link the Utility power meters and the substation RTU
- ADSL, 3G only, etc.

CEMS functions

The CEMS carries out two main functions:

1. Inform periodically or on event the coordination platform of the power willing to be shed by the relays it controls.
2. Process autonomously in real-time the frequency regulation, by driving the shedding or restoration of the loads he controls.

To do so, the CEMS leads first on the controller he embeds to measure the power consumption of the loads and forward this value to the coordination platform, thanks to its communication channel. The microcontroller is then in charge in real-time of driving the relay position, by comparing the system frequency measured locally with a frequency threshold received meanwhile from the coordination platform.

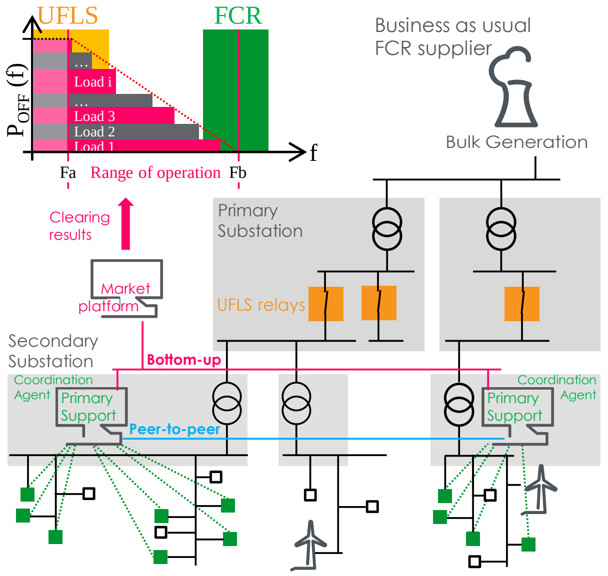
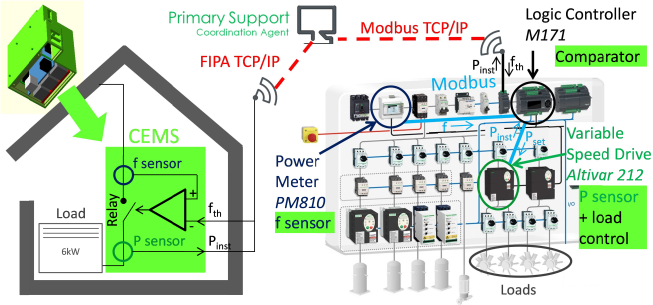


Fig 2. Large scale architecture



(a) Resistive loads (b) HVAC system

Fig 3. CEMS architectures

Coordination platform functions

The coordination platform carries out five major functions:

1. Gather from all of the CEMS the close to real-time data of the power amount available for shedding.
2. Gather the end-users load shedding acceptance, in term of both marginal activation cost and frequency range of contribution.
3. Set the load shedding order of each load of the portfolio, based on this acceptance criteria.

4. Calculate the frequency threshold of each load.
5. Broadcast the frequency threshold to each CEMS.

Coordination Platform – CEMSs Interactions

Fig. 4 presents a simplified flowchart that includes the two functions that belongs to the CEMS and the five major functions of the coordination platform previously detailed.

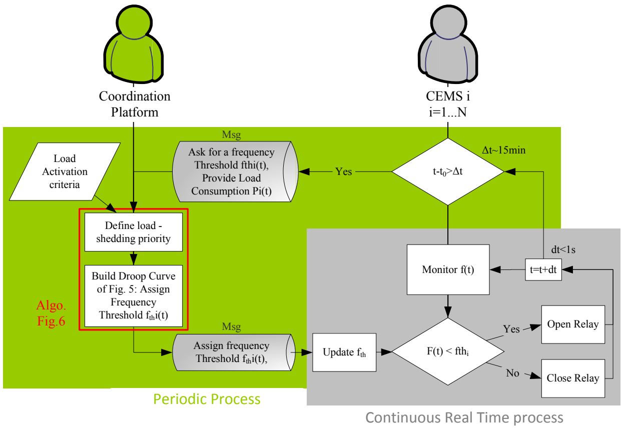


Figure 4: Flowchart and structure of the messages exchanged between a coordination platform and a CEMS

INNOVATION ADVANCES

Robustness

The robustness of the innovation proposed comes from:

- *The architecture of system monitoring*: the coordination platform gathers the power consumption of each load directly monitored by each CEMS. The frequency monitoring is then performed only by the CEMSs.
- *The coordination of the solution behavior*: the coordination platform decides by itself before real-time of the frequency behavior of all of the loads of its portfolio.
- *The distribution of the decision process*: Each CEMS decides finally autonomously of the shedding and reconnection of the loads, thanks to an on-site system frequency monitoring, in order to comply with the frequency behavior previously decided upstream by the coordination platform.
- The *replicability of the solution*: Each set of {coordination platform + coordinated CEMSs} is replicable autonomously the one from another. It enables to constitute at the system scale, several pools of reasonable size whose failure does not induce a danger for the system stability.

It can be noticed that the real-time processes – mainly the load shedding and reconnection – are performed only by the CEMs. The coordination platform performs only periodic or event processes. As detailed above, this distribution of the real-time processes among the agents is a key factor of robustness of the solution. Neither the communication delay nor even a minutes-long loss of communication links can stop the supply of these distributed frequency-controlled reserves, since the CEMSs interpret the shedding and reconnection order only from an on-site system frequency monitoring.

Intelligence

The intelligence of the innovation comes then from a combined algorithm (Fig. 6) of load-shedding order definition and frequency thresholds computation. This algorithm is run by the coordination platform. It enables to clear a market composed of several purchase and sale bids of frequency-controlled reserves. In term of price, each bid is defined by a function of marginal shedding cost, which depends on the frequency threshold. In term of power, the purchasing bids are defined by power-frequency characteristic, while the selling bids are commonly a power amount per DER which is activated in all-or-nothing for simplicity of operation.

For clearing easiness, the whole purchasing characteristics are first aggregated under a resultant power-frequency characteristic, defined in a range [Fb ; Fa], regardless their limit prices.
The sale of each DER bid to match the demand, i.e. the assignment of a frequency threshold to each DER, is then performed per J adjacent sub-frequency ranges $\Delta f_j = [fb_j ; fa_j]$, with fa_1 = Fa and fb_J = Fb. The ranges are scanned starting from the range the closest to the normal system frequency.
For each range Δf_j, the DER whose price functions are defined in the whole interval Δf_j, are selected at the merit order, up to reach the demand of the interval. The trading price can be either a bid price or a spot price. The algorithm is able to handle both capacity and energy price. In case of energy price, a probability of load-shedding depending on the frequency threshold is considered as input for the clearing.

The calculation of the frequency threshold of each DER assigned for operation within an interval Δf_j follows the equation (1).

$$(1)\quad fth_i = fb_j - (fb_j - fa_j) \times \frac{\sum_{k=1}^{i} P_k}{\sum_{k=1}^{K_j} P_k}$$

$$\text{with} \left| \begin{array}{l} K_j, \textit{the number of DER operating within } \Delta f_j \\ \Delta f_j = \left[fb_j ;\ fa_j \right], \textit{ the subrange of control} \\ sl \approx -\frac{\sum_{k=1}^{K_j} P_k}{fb_j - fa_j}, \textit{ the slope of the characteristic} \end{array} \right.$$

For simplification issue, the equation (1) assumes a power-frequency characteristic defined as linear within each range Δf_j. The slope can however be different depending on the range Δf_j. This equation could be easily adapted to comply as well with non-linear characteristic even within Δf_j. Fig. 5 presents schematically the effect of the equation (1). The key idea plotted in Fig. 5 is to extend each piled block of dispatchable power among the frequency axis up to cross the targeted power-frequency characteristic, presented as linear in the present example.

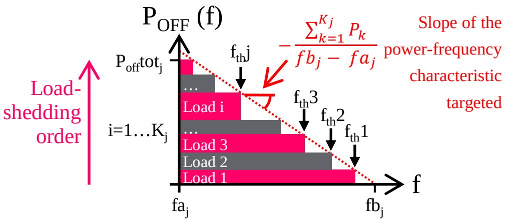


Figure 5: Targeted step-by-step droop curve

The DER offers not purchased within Δf_j are put back for sale in the range Δf_{j+1}, if they are still defined, where they can face the competition from DER that used not to be defined in Δf_j.

Since the resultant demand is usually a linear function while the resultant offer is composed of piled blocks, the algorithm considers tolerance limits, to guarantee that both curves stays close enough at the clearing output. The aggregation of small size offers is however supposed to make this discontinuity of offers negligible face to the system scale demand.

The algorithm integrates finally a loop of bids validation process to cancel the potential purchase of reserves at a trading price higher than an upper limit predefined by the purchaser. According to the same logic, a purchaser can accept the purchase of power-frequency characteristic exactly equal to his initial purchase bid, or accept as well final bid partially cut during the market clearing.

PERSPECTIVES

As much of Demand Response solutions, the success of the present concept is conditioned by its adoption upstream by the Utilities and downstream by the DER owners.

Utility acceptance

Firstly, the solution will have to convince the network operators of its benefit on system stability, its effective contribution in real-time and its robustness face to any disturbance.

The first step toward system stability is ensured by a solution design which is compliant with FCR requirements, defined in the ENTSO-E Network Code on Load-Frequency Control and Reserves [2]. Dynamic network stability studies have then been performed to test the benefit on stability. The first studies demonstrate for instance the interest of the solution to secure an almost islanded power system, following the tripping of its unique interconnection. These tests have been performed on the model of Kuching Island power system [3]. The reversibility of the solution proposed enables to smooth the opposite imbalance that occurs in Kuching after a large tripping of UFLS relays, and which is fatal for the system without the availability of enough reversible reserve [4].

Real-time physical tests have been performed as well on a 4kVA off-grid system to check first the accuracy of the droop curve supplied, compared with the curve targeted and then the time response of the five CEMS designed just for these tests [5].

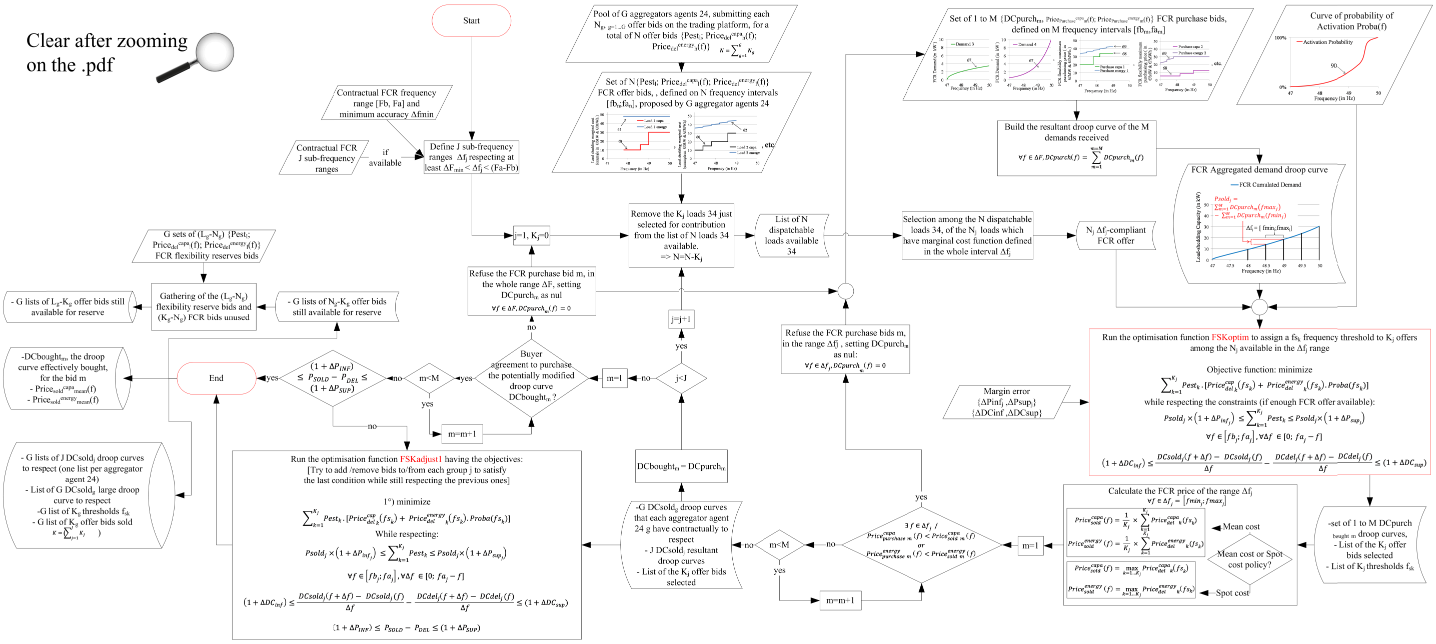


Figure 6: Frequency market clearing and threshold assignment algorithm

Finally, the robustness face to any ICT disturbance has already been challenged in the previous paragraph. Such robustness would then be challenged in 2015 by the deployment of a cloud-oriented demonstrator, controlling interconnected DER. These DER are located in Schneider Electric headquarter, Grenoble INP buildings, Milano Malpensa Airport and ICCS facilities (Greece) as Dream[1] demonstration field tests.

DER owner acceptance

On the DER side, a limited disturbance of business as usual DER owner activity will constitute a key factor of success. The three main kinds of disturbances have been identified:

1. The complexity of the CEMS integration on an existing facility.
2. The cyber-security issues inherent to the need to connect the DER to a communication channel.
3. The number and the length of DER shedding events.

The *complexity of the CEMS integration* is addressed by targeting specific loads, as described in Fig. 3. On the domestic side, existing energy boxes like Wiser [6] would become easily compliant with the present solution, by controlling the tripping of boiler or electric heaters. On the tertiary side, the association of variable speed controllers like the Altivar [7] with an M171 [8], the last logic controller from Schneider Electric for HVAC and pumping solutions is willing to provide easily the up and down flexibility required. The M171 embeds directly the CEMS script and connects to existing sensors of the installation. Some other domestic and tertiary could be compliant as well.

The *cyber-security issues* are partly solved by giving the lead to each CEMS at the expense of the coordination platform: each of them requests upstream by themselves for a frequency threshold update, that requires only the knowledge by the CEMS of building network's proxi, and no port opening to become accessible from outside.

The question of *shedding event occurrence* depends finally of the threshold assigned to each DER: the further from the nominal frequency it is, the less frequency shedding occurs. While the frequency threshold of 49.9Hz is on average reached up to 339 times per day, in ENTSO-E Northern Europe synchronous area, the number of events fall to 7.8 at 49.85Hz and 0.7 at 49.9Hz (data from may 2005 to april 2006, [9]). The ability of the frequency threshold assignment algorithm (Fig. 6) to limit a frequency range of operation for each DER enables to consider DER owner contribution wishes, that is willing to reduce its adoption relectance. Moreover the events last few seconds only, that is not willing to disturb the DER processes (at 49.8Hz, 95% last less than 27s, with an average duration of 1.5s [9]).

CONCLUSION

The present concept has been developed with the objective to propose one solution to the appearing issue of lack of frequency-controlled reserves in some locations, including microgrid. Next step is now to convince Utilities and DER owners of its robustness, through new demonstrations and to define suitable business models for the whole power system chain. That will be Schneider Electric and Grenoble INP priority up to 2016.

Acknowledgments

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