Decentralized Demand-Side Contribution to Primary Frequency Control

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***Abstract*—Frequency in large power systems is usually controlled by adjusting the production of generating units in response to changes in the load. As the amount of intermittent renewable generation increases and the proportion of flexible conventional generating units decreases, a contribution from the demand side to primary frequency control becomes technically and economically desirable. One of the reasons why this has not been done was the perceived difficulties in dealing with many small loads rather than a limited number of generating units. In particular, the cost and complexity associated with two-way communications between many loads and the control center appeared to be insurmountable obstacles. This paper argues that this two-way communication is not essential and that the demand can respond to the frequency error in a manner similar to the generators. Simulation results show that, using this approach, the demand side can make a significant and reliable contribution to primary frequency response while preserving the benefits that consumers derive from their supply of electric energy.**

***Index Terms*—Decentralized control, demand-side response, load frequency control, primary frequency control.**

I. Introduction

IMBALANCES between load and generation must be corrected within seconds to avoid frequency deviations that might threaten the stability and security of the power system. Routine deviations from this balance are usually corrected by adjustments in the output of conventional generating units driven by their governor in what is called primary frequency response [1]. The load is used explicitly to restore this balance only when the imbalance is severe and cannot be remedied quickly enough using fast acting generation. In such cases, blocks of loads are interrupted following the action of underfrequency relays. This control philosophy may need to be revised in the coming years as the demand side may take a more active role in the control of the system. As their relative size increases, intermittent and variable output renewable energy sources such as wind farms will contribute larger random fluctuations to the load/generation balance [2]. At the same time, the number of conventional generating plants that have the flexibility required to take part in primary frequency control is likely to decrease as coal-fired plants are decommissioned. One possible scenario would see the bulk of the electrical energy being produced by a combination of renewable sources and nuclear power plants [3]. Under such conditions, performing primary frequency control using only supply-side resources may become not only prohibitively expensive but also technically difficult; see, for example, [4]. It is therefore important to explore how a sufficient proportion of the loads could assume a routine role in primary frequency control to maintain the stability of the system at an acceptable cost, considering this load participation as an example of the contribution that consumers could make to ancillary services [5], [6].

The obvious challenge in including loads in frequency control is the large increase in the number of potential participants. Even in the largest control areas, at most a few hundred large generators contribute to frequency control. On the other hand, participation from the demand side might involve tens of thousands if not millions of consumers. Though this may appear technically daunting and economically unrealistic, it has to keep in mind that conventional primary frequency control is a distributed control system that relies on the availability of the frequency as a measure of imbalance between load and generation. Indeed, the response of each generating unit is determined by its droop characteristic and a local frequency measurement, not by a signal sent from a control center. Communication to and from the control center is used only in the slower secondary and tertiary control loops for better economic optimization and network security. A load or consumer thus does not have to be plugged into a communication network to take part in primary frequency control. Schweppe *et al.* originally proposed this idea in 1980 and patented this concept as the Frequency Adaptive Power Energy Rescheduler (FAPER) [7].

In the last few years, research effort on the design and application of FAPER-like controllers applied to primary frequency control gained significant momentum. The Grid Friendly Appliance controller [8] developed by the Pacific Northwest National Laboratory has shown great promise as a means to modulate load in response to certain trends in the system frequency. This controller is to be fitted into individual appliances which are essentially *energy* users rather than *power* users. Energy users are appliances which can modulate their power consumption over time as long as the final energy consumption is sensibly the same. These include primarily heating, ventilation and air conditioning equipment, tumble dryers, immersion water heaters, etc. Lu and Hammerstrom in [9] discuss, simulate, and test in a laboratory environment the effect of the triggering frequency

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and duration of interruption on the behavior of residential appliances. They consider that 61% of such appliances are compatible with the proposed Grid Friendly™ appliances (GFAs) that can detect frequency excursions and turn on or off according to a certain control logic. Due to the high penetration of cooling and heating loads, about 20% of the load in the U.S. comes from consumer appliances that cycle on and off [10] and which could make a contribution to frequency control during a normal state operation.

Taylor in [11] and [12] and Taylor *et al.* in [13] developed another distributed load controller for autonomous renewable energy systems, which uses the frequency and the rate of change of frequency as inputs to a fuzzy logic load control system. This approach was tested in an island power system with a small number of water-heating loads. Infield *et al.* have developed a low-cost load distributed frequency controller as an improvement to solutions for regulation of a wind-diesel system based on storage devices [14]. Kondoh *et al.* [15] compare independent and cooperative control techniques as applied to frequency regulation using electric water heaters. Shokooh *et al.* [16] applied a similar concept to an islanded industrial system where load shedding is a viable proposition and where, due to the characteristics of the generation capacity, fairly wide frequency excursions are acceptable. Trudnowski *et al.* [17] assume that these frequency responsive appliances will make possible a linear modulation of the load as a function of the frequency error. They then explore how this load response would improve the stability of the system. Hirst [18] proposed a more sophisticated flavor of the FAPER whose control behavior is modulated by the magnitude of the sensed frequency deviation. These devices are currently being tested in Italy and the United Kingdom. A recent demonstration showing that it is not only feasible to provide spinning reserve using demand-side resources but that it may also be preferable to rely on these resources can be found in [19], where practical experiences based on a centralized system coordinated to minimize customer confusion and process applications and installations efficiently are described from an international perspective.

Notwithstanding the significant effort in designing the algorithms for these load control devices, little systematic attention has be given 1) to power system operation and operations planning in grids with significant proportions of demand controlled by FAPER-like devices; and 2) to establish bounds on the amount of frequency-sensitive demand response which could be achieved in such power systems. The work of Short *et al.* [20] looks carefully at the first aspect. These authors demonstrate how real-time operation could be like with a significant amount of active frequency-sensitive fridge/freezer load for the National Grid system in Great Britain. They also provide evidence of the usefulness of increasing the proportion of these types of loads when power systems have to integrate large penetrations of wind generation.

This paper attempts to look at the latter aspect. In this work, we establish the general shape and bounds on the relationship between the aggregated demand responses provided by active loads with respect to the system frequency deviation. Obtaining this information will prove to be of critical importance to transmission system operators in the future (as the penetration of such loads becomes more widespread) when determining the amount of primary frequency reserves needed. In addition, and from the decentralized frequency sensitive load controller over Schweppe's FAPER [7] and Hirst's Grid Stabilizing System [18], we also consider a time-dimension grading for frequency deviations analogous to an inverse time over-current protection characteristic and extend the control logic to overfrequency situations.

Primary frequency control is so critical in keeping power systems from collapsing in the initiating moments of a major disturbance. Therefore, it requires coordinated and robust, yet economical, scheduling of frequency responsive generation and active demand. Increasing levels of frequency-responsive demand should reduce the cost of providing primary frequency response because less part loaded thermal generation is needed. However, the fact that the demand-side response will always remain uncertain—in magnitude and rate of response—requires the system operator to use caution when replacing generation-based primary reserve with active demand-side primary reserve. In so doing, the operator will need the information on the aggregated frequency-sensitive demand response characteristic. In this paper, we obtain this information from empirical simulation studies. These studies demonstrate, among other things, that the aggregated active load response characteristic is akin to the droop characteristic of a thermal generating unit with a finite power output.

The paper is organized in the following way. Section II describes the operation of a generalized frequency-sensitive load controller. Section III provides a detailed analysis of how participation from the demand side might affect the overall control of the frequency in the system. Specifically, we show how one can establish the general shape of the aggregate active frequency load response and its upper and lower bounds. We finally conclude in Section IV.

II. Generalized Frequency-Responsive Load Controller

A. Context

Neglecting local differences caused by electromechanical transients and oscillations, the angular frequency ω of a power system is determined by Newton's 2nd Law of Motion. Expressing this law in terms of small deviations around the nominal angular frequency of the system gives

$$M\frac{d\Delta\omega}{dt} + D\Delta\omega = \Delta P_g - \Delta P_l \tag{1}$$

where

$M = I\omega_0$ nominal angular momentum of the rotating masses in the system;

I total inertia of the rotating masses of the system;

ω_0 nominal angular frequency of the system;

D damping factor representing the natural frequency dependence of the load alongside the damping provided by synchronous generator damper windings;

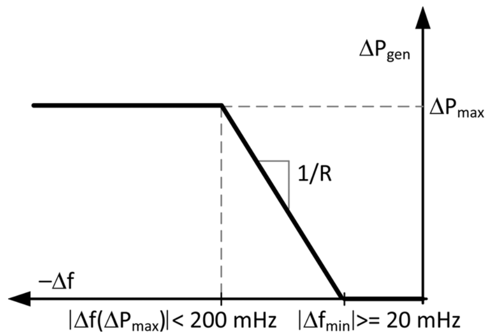

Fig. 1. UCTE specification for primary frequency reserve.

ΔP_g	change in total active power generation;
ΔP_l	change in total active power load.

In a conventional frequency control system, the load is assumed not to be controllable ($\Delta P_l = 0$) and an adjustment ΔP_g must be made to the output of the generators to correct frequency deviations. All the generating units taking part in primary frequency control must share in this adjustment. This sharing can be achieved without communication between the generators by implementing a droop characteristic in their governor [21]. In its simplest form, a droop characteristic implements a linear increase (decrease) in the output of the generating unit as the frequency drops (increases) from its nominal value. A practical droop characteristic includes a dead band which prevents unnecessary adjustments for small random fluctuations in frequency. The maximum frequency deviation for which the output adjustment of all generating units taking part in primary frequency control must be deployed is an important parameter that is specified by the security criteria. Fig. 1 illustrates the European UCTE specification for the droop characteristic of generators in the case of deviations under the nominal frequency [22].

A continuous control of the power consumed by a load—similar to what can be achieved with a generator droop characteristic—is possible only when this load is supplied through a power electronics controller. Since fitting or retrofitting loads with power electronics controllers is usually either undesirable or prohibitively expensive, frequency control from the demand side must rely on loads that can be switched on and off with minimal inconvenience for the consumers. In general, this means that the best candidates will be loads whose utility to the consumer is a function of the energy consumed over a period of time rather than their instantaneous power consumption [7]. Heating, cooling, and pumping devices are the best-known examples of such loads. These kinds of cycling loads can handle short interruptions that would be acceptable for the users. For example, a recent European survey showed that the residential electricity consumption amounts to about 30% of the total electricity demand. The largest domestic electricity demand is due to space heating loads (22%), followed by refrigerators and freezers (15%), while storage water heaters account for about 9% [23]. These numbers suggest that there is sufficient scope for fitting in such load-frequency controllers in many of those domestic appliances. Similar arguments can be invoked in the case of some process industries and for heating and cooling needs of large buildings.

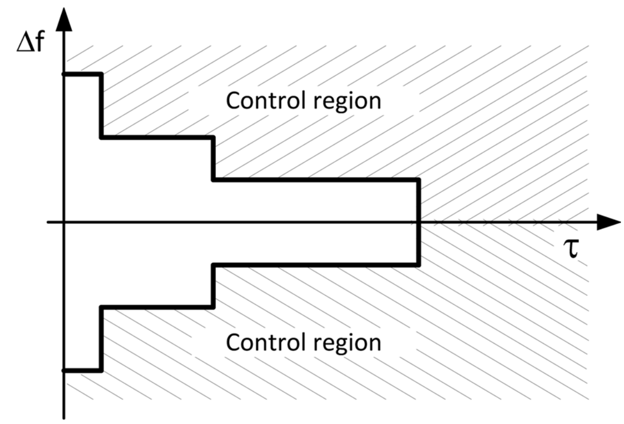

Fig. 2. Individual load controller Δf-time characteristic.

B. Time/Frequency Characteristic of the Load Controller

A basic frequency-responsive load controller turns a load on or off when the frequency goes above or below some threshold values [7], [18]. The generalized load controller described in this paper considers not only the frequency deviation Δf—referred to deviations of the measured frequency from is nominal value—but also the evolution over time of Δf. For each load controller, a Δf-time characteristic determines when the load starts taking part in the control of frequency. Fig. 2 shows an example of such a characteristic. The load controller measures the frequency over a time window Δt_{tw} and the parameter τ represents the time during which the controller has measured a particular value of the frequency. As long as the frequency deviation does not exceed a certain threshold for a certain time, the load controller remains passive and the load follows its intrinsic evolution. On the other hand, if the frequency deviation moves outside or beyond in the shaded region of Fig. 2, the controller enters its active mode and will start switching the load off and on to contribute to the control of the frequency. Because of the shape of this characteristic, larger frequency deviations will trigger a faster reaction of the controllers while smaller deviations are allowed to persist for a longer time before the load starts contributing to frequency regulation.

The time/frequency characteristic of a controller should be matched to the type of load that it regulates. Loads indeed differ in terms of their speed of response, maximum allowed off time, required recovery time, and patterns of use. Different criteria can be applied to set the time/frequency characteristic for each load group and, then, fix the order in which loads will be switched off (on) in the presence of frequency excursions. These criteria depend on the point of view that is chosen. Thus, minimizing the inconveniences on the customer comfort levels and/or minimizing the effects of the switching off (on) periods on the useful life of devices takes priority over the demand-side, whereas maximizing the response speed of the global load and/or reducing the generation reserves of the primary frequency control takes priority over the utility-side. Therefore, a trade-off solution between a set of acceptable time/frequency behaviors is normally selected.

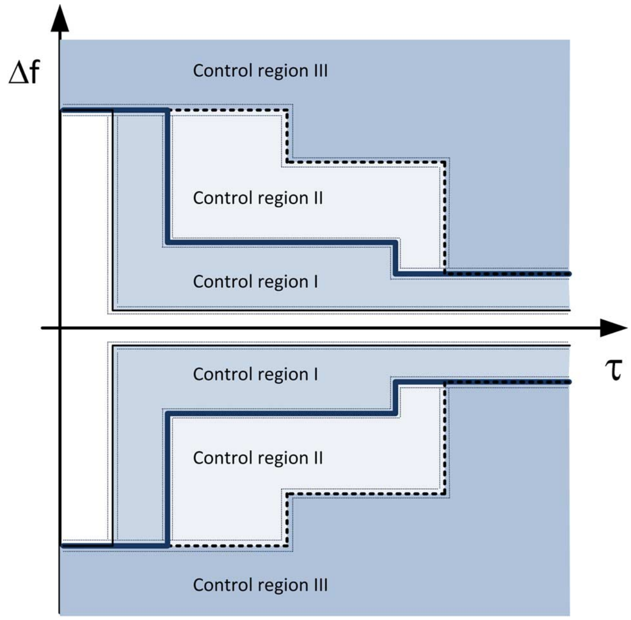

Fig. 3. Aggregated load controller Δf-τ characteristic. Different load groups.

On the other hand, similar loads (e.g., air conditioning loads) could be controlled according to the same Δf-τ characteristic. While the characteristic boundary of a single controller is "sharp", the aggregated characteristic of all the controllers regulating the same type of load exhibits some "fuzziness" because the dynamic time windows of each load controller are initialized at different times. There are also small differences in the frequency measurements of each controller and there is intrinsic variability in the tuning and manufacturing processes of appliances. Fig. 3 shows Δf–τ characteristics for different types of loads where the corresponding fuzziness is represented by horizontal and vertical uncertainty bands. Three control regions can be distinguished according to the Δf deviation and Δf duration: *Control region I* where only loads of one load group can participate in the frequency control; *Control region II* where loads of two different Δf-τ characteristic can be switched off (on); and *Control region III* that involves loads of three different load groups to be controlled. The overall response of the demand side to frequency deviations will thus depend on the shape of these various characteristics and on the amount of load associated with each one of these Δf–τ characteristics.

C. Demand Response (DR) Algorithm

As long as the frequency deviation does not exceed the threshold shown in Fig. 2, the load is supplied without interruption. Any excursion of Δf into the *Control region* triggers the participation of the load in the control of frequency. Fig. 4 illustrates the operation of the load controller using a finite state diagram and Fig. 5 provides a time-domain illustration when an underfrequency excursion is detected. We assume that the frequency is initially above the underfrequency threshold shown in Fig. 2 and that the controller is initially in *State A*. In this state, the load is allowed to follow its natural evolution and does not contribute to frequency control. The controller will

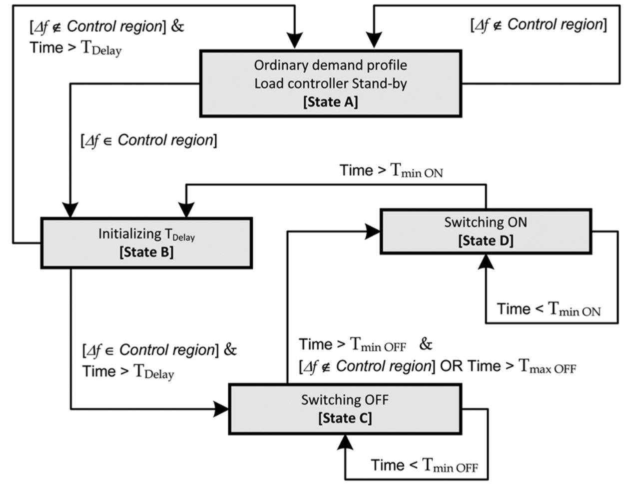

Fig. 4. Finite state machine representation of the load controller. Underfrequency.

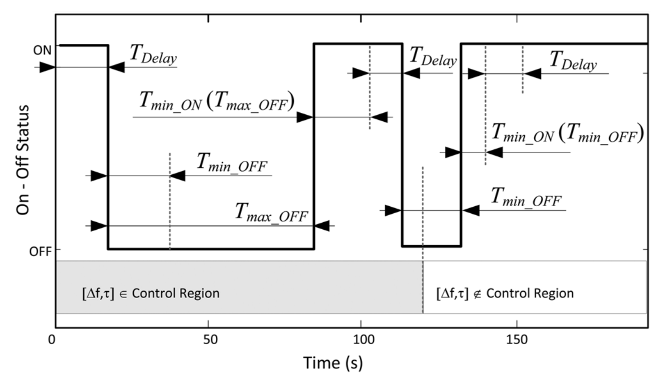

Fig. 5. Example of energy recovery time periods. Underfrequency.

remain in this state as long as the frequency deviation does not cross the Δf-τ characteristic. This state can be modified:

1) When the deviation is large enough for a sufficiently long time and thus crosses the Δf-τ characteristic. The controller will enter *State B*, where it checks that the deviation does not immediately cross back over the characteristic before a delay T_{Delay} has expired. We note here that implementing a randomly chosen T_{Delay} in each controller should avoid abrupt synchronous response by all the controllers, therefore ensuring a smooth demand response.
2) If the frequency excursion returns above the underfrequency threshold before the delay has elapsed (*State B*), the controller returns to *State A* without switching off the load. Otherwise, it moves to *State C* where the load is switched off for a minimum time T_{minOFF}.
3) The appliance is to remain off (*State C*) even if the frequency deviation returns to the acceptable region. This minimum off-time is required to avoid undesirable transients that might result from rapid connections and disconnections of loads. Its value depends on the type of appliance. While water heaters can be switched on and off as often as needed, heating, ventilation, and air conditioning (HVAC) equipment as well as refrigerators and freezers must remain switched off for some minimum time to avoid reducing their useful life.

4) After a maximum off-time T_{maxOFF}, the state of the controller moves on to *State D* and switches the load back on to ensure that the performance requirements of the appliance and the expectations of the user remain satisfied.
5) Once switched back on (*State D*), the load has to remain on for a minimum recovery time T_{minON}. This time interval is required after an interruption period to ensure that the load can continue to serve its function (e.g., maintain a temperature within an acceptable range). A minimum switching on recovery time is then considered after an interruption period that usually represents the return of thermal variables towards their ordinary values. Due to the fact that the recovering time interval depends on how long the switching off period is—varying from its minimum to its maximum value—an additional function has been implemented in the load controller in order to determine this $\Delta T_{\mathrm{minON}}$ in each case according to the switching off time period selected.
6) After the minimum recovery time period, the controller then enters *State B* again where a randomly chosen T_{Delay} should avoid synchronous power restoration of the controlled loads.

A similar time machine state representation can be deduced for overfrequency excursions. In that case, the appliances are switched on for a minimum time period and after a maximum on-time (T_{maxON}), the loads back off.

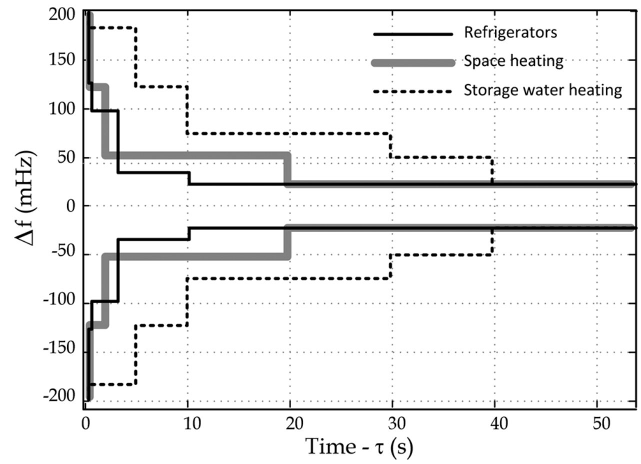

Fig. 6. Average Δf–τ switching characteristics used in simulations.

TABLE I
LOAD CONTROLLER PARAMETERS

Time parameter	Fridges/Freezers	HVAC	Water Heaters
T_{Delay}	Uniform(0.5,2)	Uniform(2.5,5)	Uniform(2.5,5)
T_{minOFF}	Normal(5,0.5)	Normal(20,2)	Normal(1,0.1)
T_{maxOFF}	Normal(40,5)	Normal(90,10)	Normal(150,15)
T_{minON} (T_{minOFF})	Normal(4,0.1)	Normal(10,1)	Normal(1,0.1)
T_{minON} (T_{maxOFF})	Normal(10,0.5)	Normal(20,3)	Normal(30,5)
T_{maxON}	Normal(20,0.5)	Normal(30,3)	Normal(50,5)

III. Analysis of the System Impacts of a Large Penetration of Frequency-Sensitive Load Controllers

A. Objectives

The previous section describes how a single generalized load controller would behave in response to frequency deviations. From a system perspective, however, it is important to understand how the frequency would evolve following disturbances if many such controllers were installed. In addition, it is of high value to be able to estimate the frequency response characteristic of those aggregated controllers. In this paper, alike in the work of [20], we make use of empirical simulation studies for investigating the shape and bounds of the responsive load frequency response.

B. Simulation Environment

Our simulations consider three types of active loads that are commonly found in residential premises and which can be subjected to short interruptions that would be acceptable by the customers: space heating loads, fridge/freezers, and storage water heaters. Taken together, these loads are assumed to represent (on average) around 10% of the total electricity demand, since the residential consumption supposes almost 30% of the global demand and these devices are close to 40% of the residential demand. The proportions of each load group have been selected according to [23]. Fig. 6 shows the average Δf–τ profiles implemented in the controllers for each of these types of loads. In this case, the criteria used to fix the Δf–τ characteristics are based on the average rate of penetration of these devices (95% of refrigerators, 20%–30% of air conditioning appliances, and 15% of electric water heaters [24]), the rate of potentially available power and the thermal capacity of the loads according to physically-based load models previously implemented and assessed by the authors [25]–[27]. Refrigerators, freezers, and air conditioning loads then have the fastest response time and are also suitable to control small Δf fluctuations. In all cases, the controllers respond before the frequency deviation reaches ± 200 mHz. Moreover, response starts when Δf reaches ± 10 mHz, which is less than the typical deadband of the primary frequency control of generating units. The controllable load (ΔP_l)—see (1)—is then determined according to the Appendix.

The parameters of individual controllers are randomized to model the heterogeneity of the aggregated loads. Table I shows the probability distributions (in minutes) of all these parameters for each load type, where the recovering time interval (T_{minON}) involves two distributions taking into account that it depends on how long the switching period is—from minimum to maximum value. An additional parameter (T_{maxON}) is included in Table I. It is related with overfrequency excursions, when the power demand has to be increased and the controlled loads are switched on. The rest of the system has been modeled using a classic single equivalent turbine-generator unit as discussed in [21]. The parameters of this equivalent system are summarized in Table II. To simulate the differences that are likely to exist between the frequency measurements of the individual controllers, a zero-mean Wiener noise signal $W(t)$ is added to the individual frequency signals, with 1 mHz variance [28]. To avoid undesirable overfrequency situations if large amounts of load are simultaneously switched-off in the presence of low underfrequency values as well as to emulate the same droop characteristic previously described in Fig. 1, the number of loads in each group considered to switch off (on) varies gradually from 0 for

TABLE II
PARAMETERS OF THE EQUIVALENT GENERATION SYSTEM

Parameter	Value
Droop coefficient, R (Hz/MWpu)	5
Frequency sensitivity of the load, D (MW/Hz)	0.02
Governor time-constant, T_G (s)	0.08
Turbine time-constant $T_{turbine}$ (s)	0.3
System time-constant T_{system} (s)	32

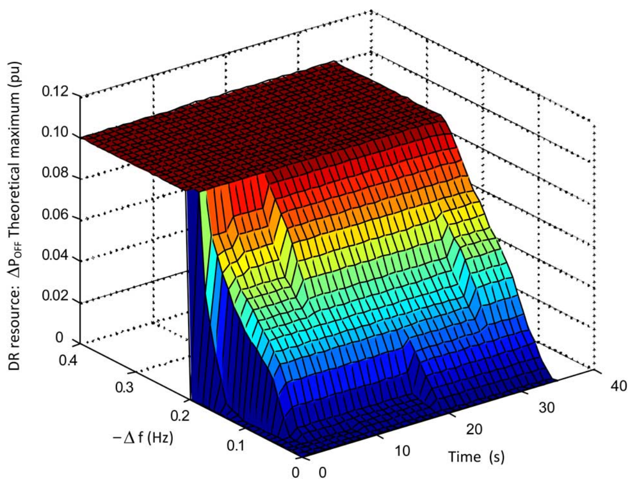

Fig. 7. Simulated DR aggregated behavior. Underfrequency.

a frequency deviation lower than the minimum considered up to 100% when the frequency deviation is 200 mHz. To implement this behavior, a random variable uniformly distributed from 0 to 1 is considered for all the loads, comparing in each case this value with the relative frequency excursion and deciding if the switching algorithm will be applied or not. Fig. 7 shows the theoretical aggregated response for the whole simulated load submitted to different frequency excursions during several time intervals. This response emulates the generator droop characteristic and offers a theoretical maximum DR resource that is higher than the practical maximum values due to the fact that most of the loads suitable for this technology operate cyclically along time.

C. Results

Fig. 8 illustrates the overall system response to a sudden $+3\%$ imbalance between generation and load followed by a sudden -2% imbalance when only primary frequency response is considered for generators. In these diagrams, the response when the primary frequency control is provided entirely by the generation is compared to the case where 10% of the load responds to the frequency deviation Δf.

The generating units are assumed to be able to provide 7% of their nominal capacity in primary frequency response. Fig. 7 shows that these additional demand-side resources for primary frequency control reduce the magnitude and duration of the frequency excursion resulting from these contingencies. At the same time, it can be deduced that the participation of the demand-side considerably reduces the amount of response required from the generators. Finally, it also shows how the response from the demand-side is distributed between the three types of load that have been included in the model. Because the

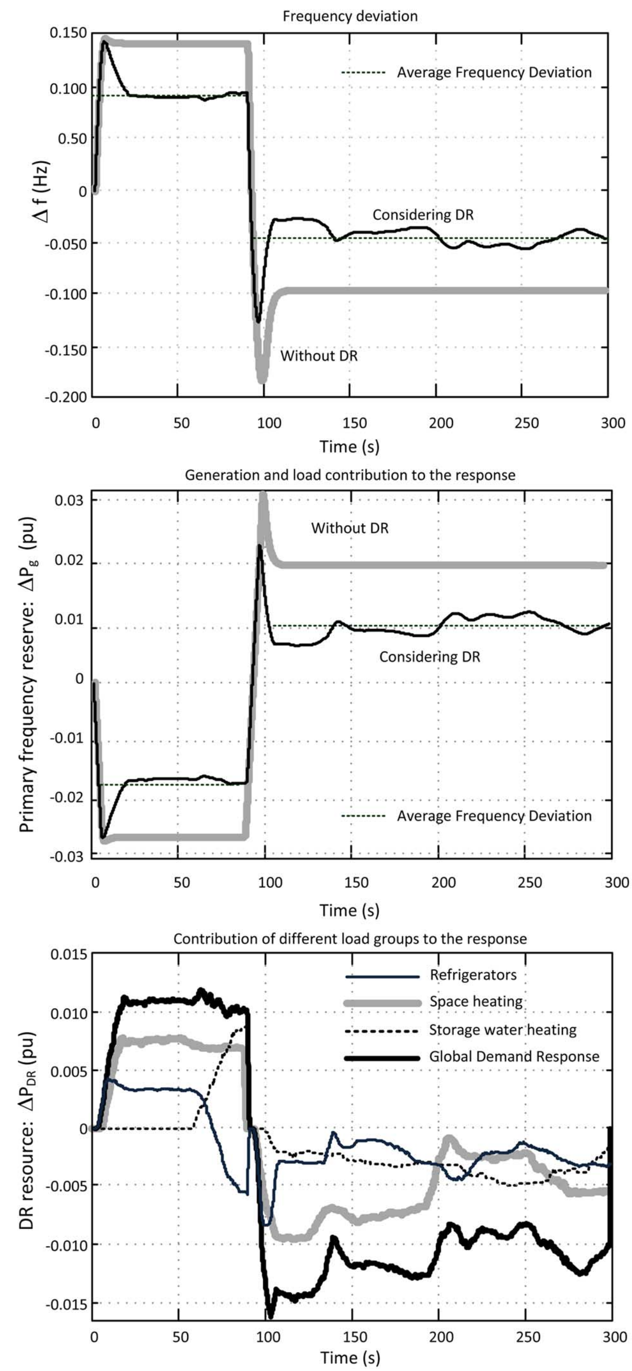

Fig. 8. Response to a sudden imbalance between load and generation with and without demand-side participation in the primary frequency control.

imbalances in this example are large and sudden, the refrigerators are the first to react, followed by the space heaters and with a smaller and later contribution from the water heaters. It is important to note that the simulation model does not represent the secondary frequency control. Unlike what would happen in an actual system, the generation is thus not re-dispatched to compensate for the imbalance. This explains the continuing response from the demand-side. The oscillations in this response are due to the different maximum interruption times of the various types of participating loads. It is necessary to point out that the main aim of our simulation is to illustrate the demand

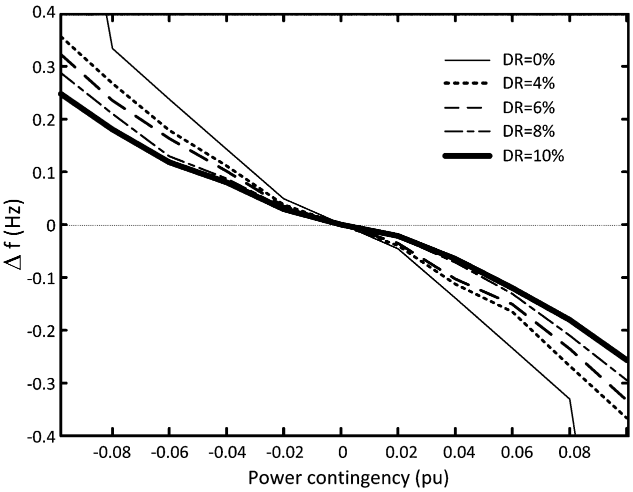

Fig. 9. Δf average simulated values with different levels of demand response (DR, expressed in percentage of the total load).

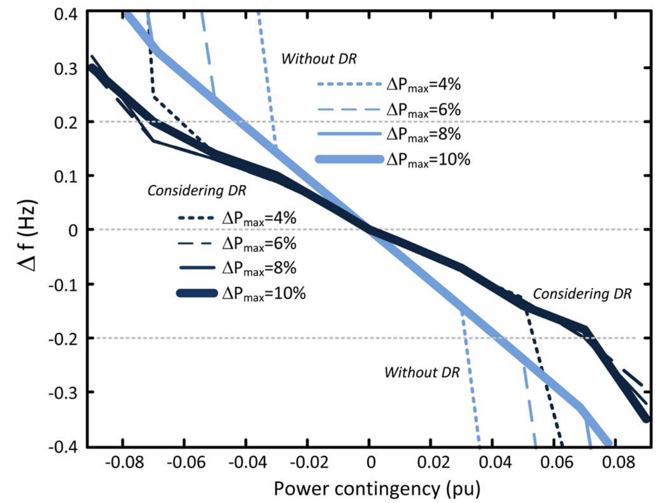

Fig. 10. Δf average simulated values with different amounts of primary frequency response available from the generation.

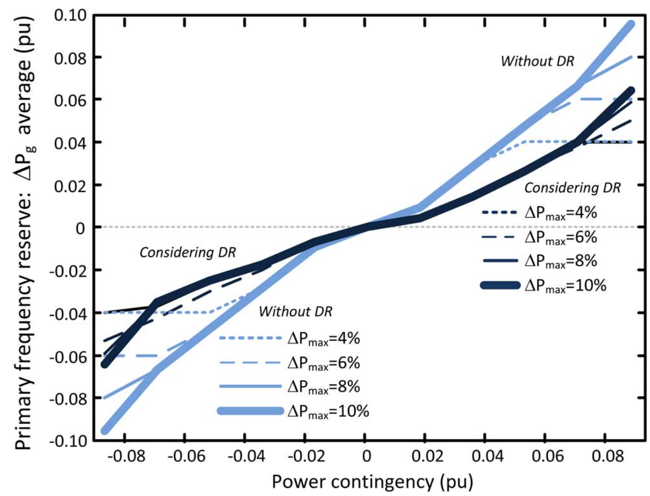

Fig. 11. Average amount of generation capacity used for primary frequency control with and without demand-side participation.

response contribution to primary frequency reserves when underfrequency or overfrequency excursions are detected, assuming these sudden positive and negative imbalances are not common in most power systems.

Fig. 9 quantifies the benefits of demand-side participation by showing the average frequency deviation, Δf—see Fig. 8—that would result from imbalance contingencies ranging from ± 0.01 to ± 0.09 $\mathrm{p.u.}$ for different levels of demand-side participation in primary frequency control, ranging from 0% to 10% of the total load. Fig. 10 shows the average values of the frequency deviation as a function of the size of the imbalance contingency, with and without demand-side participation and for various amounts of different primary frequency control capacity values for output from the generating units. As can be seen in this figure, the power system response with DR resources presents similar results, and it is possible to maintain the Δf values inside an acceptable under/overfrequency band, even with primary frequency reserves lower than their regular values. This figure then demonstrates that demand-side participation makes it possible to achieve the primary frequency control targets specified in the security standards for more severe contingencies or with less generation resources.

Fig. 11 shows how much power from the generators is used for primary frequency control as a function of the size of the imbalance contingency with and without demand-side participation. According to (1), each simulation compares the generator response in the presence (or not) of demand reserves under a set of power contingencies. It clearly shows that, with demand-side participation, it is much less likely that the system may run out of primary frequency resources, even for fairly large contingencies.

Finally, Fig. 12 shows the amount of load that participates in primary frequency control as a function of the frequency deviation. It shows the minimum and maximum contributions as well as a typical instantaneous value. This typical instantaneous value is clearly smaller than the maximum value. However, unlike the contribution of the generation side, it is not deterministic because not all loads will be contributing at the same time and because of the various random parameters that are built in the individual controllers to ensure a smooth demand response. This profile presents a droop characteristic much alike a generator's primary frequency characteristic, Fig. 1, and allows us to consider the demand response as a potential further resource for primary frequency control. The slope and the saturation level of this curve mainly depend on the load controller characteristics, and how the switch-on and off regions are selected for each load group. In our case and according to Figs. 6 and 7, the load controller responses have been distributed from 10 to 200 mHz and between 1 and 50 s time intervals, in order to achieve soft responses and avoid large frequency fluctuations. However, if the Δf and/or duration time intervals were decreased, the slope of this global behavior will increase (and vice versa). Therefore, the aggregation of the characteristics of the individual load controllers determines the profile and global behavior of the demand-side reserve. Hence, it would be possible to adjust these load controller responses based on a desired demand-side behavior. In reality, these characteristics would need to be carefully analyzed and integrated within transmission system operator grid codes.

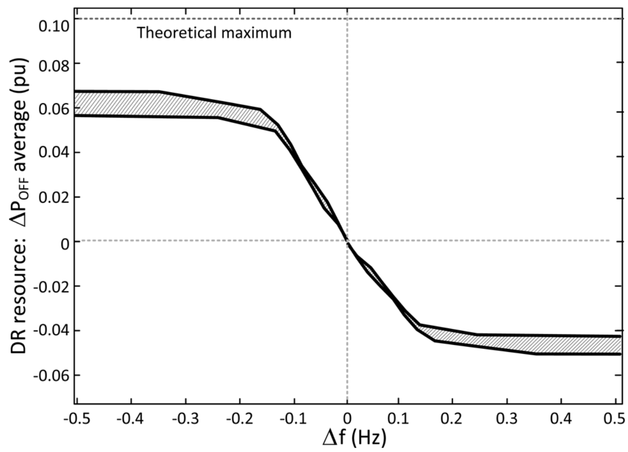

Fig. 12. DR resource characteristic as complementary primary frequency reserve.

IV. Conclusion

This paper explores how the demand-side could contribute to primary frequency control using a decentralized approach not requiring explicit communications. Instead, it is shown that simple devices can control individual loads in response not only to deviations between the frequency and its nominal value but also to the evolution of these deviations over time. The aggregated behavior of a large number of such controllers is simulated to investigate their effect at the system level. These simulation results show that this form of demand-side participation in frequency control is close to that of synchronous generators in aggregation. Future work in this area should develop methodologies to characterize robust statistical upper and lower bounds on the aggregated demand frequency response in addition to the study of incentive measures for rolling out such schemes on a large utility-wide scale.

Appendix

Taking into account the controllable load, expression (1) can be written as follows:

$$M\frac{d\Delta\omega}{dt} + D\Delta\omega = \Delta P_g - \Delta P_l = \Delta P_g - (\Delta P_{ncl} - \Delta P_{cl})$$

where ΔP_{ncl} is the change in active power of noncontrollable load, and ΔP_{cl} is the change in active power of controllable load. Assuming m groups of loads and n_i loads in each group, ΔP_{cl} has the following expression:

$$\Delta P_{cl} = \sum_{i=1}^{m}\sum_{j=1}^{n_i}\Gamma_{ij} \times \left[\Delta f_{ij}, \tau_{ij}, T_{\mathrm{Delay}_{ij}}, T_{\min OFF_{ij}}, T_{\max OFF_{ij}}, T_{\min ON_{ij}}\right]$$

where Γ_{ij} is the load controller decision function, based on the Δf–τ characteristic corresponding to the jth-*load* (in the ith-*group*), see Fig. 2, assuming each load controller has a different Δf–τ characteristic (even inside the same load group according to Table II). The equation system has been implemented under Matlab using finite difference approximation.

References

[1] Y. Rebours, D. S. Kirschen, M. Trotignon, and S. Rossignol, “A survey of frequency and voltage control ancillary services—Part 1: Technical features,” *IEEE Trans. Power Syst.*, vol. 22, no. 1, pp. 350–357, Feb. 2007.

[2] P. Sørensen, N. A. Cutululis, A. Vigueras-Rodriguez, L. E. Jensen, J. Hjerrild, M. H. Donovan, and H. Madsen, “Power fluctuations from large wind farms,” *IEEE Trans. Power Syst.*, vol. 22, no. 3, pp. 958–965, Aug. 2007.

[3] G. W. Ault, I. M. Elders, and R. J. Green, “Transmission use of system charges under future GB power system scenarios,” *IEEE Trans. Power Syst.*, vol. 22, no. 4, pp. 1523–1531, Nov. 2007.

[4] G. Strbac and ILEX Energy Consulting, Quantifying the System Costs of Additional Renewables in 2020 Department of Trade and Industry, London, U.K., 2002. [Online]. Available: http://www.berr.gov.uk/files/file21352.pdf.

[5] J. H. Eto, Demand Response Spinning Reserve Demonstration—Phase 2, Lawrence Berkeley National Laboratory, 2009. [Online]. Available: http://certs.lbl.gov/pdf/lbnl-2490e.pdf.

[6] E. Hirst and B. Kirby, Load as a Resource in Providing Ancillary Services, Oak Ridge National Laboratory, Oak Ridge, TN, 1999. [Online]. Available: http://www.ornl.gov.

[7] F. C. Schweppe, R. D. Tabors, J. L. Kirtley, H. R. Outhred, F. H. Pickel, and A. J. Cox, “Homeostatic utility control,” *IEEE Trans. Power App. Syst.*, vol. PAS-99, pp. 1151–1163, May/Jun. 1980.

[8] D. P. Chassin, M. K. Donnelly, and J. E. Dagle, “Electrical Power Distribution Control Methods, Electrical Energy Demand Monitoring Methods, and Power Management Devices,” U.S. 7149605, Dec. 12, 2006.

[9] N. Lu and D. Hammerstrom, “Design considerations for frequency responsive grid friendly appliances,” in *Proc. IEEE Transmission and Distribution Conf. Expo.*, Dallas, TX, May 2006.

[10] R. Pratt, “Transforming the US electricity system,” in *Proc. IEEE Power Systems Conf. Expo.*, New York, Oct. 2004.

[11] P. Taylor, “Distributed intelligent load control of autonomous renewable energy systems,” Eng.D. dissertation, Univ. Manchester Inst. Sci. Technol., Manchester, U.K., 2001.

[12] P. Taylor, “Increased renewable energy penetration on island power systems through distributed fuzzy load control,” in *Proc. Int. Conf. Renewable Energies for Islands: Toward 100% RES Supply*, Chania, Greece, Jun. 2001.

[13] K. Pandiaraj, P. Taylor, N. Jenkins, and C. Robb, “Distributed load control of autonomous renewable energy systems,” *IEEE Trans. Energy Conv.*, vol. 16, no. 1, pp. 14–19, Mar. 2001.

[14] D. G. Infield, G. W. Slack, and P. J. Musgrove, “Review of wind-diesel strategies,” *Proc. Inst. Elect. Eng.*, vol. 130, no. 9, pp. 613–619, Dec. 1983.

[15] J. Kondoh, H. Aki, H. Yamaguchi, A. Murata, and I. Ishii, “Consumed power control of time deferrable loads for frequency regulation,” in *Proc. IEEE PES Power Systems Conf. Expo.*, New York, Oct. 2004.

[16] F. Shokooh, J. Dai, S. Shokooh, J. Taster, H. Castro, T. Khandelwal, and G. Donner, “An intelligent load shedding (ILS) system application in a large industrial facility,” in *Proc. 40th IEEE Ind. Appl. Soc. Annu. Meeting*, Kowloon, Hong Kong, Oct. 2005.

[17] D. Trudnowski, M. Donnelly, and E. Lightner, “Power-system frequency and stability control using decentralized intelligent loads,” in *Proc. IEEE Transmission and Distribution Conf. Expo.*, Dallas, TX, May 2006.

[18] E. Hirst, “Grid Stabilising System,” U.S. 20070198133, Aug. 23, 2007.

[19] G. Heffner, C. Goldman, B. Kirby, and M. Kintner-Meyer, Loads Providing Ancillary Services: Review of International Experience, Berkeley National Laboratory, 2007. [Online]. Available: http://eetd.lbl.gov/EA/EMP/reports/62701.pdf.

[20] J. A. Short, D. G. Infield, and L. L. Ferris, “Stabilization of grid frequency through dynamic demand control,” *IEEE Trans. Power Syst.*, vol. 23, no. 3, pp. 1284–1293, Aug. 2007.

[21] A. Wood and B. Wollenberg, *Power Generation Operation and Control*, 2nd ed. New York: Wiley Interscience, 1996.

[22] UCTE Operation Handbook, Appendix 1: Load-Frequency Control and Performance, 2004. [Online]. Available: http://www.entsoe.eu/_library/publications/ce/oh/appendix1_v19.pdf.

[23] R. Pearmine, Y. Song, T. Williams, and A. Chebbo, “Identification of a load-frequency characteristic for allocation of spinning reserves on the British electricity grid,” *Proc. Inst. Elect. Eng. Gen., Transm., Distrib.*, vol. 153, no. 6, pp. 633–638, Nov. 2006.

[24] P. Bertoldi and B. Atanasiu, Electricity Consumption and Efficiency Trends in the Enlarged European Union, European Commission-Institute for Environment Sustainability, Luxemburg, 2007. [Online]. Available: http://sunbird.jrc.it/energyefficiency/pdf/EnEff%20Report%202006.pdf.

[25] A. Molina-García, A. Gabaldón, M. Kessler, and J. A. Fuentes, "Application of smoothing techniques to solve the cooling and heating residential load aggregation problem," *Int. J. Comp. Math. Elect. Electron. Eng. COMPEL*, vol. 23, no. 1, pp. 48–64, Jan. 2004.

[26] A. Molina-García, A. Gabaldón, J. A. Fuentes, and C. Álvarez, "Implementation and assessment of physically based electrical load models: Application to direct load control residential programs," *Proc. Inst. Elect. Eng. Gen., Transm., Distrib.*, vol. 150, no. 1, pp. 61–66, Jan. 2003.

[27] A. Molina-García, A. Gabaldón, C. Álvarez, J. A. Fuentes, and E. Gómez, "A physically based load model of residential electric thermal storage: Application to LM programs," *Int. J. Power Energy Syst.*, vol. 24, no. 1, pp. 24–31, Jan. 2004.

[28] F. Dawei and V. Centeno, "Phasor-based synchronized frequency measurement in power systems," *IEEE Trans. Power Del.*, vol. 22, no. 4, pp. 2010–2016, Oct. 2007.

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