CONTROLLING THE SYNCHRONIZATION AND PAYBACK ASSOCIATED WITH THE PROVISION OF FREQUENCY SERVICES BY DYNAMIC DEMAND

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ABSTRACT

An increasing share of nuclear and renewable generation is reducing the ability of the power system to withstand the sudden loss of a generating unit. Hence, there is a need for additional response and reserve services. Previous research has shown that frequency-responsive thermostatic loads would be able to support the system, but the proposed control methods typically suffer from undesirable side-effects at the device or system level. We propose a hybrid controller that addresses the observed shortcomings and illustrate its effectiveness using simulations in a model system. Quantitative comparisons are made with two control schemes from the literature.

INTRODUCTION

The GB system is faced with large impending changes driven, mainly, by EU and GB emission targets; over the next decade, ample renewable energy sources must be integrated. As a consequence of this and the increased reliance on nuclear generation, the power system will become less flexible. Furthermore, the possible infeed loss of generation will grow as the largest power plant size reaches 1.8 GW [1]. Therefore, there is a clear need for increasing the amount of response and reserve services in order to maintain grid security. Traditionally, synchronous conventional generators are the main suppliers of ancillary services [2]. However, in order to provide these services, these units must be operated part loaded. This results in decreased plant efficiency, consequently higher fuel costs and CO_2 emissions. As previous studies show [1], a critical consequence will be a reduced ability of the grid to absorb ever more wind generation. Responsive demand [3] represents a promising contribution to the solution of these problems. During normal operation, one can manage the devices' power consumption, shifting demand from peak to off-peak hours in order to re-shape the system demand profile. However, in this paper we focus the provision of frequency services that aim to support the system after a large frequency drop, typically after the sudden outage of a generating unit. Specifically, we consider the smart control of thermostatic loads. In this application each "smart" load identifies the frequency deviation and, according to the algorithm implemented, adjusts its power consumption. In case of a generation shortage resulting in a frequency drop, the devices will tend to switch off in order to quickly reduce the system imbalance. Fig.1 shows a schematic time evolution of the aggregate power consumption of the smart devices after a frequency drop, starting from the steady state consumption level P_{DSS}

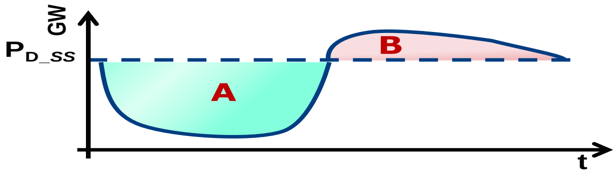

Fig. 1 Time evolution of the aggregate power consumption of the smart devices. The curve starts from the steady state consumption level; after the power reduction and its consequent payback period, the aggregate power recovers the pre-fault level.

The area A represents the energy exploited by the system and borrowed from the appliances; conversely B is the amount of energy that must be paid back in order to come back to the steady state condition, defined by a nominal total power consumption and an average temperature. In general we have B<A: not all the borrowed energy needs to be paid back as a result of real energy savings in the form of reduced leakage losses. It is worth pointing out that the payback can be eliminated entirely, but only at the expense of a very slow asymptotic recovery to steady state appliance temperatures. Previous research on this topic has demonstrated the potential of responsive domestic refrigerators to enhance the performance of the electricity grid. We specifically mention two control strategies for refrigerators, using different approaches: a deterministic control [4-5] and a stochastic control [6]. Both methods work, but each also has drawbacks; in the former, the thresholds of refrigerator's thermostat are varied as linear function of the frequency deviation; the resulting control methodology is strongly affected by the synchronization issue. This is a troublesome side effect caused by a large number of individual devices that, switched off to support the grid, revert to the *on* state together at the same time. These devices may remain synchronized for a long time, causing long-term power fluctuations with alternating phases of 'borrowing' and 'payback'. The latter approach [6] is designed to solve the synchronization between the fridges; however this positive target is achieved at the expense of limiting the speed and magnitude of the power reduction that is available for the system. Another drawback is the resulting on-off cycling frequency, which may place excessive demands on the devices' engines. We summarize the following three system-level performance criteria for responsive thermostatic loads:

- The ability to provide a sufficient reduction in power consumption at short notice.
- The capability to delay and control the payback of energy that the power system 'borrows' from the responsive demand.
- Avoiding synchronization of the duty cycles, which causes large-scale cyclic load patterns.

In the following sections, we introduce the methodology of a hybrid controller that extends the deterministic controller [4-5]. Afterwards, we present the corresponding device and power system models. These are used in simulations in which we compare the proposed controller with the deterministic and stochastic controllers. In particular, we evaluate their performance with respect to the three criteria mentioned above.

THE HYBRID CONTROL STRATEGY

We consider responsive demand in the form of domestic fridges, freezers and fridge-freezers. These are traditional thermostatic loads governed by a thermostat. During normal operation they operate within maximum and minimum threshold temperatures, respectively, T_{max} and T_{min}, resulting in alternating ON and OFF phases. In the on state, the electrical absorption equals the nominal power of the device, while, in the off state, we assume it nil. The hybrid control strategy aims to achieving the three performance targets previously described and not guaranteed in [4-6]. Fig.2 highlights the general framework of the algorithm. It is a decentralized approach as each appliance works individually.

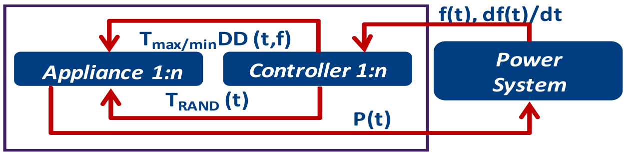

Fig. 2 Framework of the hybrid control strategy.

Each appliance switches on (off) when the cabinet temperature reaches the lower (upper) limit T_{minDD} (T_{maxDD}). The controller of each device identifies the frequency deviation Δf (Hz), evaluates its rate of change, $d(\Delta f)/dt$ and updates the temperature limits according to:

$$\begin{aligned} T_{maxDD}(t,f) &= T_{max} - K_{DD}\left[\Delta f(t) + K_{ROC}\, d\left(\Delta f(t)\right)/dt\right] \\ T_{minDD}(t,f) &= T_{min} - K_{DD}\left[\Delta f(t) + K_{ROC}\, d\left(\Delta f(t)\right)/dt\right] \end{aligned} \quad (1)$$

By increasing the threshold temperatures when a frequency drop is observed, the devices collectively spend more time in the off state, reducing their aggregate power consumption. K_{DD} is a positive gain that controls the overall sensitivity and K_{ROC} controls the relative weight of the rate-of-change term. We used the values K_{DD} =2.0 K s and $K_{ROC} = 2s$, which were empirically determined to produce a sufficiently large response whilst avoiding frequency oscillations The introduction of the rate of change in the update of temperature set points enables a faster response of the devices. Furthermore, we consider a sampling rate of 1 Hz for the frequency evaluation. Each appliance therefore needs 1s (2 consecutive samples) to estimate the rate of change of frequency, and one additional second to switch itself on or off. In general, a faster response is more effective.

Moreover, a drastic reduction of the synchronization and a delayed payback is obtained due to the inclusion of a randomized disengagement strategy, which is triggered when $(t \geq t_r)$ and $\Delta f(t) \leq 0.05$Hz. Then, each appliance selects a random temperature T_{rand} within the uniform distribution [T_{min}, T_{max}]. We used t_r=300s; increasing t_r entails a slightly delayed onset of payback but also a faster recovery of the devices. As consequence of this, the initial ramp rate of conventional generators is higher.

MODELLING

Domestic Devices' Dynamic Models

For our studies, we use a 4th order device model:

$$\begin{bmatrix} \dot{T}_1 \\ \dot{T}_2 \\ \dot{T}_3 \\ \dot{T}_4 \end{bmatrix} = \begin{pmatrix} a_{11} & a_{12} & a_{13} & 0 \\ a_{21} & a_{22} & 0 & 0 \\ a_{31} & 0 & a_{33} & a_{34} \\ 0 & 0 & a_{43} & a_{44} \end{pmatrix} \cdot \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix} + \begin{bmatrix} b_{1on/off} \\ 0 \\ b_3 \\ 0 \end{bmatrix} \quad (2)$$

The model describes the dynamics of the cabinet temperature T_1 and the food temperature T_2, for the freezer compartment, and, again, the dynamics of the cabinet temperature T_3 and the food temperature T_4, for the fridge compartment. In case of a fridge or freezer, the model simplifies to a second order model as there is only one compartment. Fig. 3 shows the thermal model with the heat flows inside and outside a schematic fridge/freezer.

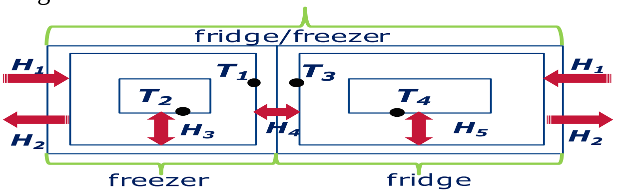

Fig. 3 Schematic thermal model for a cold appliance with the heat flows involved. H_1, the heat flow between the ambient and the cabinet (fridge and freezer); H_2, between the refrigerant and the cabinet (controlled by the motor); H_3, between the freezer cabinet and the freezer contents; H_4 between the freezer cabinet and the fridge cabinet; H_5 between the fridge cabinet and the fridge contents.

The parameters a_{xy} [s^{-1}] are defined as the ratio between the thermal conductance $K_{x,y}$ [W/K] and the thermal capacity $C_{x,y}$ [J/K], as defined in [7]. The values for these coefficients are obtained starting from reasonable initial values for the conductance, the thermal conductivity of the expanded polyurethane (the main insulating material) (K_p=0.03W/mK), the internal convection coefficient (h_{ex}=40W/m^2) and the external convection coefficient (h_{in}=8W/m^2); regarding the capacity, the specific heat of the cabinet (c_c=2kJ/kgK) and the water (c_w=4.2kJ/kgK). We used the following dimensions and thickness of insulation: fridge: 1.8x0.6x0.5m, 4.5cm; freezer:

0.9x0.6x0.6m, 7cm; fridge/freezer: 0.6x0.7x0.6m, 8cm (freezer compartment) and 1.2x0.7x0.65m, 4.5 (fridge compartment). Furthermore we consider the weight of the contents: fridge 17kg; freezer: 20kg; fridge/freezer: 10kg for the fridge compartment and 4kg for the freezer compartment. Afterwards, parameters in (2) have been tuned to achieve a better match in accordance with desired average characteristics listed in Table 1 (e.g. [5, 9]). The ambient temperature is taken to be 20°C.

	Power	COP	T_{max}/T_{min}	Duty Cycle
Fridge	70 W	2.5	2/7 °C	0.24
Freezer	100 W	1.6	-15/-21 °C	0.26
Fri-Free	180 W	1.6	-14/-21 °C	0.21

Table 1 Characteristics of thermostatic loads

We simulate 10000 individual appliances for each class; each set is scaled up so as to approximate, respectively, 11 million fridges, 14 million freezers and 22 million fridge-freezers. The temperatures and the status of each device are randomly initialized according to the steady-state distribution; moreover the parameters of each appliance are chosen randomly within a ±20% uniform interval around the nominal values. The aggregate power of the devices P_{DSS} is 1.37 GW.

Fridge – second order model parameters [s^{-1}]				
a_{11}	a_{12}	$a_{21}=-a_{22}$	b_{1on} [°Cs^{-1}]	b_{1off} [°Cs^{-1}]
$-7.05\cdot10^{-4}$	$5.56\cdot10^{-4}$	$1.04\cdot10^{-4}$	$-6.43\cdot10^{-3}$	$2.97\cdot10^{-3}$
Freezer – second order model parameters [s^{-1}]				
a_{11}	a_{12}	$a_{21}=-a_{22}$	b_{1on} [°Cs^{-1}]	b_{1off} [°Cs^{-1}]
$-8.01\cdot10^{-4}$	$7.38\cdot10^{-4}$	$1.22\cdot10^{-4}$	$-8.37\cdot10^{-3}$	$1.30\cdot10^{-3}$
Fridge/freezer – fourth order model parameters [s^{-1}]				
a_{11}	a_{12}	a_{13}	a_{21}	a_{22}
$-8.32\cdot10^{-4}$	$7.37\cdot10^{-4}$	$6.40\cdot10^{-4}$	$1.90\cdot10^{-4}$	$-1.90\cdot10^{-4}$
a_{31}	a_{33}	a_{34}	a_{43}	a_{44}
$6.41\cdot10^{-5}$	$-2.38\cdot10^{-3}$	$2.22\cdot10^{-4}$	$7.09\cdot10^{-4}$	$-7.09\cdot10^{-4}$
b_{1on} [°Cs^{-1}]	b_{1off} [°Cs^{-1}]	b_3 [°Cs^{-1}]		
$-10.60\cdot10^{-3}$	$6.10\cdot10^{-4}$	$1.90\cdot10^{-3}$		

Table 2 Nominal parameters of the dynamic model of cold appliances

Splitting the dynamics of the food temperature and the cabinet temperature is useful to capture the fact that the temperature of the food changes much slower than that of the cabinet. This increases the possible time that the devices can be switched off for, without damaging the food.

Power System Dynamic Model

We use a simplified power system model detailed in [8]. It consists of a linear 6th order model where we integrate the responsive demand and considers the contribution of primary control and the secondary response supplied by selected machines. We simulate a sudden loss of generation, set at 1.8 GW. The total system demand is 60 GW. The parameters are chosen to qualitatively match the behavior of the GB power system as detailed by the National Grid [2]. In particular, H=4.5s, D=1, T_g=0.2s, R=0.3, T_c=7s and K_I=0.01. Matlab has been used for the simulations.

RESULTS

In this section we evaluate the ability of the proposed algorithm to enhance the control of thermostatic loads and their ability to provide frequency services. We compare the performances of the hybrid control strategy with three alternatives:

- *Reference case*: no dynamic demand contribution.
- *Deterministic control [4-5]*: controller as in (1) with K_{DD}=2 K s, $K_{ROC} = 0\ s$; no disengagement strategy.
- *Stochastic control [6]:* first order model for fridges and freezers; $\alpha_r=7.05\cdot10^{-4}s^{-1}$, T_{on_r}=-5.17°C, T_{off_r}=8.15°C; $\alpha_f=8.01\cdot10^{-4}s^{-1}$, T_{on_f}=-26.5°C, T_{off_f}=-13.09°C.

Note that the stochastic control in [6] is designed for first order device models; hence, the state variable is the cabinet temperature and its time evolution is described by a first order ODE depending on its status:

$$\dot{T}(t) = -\alpha\left(T(t) - T_{on/off}\right) \quad (3)$$

The first order model is computed assuming a constant food temperature; it is a good approximation of the second order model within the nominal interval [T_{min}, T_{max}]. We use only fridges and freezers as the cabinet temperature evolution of a fridge-freezer is not well approximated moving from a fourth to a first order model; thus the number of fridges and freezers is increased proportionally to reach the same aggregate power value, at steady state condition, as in the other cases.

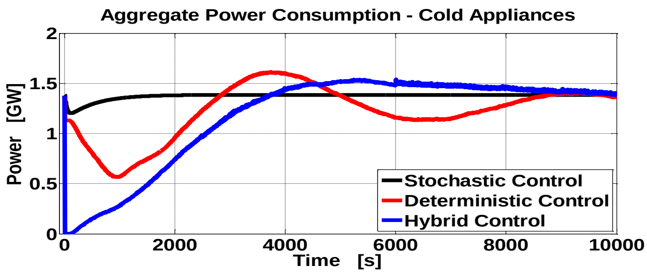

Fig. 2 Time evolution of the aggregate power consumption of dynamic demand cold appliances after a 1800 MW loss with 60 GW of system demand: comparison between hybrid control, stochastic control and deterministic control.

Fig.4 shows the power consumption of the cold appliances after a generator loss event at t=1s. The hybrid control, by using the rate of change of the frequency in the update of the temperature set points, permits a complete reduction in power consumption at short notice; this is not guaranteed with other strategies. The random disengagement procedure delays the payback energy compared to the deterministic solution and avoids large-scale cyclic load patterns. Fig. 5 demonstrates that controlling smarts loads with the hybrid strategy ensures the fastest recovery of frequency within a narrow range.

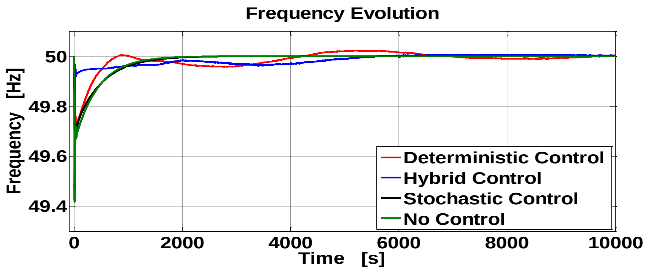

Fig. 3 Frequency evolution after 1800MW loss and 60GW of system demand: comparison between the strategies and the reference case.

Moreover Fig.6 provides a zoom of the frequency curves on the first 15s after the generation loss. The fast and consistent reduction of power consumption in case of hybrid control is translated in a higher frequency nadir.

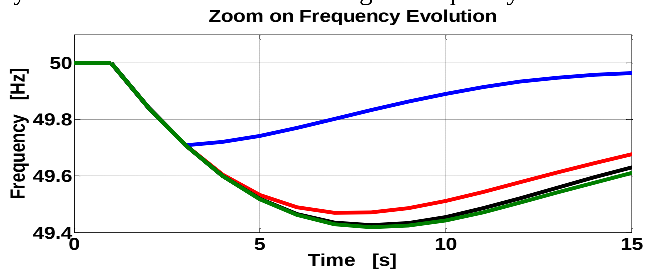

Fig. 4 Zoom on frequency evolution: comparison between the hybrid control (blue), deterministic control (red), stochastic control (black) and the reference case (green).

Finally, in Fig.7, we also highlight the ability of dynamic demand to replace fast frequency services provided by expensive and pollutant generators. A good benchmark is comparing the time evolution of the primary and secondary control support provided by conventional generators.

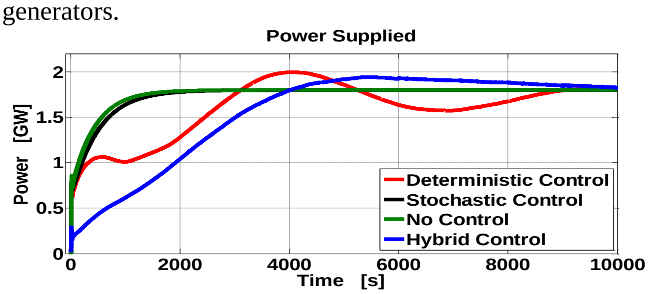

Fig. 5 Power supplied by selected generators in charge of primary and secondary control. Comparison between the control strategies and the reference case in case of 1800 MW loss and 60 GW of system demand.

The graph shows that there is no substantial difference between the reference case and stochastic control; as a consequence of this, dynamic demand, operated in this way, is neither economically nor technically convenient. Using the hybrid control, the concrete benefits of dynamic demand in the provision of primary support are highlighted as the curve starts from a much lower value. Moreover, up to slightly more than one hour after the generator outage, the hybrid curve is always below the reference case, so less conventional generation is required. The initial ramp rate conventional of generators decreases from ≈115 MW/min to ≈23MW/min. This is the key outcome of the hybrid strategy, as the amount of fast but perhaps expensive and/or pollutant generation for frequency support can be reduced, leading to economic and environmental savings. Furthermore, the payback effect doesn't undermine these benefits since the extra generation required is limited and occurs more than an hour after the initial event, a sufficient time to reschedule the system in a more efficient way.

CONCLUSIONS

The paper describes a new hybrid control strategy for thermostatic appliances for the provision of frequency services. By monitoring the rate of change of frequency, the control enables a rapid response after the loss of a generating unit. Furthermore, the addition of a randomized disengagement strategy both postpones the payback and suppresses the synchronization effect observed in simpler control schemes. We have investigated the performance of the hybrid control using a second order model for refrigerators and freezers and a fourth order model for fridge-freezers, coupled to a simple power system model. Comparisons with the deterministic [4-5] and stochastic [6] controllers are included, confirming that the hybrid controller addresses previously identified shortcomings.

Acknowledgments

ST has received funding from the European Union Seventh Framework Programme (FP7/2007/2013) under grant agreement n°274387.

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