MULTIPLE SERVICES ALLOCATION FOR FLEXIBLE THERMOSTATIC LOADS

Vincenzo TROVATO
Imperial College London – United Kingdom
v.trovato10@imperial.ac.uk

Goran STRBAC
Imperial College London – United Kingdom
g.strbac@imperial.ac.uk

ABSTRACT

Flexible Thermostatically Controlled Loads (TCLs) may be successfully employed to provide multiple services to transmission and distribution system operators. This paper introduces a linear-programming model which simultaneously optimizes the provision of energy arbitrage, various frequency response services (to the transmission operator) and a congestion management service to the distribution network operator. Case studies investigate the potential TCL net savings under different regulatory frameworks.

INTRODUCTION

Thermostatically Controlled Loads (TCLs) represent a distributed source of flexibility that may be used to provide a variety of ancillary services to different sectors of the electricity industry [1]. These devices could realize energy price arbitrage; when the energy price is high, TCLs reduce their consumption, which is shifted to adjacent low-price time periods. TCLs would be able to supply short/medium term frequency services, reducing the number of conventional generators that are inefficiently operated part-loaded. The intrinsic flexibility of TCLs may be used to relieve network congestions at both transmission and distribution level.

Recent studies performed a cost-based analysis in which TCLs contributed to the minimization of the transmission system operation cost by providing frequency response [2] or, in addition, energy arbitrage and congestions management [3]. However, it is not straightforward to infer the final benefits and revenues for TCL owners (e.g. single customers or aggregators) with such a centralized system-centric approach. Moreover a decentralized market-based environment still requires clear regulatory frameworks to ensure an adequate rewarding mechanism for investors on controlled TCLs. A focus on Great Britain (GB) reveals that the Transmission System Operator (TSO) is actively encouraging the demand-side frequency support, launching a new service, the Enhanced Frequency Response (EFR) [4], which has been designed for demand-side actors. However, the system requirements and the rewarding mechanism for EFR is still under debate. Furthermore, it is not clearly defined if TCLs will be able to realize energy arbitrage exploiting the energy price differentials of the wholesale market or those resulting from a time-dependent distribution tariff e.g. an *off-peak* price vs a *peak-time* price [5]. Finally yet importantly, there is currently no formal treatment in the regulatory framework to remunerate services provided by demand-side actors to the Distribution System Operator (DNO).

In this context, an effective liner-programming (LP) model that co-optimizes the energy consumption and the allocation of multiple network services through the active power control of a cluster of heterogeneous TCLs is introduces in this paper. The services considered are energy arbitrage, primary, secondary, high frequency response [6] and EFR [4]. A distribution network service is also taken into account. Individual devices are effectively modelled as an aggregate battery-like storage unit [1]. The feasibility of the optimal energy/power profile, the deliverability of the contracted services and the respect of the TCL primary heating/cooling function are ensured by a decentralized and non-disruptive control strategy [1]. Case studies compare the TCL net savings under different regulatory frameworks, demonstrating that the revenues in association with flexible allocation of frequency services are more profitable.

MODELLING AND CONTROL OF TCLS

A cluster of $N \gg 1$ heterogeneous TCLs can be accurately described as a single energy storage unit [1].

$$\frac{dS(t)}{dt} = -\frac{1}{\hat{\tau}}S(t) + P(t) \qquad (1)$$

where $S(t)$ [MWh], $P(t)$ [MW] and $\hat{\tau}$ [h] are the aggregate energy, power and time constant for the population model, respectively. The fundamental property of the control strategy envisages the ability of individual TCLs to target in expectation a desired reference power curve $\Pi(t)$, so that the aggregate power consumption equals (2).

$$P(t) = \hat{P}_0 \Pi(t) + O(N^{-1/2}) \qquad (2)$$

Note that $\hat{P}_0$ [MW] is the average steady state population consumption. The controller also imposes constraints on the instantaneous power excursions (3) and energy bounds (4), preventing the TCLs from being excessively warm or cold.

$$\hat{\mathrm{P}}_{min} = \max_a \mathrm{P}^a_{min} \le P(t) \le \hat{\mathrm{P}}_{max} = \min_a \mathrm{P}^a_{max} \qquad (3)$$

$$\hat{\mathrm{S}}_{min} = \max_a \mathrm{S}^a_{min} \le S(t) \le \hat{\mathrm{S}}_{max} = \min_a \mathrm{S}^a_{max} \qquad (4)$$

This feature makes the controller non-disruptive. Note that the superscript a characterizes single device parameters. Moreover, device-level simulations are not necessary to ascertain the feasibility of any power profile bounded by (3)-(4), as discussed in [1].

PROBLEM DESCRIPTION

The proposed LP model schedules the power/energy consumption of a cluster of TCLs by optimizing the simultaneous allocation of multiple services. The first service is energy arbitrage, which implies the alteration of the steady state consumption to exploit the time-variant energy prices. The model includes the possibility to hold energy/power margins to allocate various frequency response services. In particular, short term services i.e. primary response and high frequency response [6] envisage a power reduction (the first) or increment (the second) to be supplied within 10s after the triggering frequency event and sustained for further 20s. Secondary response, a medium-term service, imposes a constant power reduction up to 30min [6]. Besides these traditional (in GB) frequency services, the model evaluates the benefits of allocating power margins to provide EFR. In this case, a power reduction has to be performed within 1s sustained for 10s [4]. It is worth pointing out that energy arbitrage implies actual changes to the power consumption, while the devices receive an availability fee even when the allocated response services are not actually supplied. The TCL cluster is assumed to be connected to a distribution primary substation along with additional static load [7]. Hence, the devices may also provide a congestion management service to the DNO in order to help the total distribution network demand to not exceed the power capacity of the substation. In contrast with energy arbitrage and response services, which should be contracted with the TSO, the distribution network service should be rewarded by the DNO. Note that synergies or conflicts between energy arbitrage and the DNO service may arise, reflecting the correlation or anti-correlation between the energy price and the distribution demand profiles. The actual TCL ability to simultaneously provide multiple services is guaranteed by the properties of the control strategy [1], which are enforced in the proposed model.

A generic day with w=24 hours with periodic boundary conditions is considered. The horizon is divided into m=48 periods i of Δt = 30 minutes. The discrete energy evolution (5) follows from solving (1) on the interval $[0, \Delta t]$ and imposing a constant power level P_i within the time step i.

$$S_{i+1} = S_i \cdot e^{-\frac{\Delta t}{\hat{\tau}}} + \hat{\tau} P_i \cdot \left(1 - e^{-\frac{\Delta t}{\hat{\tau}}}\right) \tag{5}$$

S_i and S_{i+1} are the energy levels [MWh] at the extremities of interval i. The set of discrete energy levels $\mathcal{S} = \{S_i\}_{i=1}^{m}$ are therefore decision variables together with the sets of frequency response services $\mathcal{P}^x = \{P_i^x\}_{i=1}^{m}$, for each frequency service x. with. The corresponding discrete power levels P_i can be found by inverting (5). As TCLs are modelled as a price-taking aggregate energy storage component, the optimization takes the form of payment minimization problem that subtracts the any availability fees for frequency services to the expense for energy consumption. Electricity prices ρ_i and the availability fees h^x for each frequency service are known in advanced and expressed in £/MWh.

$$\min_{\mathcal{S},\mathcal{P}^p,\mathcal{P}^s,\mathcal{P}^h,\mathcal{P}^e} \sum_{i=1}^{m} \left[\rho_i \cdot P_i(\mathcal{S}) \cdot \Delta t - h^p \cdot P_i^p - h^h \cdot P_i^h - h^s \cdot P_i^s - h^e \cdot P_i^e\right] \tag{6}$$

subject to (for all i, where applicable)

$$\widehat{\mathrm{P}}_{min} \le P_i(\mathcal{S}) \le \widehat{\mathrm{P}}_{max} \tag{7}$$

$$\widehat{\mathrm{S}}_{min} \le S_i \le \widehat{\mathrm{S}}_{max} \tag{8}$$

$$\frac{1}{m}\sum_{j=1}^{m} S_j = S_0 \tag{9}$$

$$0 \le P_i^p \le P_i(\mathcal{S}) - \widehat{\mathrm{P}}_{min} \tag{10}$$

$$0 \le P_i^h \le \widehat{\mathrm{P}}_{max} - P_i(\mathcal{S}) \tag{11}$$

$$0 \le P_i^s \le P_i(\mathcal{S}) - \widehat{\mathrm{P}}_{min} \tag{12}$$

$$0 \le P_i^e \le P_i(\mathcal{S}) - \widehat{\mathrm{P}}_{min} \tag{13}$$

$$S_{i+1} - \hat{\tau} P_i^s \left(1 - e^{-\frac{\Delta t}{\hat{\tau}}}\right) \ge \widehat{\mathrm{S}}_{min} \tag{14}$$

$$P_i(\mathcal{S}) + P_{static_i}^{DNO} \le P_{max}^{DNO} \tag{15}$$

The optimal solution is bounded by the controller's power (7) and energy constraints (8). In addition, (10) makes the average energy equal the steady state energy $\hat{S}_0 = \hat{P}_0 \hat{\tau}$. This way, those power profiles implying the energy consumption always equal to the lower/upper bound are eliminated, although feasible according to (8-9). Constraints (10-13) guarantee sufficient power margins reserves for primary response, high frequency response, secondary response and EFR. It is assumed that the provision of short-term services has a negligible impact on energy levels [1]. With (14) the respect of energy limits associated with the provision of secondary response is ensured. The DNO service is directly included in the set of constraints (see (15)) and not in the formulation of the objective function, as in [7]. In accordance with the service's aim, the primary substation capacity P_{max}^{DNO} is not exceeded at any point in time. We apply the same reward mechanism presented in [7] for conventional energy storages. The model quantifies the revenue increase in energy and response services markets when no TCL capacity is dedicated to the DNO service (i.e. relaxing of (15)). In other words, TCLs would request the DNO at least a value equal to such a revenue increase in order to provide the congestion relief service.

CASE STUDY AND RESULTS

Four distinct types of refrigeration units are considered. Domestic fridges with built-in freezer compartments, commercial bottle coolers, upright freezers and multidecks. The parameters describing these devices are taken from [1]. For all the studies, we consider a cluster of TCLs, whose aggregate steady-state consumption $\hat{P}_0$ is 1MW. Two case studies are analyzed. The first investigates the potential daily savings realized by TCLs under different regulatory frameworks. Only domestic TCLs are taken into account although the outcomes can be extended to the other refrigeration units. Two different price profiles are envisaged (see Fig.1a). The first (blue dotted) is the Economy 7 distribution tariff, which consists of a *peak-time* rate (17.1 p/kWh between 7:30am and 7:00pm) and an *off-peak* rate (6.27 p/kWh, from 7:00pm until 7:30am) [5]. The second is the half-hourly energy price profile, representative of the GB wholesale energy market outcomes in a winter day (blue solid). Figure 1a also shows the aggregate distribution demand profile (black solid) as sum of the steady state TCL consumption ($P_i = \hat{P}_0$) and the static load $P^{DNO}_{static_i}$. The aggregate distribution level consumption exceeds in some hours the maximum capacity limit of the primary substation (up to 6% with P^{DNO}_{max}=10MW). Note that the distribution demand peak occurs between 06:00am and 08:00am, in contrast with the typical evening energy price peak. Six scenarios are compared to the base case in which the TCLs are inflexible (i.e. $S_i = S_0$ and $P_i = \hat{P}_0$) and do not provide any frequency service and DNO service. In each of the scenarios described in Table 1, TCLs may provide energy arbitrage, exploiting the price differentials of the DNO tariff or the energy market prices. Moreover, in some scenarios the provision of response services is not allowed. This is permitted instead in scenarios 2 and 4-6 with the exception of the EFR service, which is included in the scenario 7. In addition, the allocated response for the services may be constant for the entire optimization horizon or flexible i.e. potentially different at each time interval. The response services are priced at h^p=£6/MWh, h^h=£7/MWh, h^s=£5/MWh [1] and h^e=£12/MWh, twice the primary response price [4]. Note that, although in all the scenarios TCLs provide DNO services (i.e. (15) is respected), only in scenarios 5-7 TCLs are remunerated from the DNO; the formal rewarding treatment has been explained in the previous section. Finally, some scenarios may require minor changes to the problem (6-15). For example, when the provision of some (or all) frequency response services are not allowed, the corresponding sets of decision variables $\mathcal{P}^x = \{P_i^x\}_{i=1}^m$ should be nil. In addition, $P_i^x = P_{i+1}^x$ for $i = 1 \dots m-1$ if the allocation of generic response service x is constant across the whole day.

Table 1 Description of the regulatory frameworks

Scenario	Energy Price		Response services		DNO services	
	price	arbitrage	provision	allocation	provision	reward
Base Case	DNO tariff	no	no	n.a.	no	no
1	DNO tariff	yes	no	n.a.	yes	no
2	DNO tariff	yes	yes (no EFR)	constant	yes	no
3	market	yes	no	n.a.	yes	no
4	market	yes	yes (no EFR)	constant	yes	no
5	market	yes	yes (no EFR)	constant	yes	yes
6	market	yes	yes (no EFR)	flexible	yes	yes
7	market	yes	all	flexible	yes	yes

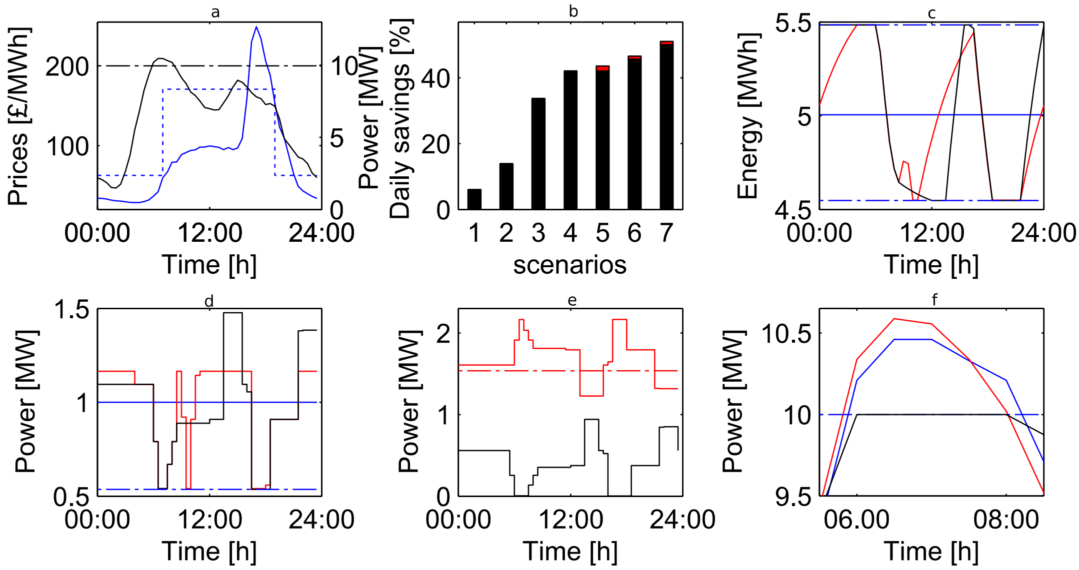

Figure 1 Daily savings and optimal multiple service allocation for 1 MW of domestic fridge-freezers.

As shown in Fig.1b, TCLs may realize minor savings compared to the base case daily expense (2803.2 £/day) if they are subject to the DNO dual tariff (6% in scenario 1, 13% in scenario 2). The daily savings are more than doubled when TCLs provide arbitrage exploiting the market energy prices (33%, scenario 3) and, in addition, frequency response services (42% in scenario 4). Scenario 5 indicates that the devices may increase their savings by £40/day if no TCL storage capacity is allocated to provide the DNO service (total savings 44%). Hence, according to the methodology proposed in [7] and adopted in this paper, £40/day is the minimum level of revenue that aggregate TCLs will request for the provision of the DNO service. The daily increment following the DNO service reward is illustrated with red bars. Finally, a flexible provision of frequency response services (scenario 6) and the ability to provide EFR (scenario 7) further increase the daily savings (47% and 51% respectively). In these cases, the DNO service rewards are £26/day (scenario 6) and £27/day (scenario 7). Figure 1c shows the aggregate TCL energy profiles for scenarios 4 (red) and 6 (black). Both profiles are bounded by energy limits (blue dashed) and differ from the steady state profile (base case, blue solid). The energy trends are similar and largely driven by the market prices profile. In fact, when the energy prices show significant increments (early in the morning and late in the evening), the TCL storage capacity is high before these moments and almost fully deployed afterwards. Similar considerations can be extended to the TCL power consumptions showed in Fig.1d (red for scenario 4, black for scenario 6 and blue for the base case). Figure 1e illustrates the different allocation of response services for the scenarios 4 and 6. Only high frequency response is contracted in scenario 4 (red dotted). Maintaining a constant power/energy buffer across the whole day to provide primary/secondary response is not convenient; in this case, due to the high market price peak, TCL consumption drops, in some hours, to the minimum level $\hat{P}_{min}$. In scenario 6 instead, due to a flexible service commitment, different levels of high frequency response (red solid) are contracted. Primary response (black solid) is allocated when the power consumption exceeds $\hat{P}_{min}$. Finally, Fig.1f demonstrates the TCL provision of the DNO service with respect to scenario 4. The aggregate demand connected to the distribution primary substation (black) is maintained below P^{DNO}_{max}=10MW. This limit was violated in the base case (blue solid). It is worth pointing out that if no TCL capacity is dedicated to the DNO service (i.e. constraint (16) is relaxed), the aggregate distribution demand (red solid) would be higher than in the base case. In other words, the provision of DNO service conflicts with the energy arbitrage service for this particular distribution demand profile.

Figure 2 shows the potential daily savings resulting from the optimal allocation of energy arbitrage, frequency response services (including EFR) and DNO service for different classes of TCLs.

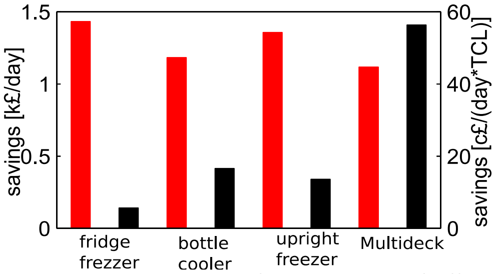

Figure 2 (a) Aggregate daily savings for 1MW clusters of different types of refrigeration units; (b) daily savings per individual TCL within each clusters of refrigeration units.

Considering aggregate clusters of devices ($\hat{P}_0$=1MW for each class), domestic fridge-freezers realize the highest net savings (black bars, £1432/day) followed by the upright freezers (£1357/day), bottle coolers (£1182/day) and multidecks (£1117/day). Domestic appliances make most of their savings providing high-frequency response; in fact these devices can exploit large power headroom ($\hat{P}_{max} - \hat{P}_0$). Conversely, bottle coolers and multidecks do not offer similar capabilities. Bottle coolers and upright freezers benefit from energy arbitrage due to large storage capacities. On the other side, the black bars illustrate the savings realized per individual device within each cluster. Multidecks save up to c£56/day, ten times more than the daily savings per individual domestic TCL due to a much smaller number of devices within the cluster (25428 fridge-freezers vs 1984 multidecks). In fact, individual multidecks offer a higher steady state consumption $\hat{P}^{a}_{0}$ [1].

CONCLUSION

This paper proposed a linear-programming model that co-optimizes the provision of multiple services by aggregate thermostatic loads. The devices realize energy arbitrage and offer availability for various frequency response services to relevant markets, while providing a congestion management service to the DNO. Case studies employed four classes of refrigeration units and considered seven potential regulatory frameworks. Results demonstrated the benefits of realizing energy arbitrage exploiting the energy market prices and contracting flexible frequency response services (including the EFR) and a DNO service (under proper reward mechanisms).

REFERENCES

[1] V. Trovato, S. Tindemans and G. Strbac, « Leaky Storage Model for Optimal Multi-service Allocation of Thermostatic Loads,» *IET Generation, Transmission & Distribution,* vol. 10, n. 2, 2015.

[2] M. Aunedi et al., «Economic and Environmental Benefits of Dynamic Demand in Providing Frequency Regulation,» *IEEE Trans. on Smart Grids,* vol. 4, n. 4, 2013.

[3] V. Trovato, S. Tindemans and G. Strbac, «Security Constrained Economic Dispatch with Flexible Thermostatically Controlled Loads,» in *IEEE ISGT Europe Conference*, Istanbul, 2014.

[4] National Grid, «Enhanced Frequency Response,» [Online]. Available: http://www2.nationalgrid.com/Enhanced-Frequency-Response.aspx.

[5] EDFenergy, «Unit Rate Calculator,» [Online]. Available: https://my.edfenergy.com/gas-electricity/unit-rate-comparison.

[6] National Grid , «Frequency response services,» [Online]. Available: http://www2.nationalgrid.com/uk/services/balancing-services/frequency-response/.

[7] R. Moreno, R. Moreira and G. Strbac, «A MILP model for optimising multi-service portfolios of distributed energy storage,» *Applied Energy,* vol. 137, 2015.