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Economic Dispatch of Demand Response Balancing Through Asymmetric Block Offers

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***Abstract*—This paper proposes a method of describing the load shifting ability of flexible electrical loads in a manner suitable for existing power system dispatch frameworks. The concept of an asymmetric block offer for flexible loads is introduced. This offer structure describes the ability of a flexible load to provide a response to the power system and the subsequent need to recover. The conventional system dispatch algorithm is altered to facilitate the dispatch of demand response units alongside generating units using the proposed offer structure. The value of demand response is assessed through case studies that dispatch flexible supermarket refrigeration loads for the provision of regulating power. The demand resource is described by a set of asymmetric blocks, and a set of four blocks offers is shown to offer cost savings for the procurement of regulating power in excess of 20%. For comparative purposes, the cost savings achievable with a fully observable and controllable demand response resource are evaluated, using a time series model of the refrigeration loads. The fully modeled resource offers greater savings; however the difference is small and potentially insufficient to justify the investment required to fully model and control individual flexible loads.**

***Index Terms*—Demand-side management, electricity markets, mixed-integer linear programming, refrigeration, time-series analysis.**

I. Introduction

DEMAND response is frequently presented as a solution to a multitude of challenges in the power system. It is said to bring about such benefits as supporting higher penetrations of renewable generation [1], increasing economic efficiency [2], and alleviating distribution network congestion [3], among others [4], [5]. Demand response is not without its challenges however. Chief amongst these is the uncertainty over the value that demand response provides to the power system

A number of academic works have attempted to quantify this value. The concept of price elasticity of demand is often adopted as a representation of the flexibility of demand in the presence of dynamic or real-time prices [6]–[8]. This approach assumes economic rationality and overlooks the significant complexities of electrical demand. Demand response is fundamentally characterized by the physical limitations and dynamics of electrical end-uses and highly complex interaction with consumers, which are not accurately described in the form of a linear price curve or single elasticity value.

On the other end of the scale, detailed models are used to assess the abilities and value of demand response resources, where it is assumed that the internal states of individual resources are known and can be controlled [9]–[12]. This approach is a valid method of establishing the theoretical value of demand response, however, the financial and computational costs of establishing a framework to dispatch many thousands of individually modeled flexible loads are prohibitive. Furthermore, current market clearing and power system dispatch algorithms interface with large conventional generating resources through bids consisting of a volume and a price [13], or limited set of constraints [14]. These frameworks are unsuitable for the management of a large number of individually modeled and controlled flexible loads.

This paper demonstrates the value that demand response can provide to the power system when its representation in the system dispatch algorithm is limited to one that is comparable in complexity to that of conventional generating units. The representation described here is suitable for the interface between an aggregator, managing a population of responsive loads, and the market or system operator. The interface between the aggregator and the individual loads can be handled using such control frameworks as detailed in [11] and [12].

This work contains two novel contributions to the field of demand response research. Firstly, building on material presented in [15], we develop a methodology of defining block bids that populations of flexible demand units can offer to the power system or market operator. The block offers reflect the load shifting abilities of individual demand units, considering their flexibility to provide a response to the power system and the subsequent necessity of energy recovery. The dispatch of these block offers is considered in the context of the regulating power market, where energy is sourced on an hour-ahead basis to serve forecasted imbalances close to real-time. Offers on the regulating power market must be fully activated within 15 min of being called by the system operator, and the rapid ramping capabilities expected from flexible loads makes them well suited to the provision of this service [16].

Secondly, we present an optimization framework to dispatch these block offers for demand response alongside conventional

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generating units for the provision of regulating power. This optimization differs from conventional economic dispatch algorithms as it is a combinatorial problem, where demand response blocks can be accepted in their entirety, or not at all.

Case studies are conducted to assess the value of demand response when represented by a limited set of block offers in the system dispatch algorithm. A comparative study evaluates the demand response resource when described as a fully observable and controllable system, using a time-series model. The flexible load considered in these case studies is supermarket refrigeration, which has with significant potential for load shifting demand response [17]–[19].

The remainder of this paper is structured as follows. Sections II and III present the demand response model, both the full and limited representations. The optimization framework employed to dispatch the system considering demand response is detailed in Section IV. The case study framework is outlined in Section V and results are given in Section VI. Concluding remarks can be found in Section VII.

II. Demand Response Resource Model

In this work we consider load shifting demand response on a short-term horizon, specifically for the provision of regulating power. A number of load types are considered as candidates for load shifting. In particular, thermal-electric loads such as building heating and cooling [10], [20], water heating [21], and refrigeration [17]–[19], are considered ideal candidates due to their ability to alter their power consumption while maintaining an acceptable temperature range. These thermal loads share two key characteristics, namely, saturation and rebound. Saturation refers to the limited time extent of the response from a thermal load. This is due to the temperature constraints that limit the duration for which power can be adjusted either upwards or downwards from a given baseline. Rebound refers to the phenomenon that is observed after control is returned to the device from the aggregator. Upon return of control, the device will attempt to return to the state it occupied directly preceding the request from the aggregator, resulting in a sudden reverse in the direction of the power consumption deviation.

The representations of flexibility developed in this work are applicable to all flexible loads capable of providing load-shifting demand response. Different load types will exhibit differing dynamics, and consequently the block offers and saturation curves for each will have different parameter values, but the concepts underlying these representations hold. Supermarket refrigeration is employed in this work as an example case study, owing both to its suitability for the provision of load shifting demand response and the availability of data and models describing its flexibility. Supermarket refrigeration systems are well suited to demand response as they have the ability to respond, the volume to provide a tangible service to the power system, and the financial incentive to participate in the power market [15].

The demand response capabilities and characteristics of supermarket refrigeration systems are explored through the combined use of time-series modeling and simulation. A second order auto-regressive moving average with exogenous inputs (ARMAX) model of a supermarket refrigeration system is identified from data procured from a Danfoss refrigeration test center in Denmark. Full details of this model are provided in [15].

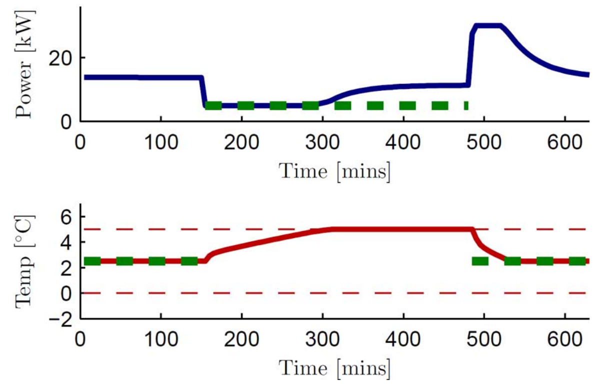

Fig. 1. Power consumption and representative medium temperature of the refrigeration system when a reduction of power consumption to 5 kW is requested. The heavy dashed lines indicate the temperature/power references to be tracked.

The demand response behavior of a single supermarket refrigeration system is simulated in a model predictive control framework, where the refrigeration system tracks a temperature or power reference. A demand response aggregator can request a response from the refrigeration system for a specified duration. When providing a response, the refrigeration system follows a power reference, at all other times the refrigeration system follows a temperature reference. The control objective for the refrigeration system is given as

$$\min \quad \sum_{t=1}^{T} a_t(P_t^{ref} - P_t)^2 + (1-a_t)(T_t^{ref} - T_t)^2 \tag{1}$$

where the control variables are temperature, T_t, and power, P_t. A binary indicator, a_t, governs the effective control objective at time t. When a_t is 1, the aggregator specifies a power reference, P_t^{ref} for the refrigeration system to track. When a_t is zero, the supermarket tracks a temperature reference, T_t^{ref}. The power consumption and system temperatures are inter-dependent and cannot be independently controlled simultaneously. The control is subject to upper and lower bounds on temperature in both the medium and low temperature display units. Power consumption is limited by the capacity of the compressors on the system. As the flexibility of this system is restricted by the least flexible system temperature, that of the medium temperature display unit, there is no further reference to the low temperature unit in this work.

The behavior of the refrigeration system over a period of both supermarket and aggregator control is illustrated in Fig. 1. During this simulation the aggregator requests a reduction in power consumption to 5 kW for 325 min. Saturation occurs when the upper temperature bound is reached. Rebound occurs upon return of control from the aggregator to the supermarket; power consumption increases to the upper limit, facilitating the fastest return to the supermarket defined reference temperature.

Under the described control framework, the power consumption of the refrigeration system can be considered to consist of a baseline power consumption and a deviation from this baseline.

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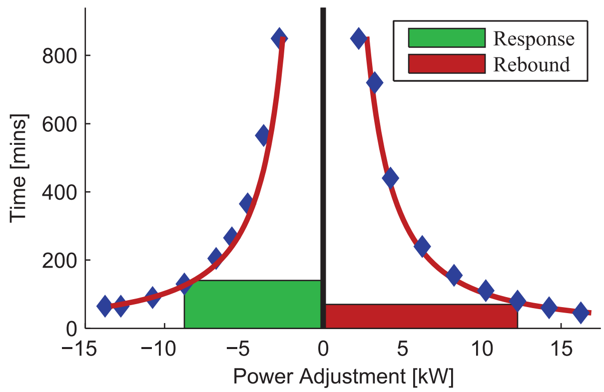

Fig. 2. Saturation curve of a supermarket refrigeration system, with a sample response-rebound block definition.

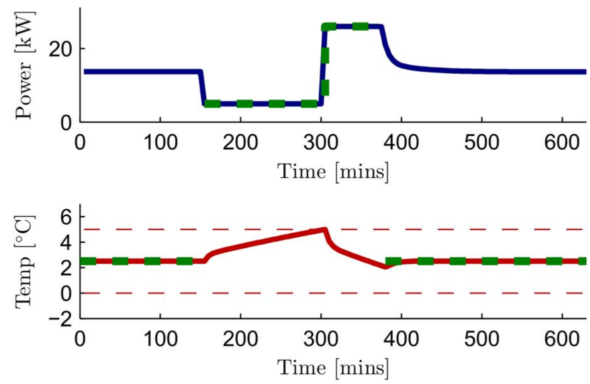

Fig. 3. Power consumption and representative medium temperature of the supermarket refrigeration model during a controlled response and rebound event, with power and temperature references indicated by the heavy dashed lines.

In the current model, the baseline power consumption is constant. This is because the system used for model identification is not a fully operational supermarket, and therefore does not include the complexities of customer interaction or widely varying external temperatures. On an operational system the baseline power consumption varies according to a number of factors. This baseline power consumption can be modeled and forecast [22], and purchase of the necessary energy to meet this demand can take place on the day-ahead market. Any deviation from the baseline can be employed to provide regulating power. In order to achieve this it is imperative that the saturation and rebound characteristics are fully described in a manner that can be easily communicated to a power system operator.

III. Characterizing Demand Response

A. Saturation Curve Concept

The time to saturation defines the maximum duration for which any deviation from the baseline can be reliably maintained. This can be found by simulating the response of the system to a range of power adjustments and finding the duration for which the requested power reference can be maintained before a temperature constraint is reached and saturation occurs. The results of these simulations are presented in Fig. 2, which plots the time to saturation against the power adjustment, and shows the closest fit to these points.

The rebound phenomenon can also be described using this curve. If the system is allowed to rebound in an uncontrolled manner, it will tend to do so at either its maximum or minimum power consumption levels, and the duration of this rebound is found at the outer points of the curves. If the aggregator includes a power reference for the rebound, the necessary duration can be found from the corresponding point on the saturation curve. In order to avoid any unexpected saturation or rebound, any service offer from the aggregator to the power system operator must consist of power levels and durations for both response and rebound as defined by the saturation curve. The offer thus has the form of an asymmetric block.

Fig. 3 illustrates the behavior of the refrigeration system under a request for a response-rebound block consisting of a reduction in consumption by 8.75 kW for 145 min (response) and an increase in consumption by 12.25 kW for 75 min (rebound), the block definition shown in Fig. 2. The adjustments occur from a baseline power consumption of 13.75 kW. It can be observed from Fig. 3 that the temperature reaches its upper bound, which indicates saturation, and the subsequent rebound is fully controlled. This is achieved without feedback from the supermarket to the aggregator; the aggregator decides on the composition of the entire block before issuing the power references to the supermarket.

The use of the saturation curve to achieve this response illustrates the ability of an aggregator to obtain effective demand response from a single refrigeration unit without the need for detailed modeling, monitoring or communications infrastructures. A similar representation can be found for a population of supermarkets by summing individual saturation curves to form an aggregate curve. The saturation curve of a homogeneous population of supermarkets will have the same form as the saturation curve of an individual supermarket, with a scaled power axis. For example, the combined flexibility of 1000 identical supermarkets is described by the saturation curve of a single supermarket, scaled in mega-watts rather than kilo-watts.

B. Saturation Curve Extension

The saturation curve presented in Fig. 2 represents the limits of the demand response capabilities of the refrigeration system. Naturally, the system is also capable of maintaining a power adjustment for a duration less than the saturation time, however the necessary rebound following such a response must be defined.

Temperature behavior within refrigeration units exhibits an exponential relationship with time, for a given power consumption level [17]. However, for small values of t the temperature trajectory can be approximated as linear. Within the refrigeration systems considered here, the temperature range is relatively small, and the duration for which a given power adjustment can be maintained is limited by saturation. Consequently for values of ΔP above a given threshold, the duration for which ΔP is maintained is short and the temperature behavior in the refrigeration system can be considered linear. This facilitates the identification of partial saturation curves and the definition of the corresponding rebound, if power deviations are only considered outside of a dead-band region. This has been verified

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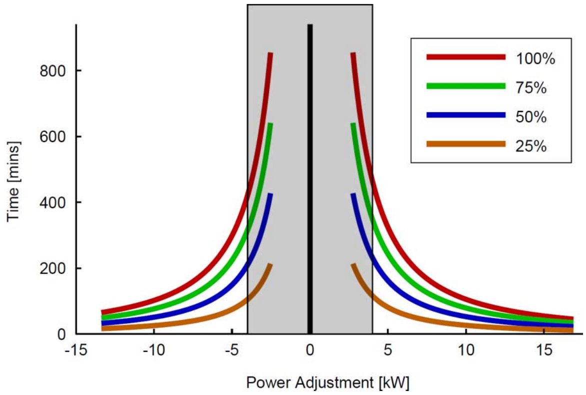

Fig. 4. Partial saturation curves with the dead-band indicated by the shaded grey section. To ensure accuracy, partial saturation curves should not be considered for power adjustments within the shaded region.

through simulation for the model considered in this work, where the dead-band range is $\{-4, 4\}$ kW.

Consider the extension of the saturation curve concept to incorporate the case where the response is maintained for $X\%$ of the saturation time. An $X\%$ saturation curve can be found for all power adjustments within the linear region by multiplying the original saturation curve by $X/100$. This facilitates the identification of the appropriate rebound following an $X\%$ response. Fig. 4 illustrates the case where $X = \{25, 50, 75, 100\}$. The advantage of using $X\%$ saturation curves is that the refrigeration units are not stressed to their temperature limits, but instead occupy a limited region around the baseline temperature.

IV. Scheduling Demand Response for Provision of Regulating Power

A. Problem Context and Assumptions

Demand response units are scheduled alongside conventional generating units for the provision of regulating power. The system dispatch is subject to two key simplifying assumptions. Firstly, that the system operator has perfect foresight of the required regulating power within the considered horizon. Typically regulating power is dispatched on an hourly basis [23], which is less than the 4-h horizon considered in the simulations that follow. It is acknowledged that there is a degree of uncertainty in the regulating power required over the considered dispatch horizon. The risk of dispatching excess or insufficient regulating power could be mitigated by employing a chance constrained or robust optimization framework for system dispatch, however determining uncertainty sets for the required regulating power is non-trivial. Furthermore, employing a stochastic optimization framework is computationally expensive and potentially infeasible at the short horizons considered here. Therefore, the simplification of accepting a perfect forecast of the required regulating power is accepted as necessary and representative of the practical manner in which regulating power is currently dispatched on existing power systems.

The second simplification is that all conventional generating units can provide up- and down-regulation, and the capacity available for each is fixed for the duration of the optimization. It is assumed that their existing dispatch (e.g., from the day-ahead market) allows for this.

B. Problem Formulation

The optimal dispatch of conventional and demand response units is found by employing the mixed integer linear programming optimization given as

$$\min_{\mathbf{x}} \mathbf{c}^{\mathbf{T}}\mathbf{x} \tag{2a}$$

$$\text{subject to}:$$

$$\mathbf{h}(\mathbf{x}) = 0 \tag{2b}$$

$$\mathbf{g}(\mathbf{x}) \geq 0 \tag{2c}$$

where $x = \{P_{i,t}, P^{DR}_{d,c,t}, v_{d,c,t}, SU^{DR}_{d,c,t}, SD^{DR}_{d,c,t}\}$, the conventional generator power output of each generating unit, i; the demand response power output for each block, c, and unit, d; the online status of the demand response block, c at unit d; and its start-up and shut-down indicators, respectively. The objective function, (2a), minimizes the cost to the system operator of sourcing regulating power subject to the sets of equality and inequality constraints governing the generating and demand response units on the power system. The generating unit constraints are those typically employed in economic dispatch and can be found in a number of references, including [24].

The constraints governing the behavior of the demand response units are provided in (3)–(6). The initialization and conclusion of a demand response block are indicated by a change in the online status of a given block, $v_{d,c,t}$, as detailed in (3).

When a demand response block is requested by the system operator, the demand response unit must follow the profile of the block, as defined in (4). This profile is comprised of the response, $P^{DR,resp}_{d,c}$, and rebound, $P^{DR,reb}_{d,c}$, for the corresponding response and rebound durations, $T^{resp}_{d,c}$ and $T^{reb}_{d,c}$. There may also be a recovery period following the completion of a demand response block, $T^{rec}_{d,c}$. Each demand response unit offers a number of demand response blocks, however simultaneous activation of blocks from a single demand response unit is not allowed. This is imposed in (5). Finally, any activated block must be fully realized within the dispatch horizon. This constraint is enforced in (6) which ensures that demand response blocks cannot commence in the final periods of the dispatch window, where this restricted region is defined by the response and rebound durations of each block. These constraints are summarized as

$$v_{d,c,t} - v_{d,c,t-1} = SU^{DR}_{d,c,t} - SD^{DR}_{d,c,t}, \tag{3}$$

$$P^{DR}_{d,c,t'} = \begin{cases} P^{DR,resp}_{d,c}, & \text{if } t \leq t' < t + T^{resp}_{d,c}, \\ & \forall t : SU^{D,R}_{d,c,t} = 1 \\ P^{DR,reb}_{d,c}, & \text{if } t + T^{resp}_{d,c} \leq t' < t + T^{resp}_{d,c} + T^{reb}_{d,c}, \\ & \forall t : SU^{D,R}_{d,c,t} = 1 \\ 0, & \text{if } t + T^{resp}_{d,c} + T^{reb}_{d,c} \leq t' < t + T^{resp}_{d,c} \\ & + T^{reb}_{d,c} + T^{rec}_{d,c}, \forall t : SU^{D,R}_{d,c,t} = 1 \end{cases} \tag{4}$$

$$\sum_{d=1}^{D} v_{d,c,t} = 1, \tag{5}$$

$$SU_{d,c,t} = 0 \quad \forall t > T - (T^{resp}_{d,c} + T^{reb}_{d,c}). \tag{6}$$

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C. Implementation

The limits on the power supplied by demand response block d from unit c depend on the orientation of the block. A block which commences with up-regulation followed by down-regulation is positively orientated, and the orientation parameter $\alpha_{d,c}$ is assigned the value 1. The opposite orientation has the value zero. Consideration of the orientation of the block is necessary when defining its power limits, as described in equation set (7). This set of four equations employs the "Big M" formulation such that only two constraints are active for any given block, depending on its orientation. For a positively oriented block, the second-half of the right hand side of (7a) and (7b) becomes zero and these constraints are active. The other two constraints are not relevant as an arbitrarily large value of M (e.g., 10 000) ensures that the these constraints are overridden by (7a) and (7b). The converse applies for a negatively oriented block. These power limits are given as

$$P^{DR}_{d,c,t} \le P^{resp}_{d,c} v_{d,c,t} + (1-\alpha_{d,c})M, \tag{7a}$$
$$P^{DR}_{d,c,t} \ge P^{reb}_{d,c} v_{d,c,t} - (1-\alpha_{d,c})M, \tag{7b}$$
$$P^{DR}_{d,c,t} \ge P^{resp}_{d,c} v_{d,c,t} - \alpha_{d,c}M, \tag{7c}$$
$$P^{DR}_{d,c,t} \le P^{reb}_{d,c} v_{d,c,t} + \alpha_{d,c}M. \tag{7d}$$

During the response and rebound portions of a demand response block, the demand response unit must maintain the dictated power supply level. This is imposed in equation set (8). Considering constraint (8a), for a positively oriented block, the power consumption must be at least as large as the defined response power, $P^{DR,resp}_{d,c}$, for the response duration $T^{resp}_{d,c}$, given that a block has commenced at time t. As the power supply of the block is simultaneously limited to be less than or equal to the response power, the combination of constraints (8a) and (7a) ensures the power supply of the block is equal to the defined response power. Equation (8b) ensures the corresponding power limit for the rebound portion of the block. Equation (8c) imposes a minimum recovery period, $T^{rec}_{d,c}$, between the activation of blocks from unit c. This constraint ensures that no block is active (i.e., $v_{d,c,t} = 0$) for the recovery period following the response and rebound, given that a block has been activated at time t. This implementation is given as

$$\sum_{t'=t}^{t+T^{resp}_{d,c}} \left(P^{DR}_{d,c,t'} - SU^{DR}_{d,c,t} P^{resp}_{d,c}\right) \begin{cases} \ge & (1-SU^{DR}_{d,c,t})M, \\ & \text{if } \alpha_{d,c}=1 \\ \le & (1-SU^{DR}_{d,c,t})M, \\ & \text{if } \alpha_{d,c}=0 \end{cases} \tag{8a}$$

$$\sum_{t'=t+T^{resp}_{d,c}}^{t+T^{resp}_{d,c}+T^{reb}_{d,c}} \left(P^{DR}_{d,c,t'} - SU^{DR}_{d,c,t} P^{reb}_{d,c}\right) \begin{cases} \le (1-SU^{DR}_{d,c,t})M, \\ \quad \text{if } \alpha_{d,c}=1 \\ \ge (1-SU^{DR}_{d,c,t})M, \\ \quad \text{if } \alpha_{d,c}=0 \end{cases} \tag{8b}$$

$$\sum_{t'=t+T^{resp}_{d,c}+T^{reb}_{d,c}}^{t+T^{resp}_{d,c}+T^{reb}_{d,c}+T^{rec}_{d,c}} \sum_{d=1}^{D} \left((1-v_{d,c,t'}) - SU^{DR}_{d,c,t}\right) \ge 0. \tag{8c}$$

V. Case Study Definition

Case studies are employed in this work to demonstrate the value of demand response to the system operator when its abilities are described using the limited form of a response-rebound block. Demand response is considered for the provision of regulating power on the Belgian regulating power market. Three cases are considered:

1) dispatch of the system without demand response;
2) dispatch of the system considering a limited set of demand response block offers;
3) dispatch of the system considering a fully observable and controllable demand response resource.

Historical regulating power data from the Belgian system operator, Elia, is employed in all case studies. On this power system, regulating power is recorded at a 15-min resolution. The data is interpolated to 5-min resolution using cubic splines to match the time resolution of the demand response models. The only further adjustment to this historic data is down-scaling such that the required regulating power can be serviced by the available generating capacity. This ensures that the regulating power dispatch is feasible both with and without demand response. To provide context, Elia is a mid-sized power system, its peak-load in 2012 was 13 362 MW [25]. Each case study considers a dispatch window of 4 h, using data from 2012.

The demand response resource consists of two demand response units, which each consist of a population of flexible loads. The flexibility of each unit is described using six response-rebound block offers, as detailed in Table I. While the physical capabilities of the units are the same, different blocks are offered for dispatch. This reflects the expectation that in a real-world implementation supermarkets would be clustered together to offer different services to the system operator. The blocks are selected from the 50% saturation curve shown in Fig. 4.

TABLE I
DR Response-Rebound Units and Blocks for 50% Saturation

Unit	Block	P^{resp} [MW]	τ^{resp} [min]	P^{reb}[MW]	τ^{reb} [min]
1	1	13	30	-17	20
	2	-17	30	13	30
	3	10	50	-10	50
	4	-17	20	10	50
	5	-9	40	11	45
	6	11	45	-9	40
2	1	-17	20	8	70
	2	8	70	-17	20
	3	13	30	-15	25
	4	-15	25	13	30
	5	-10	50	12	35
	6	12	35	-10	50

For comparative purposes, the demand response resource is also implemented in its fully observable and controllable form, as a time series model. The time series model is that from which the saturation characteristic and block offers are obtained. Dispatch of the fully modeled units is subject to the restriction that they must reach the mean of their temperature bounds at the end of the dispatch horizon. This ensures an approximate energy balance and a fair comparison between the full and limited representations of the demand response resource.

Each demand unit has a maximum up-regulating capacity of 13 MW and down-regulating capacity of 17 MW. The capacity of the demand response units is scaled to be comparable to the capacity of the conventional units considered in the case study. This scaling can be interpreted to represent a homogeneous population of 1000 individual supermarkets. The cost of acquiring

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TABLE II
CONVENTIONAL GENERATION UNIT DEFINITIONS

Unit	P^{max} [MW]	P^{min} [MW]	R^{max} [MW/min]	C^{up} [€/Mwh]	C^{down} [€/Mwh]
1	30	-30	3	11.51	9.32
2	40	-40	2	15.57	12.18
3	60	-60	1	28.56	23.87
4	70	-70	7	22.64	18.93

up- and down-regulation from the demand response units is set at €2/MWh. This is less than the cost of sourcing regulating power from any of the conventional units, ensuring that the demand response resource will be first in the merit order.

Four conventional generating units are considered in the case studies. Table II contains the technical specifications of each unit and the costs of acquiring up- and down-regulation from each. These costs are based on the production cost of each unit, where the up- and down-regulating costs are the production costs multiplied by a factor greater than and less that one, respectively. The scaling factors are found through an analysis of the difference between the day-ahead price on the Nordic power market and the up- and down-regulating prices [13].

Six regulating power profiles are employed in the case studies to evaluate the demand response resource, as shown in Fig. 5. Case A comprises 3 slowly varying profiles, while Case B comprises 3 fluctuating profiles, each is a historic time series of activated regulating power on the Elia power system, as detailed above. It is expected that the demand response blocks will have greater value in situations where the regulating power requirement fluctuates significantly due to their asymmetric shape and the large effective ramp rate between the response and rebound portions of the block. The two sets of regulating power profiles are considered for comparison. It is the experience of the authors from sourcing these profiles from historic data that Case B is more representative than Case A of typical operating conditions on the Elia power system.

VI. RESULTS AND DISCUSSION

The case study results are presented in Tables III and IV. The theoretical value of demand response is defined as the amount by which the cost of meeting regulating requirements is reduced when demand response is represented using a fully observable and controllable model. This is compared to the practically accessible value that this resource can provide to the system when represented by a limited set of blocks. It is evident that demand response is capable of providing substantial value to the system, and as expected there is a significant difference between the theoretical and practical resources.

This difference is due to two key factors. Firstly, the block definition imposes the need for a response and rebound that directly follow one another. This differs from the operation using the full model of the refrigeration system, where the only restriction is that an approximate energy balance is maintained (as imposed with a final temperature constraint). This allows the response and rebound to be separated. Consequently, the flexible demand unit has greater flexibility to follow the regulating power profile rather than requiring a rebound which may be in the opposite direction to the required regulating power. Secondly, the block definitions are formulated using the 50%

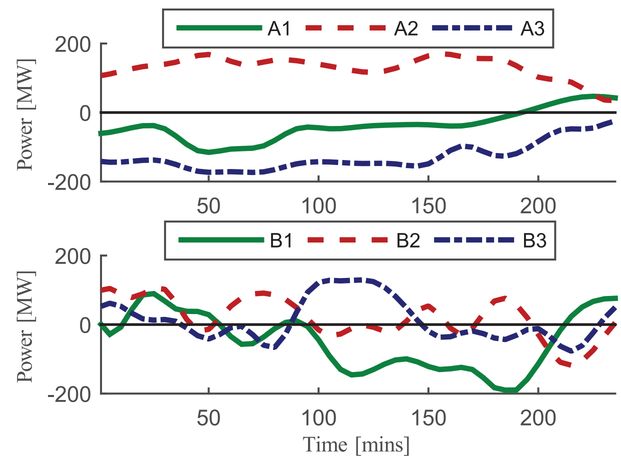

Fig. 5. Regulating power profiles–smooth (Case A–upper) and fluctuating (Case B–lower).

TABLE III
COST REDUCTION WITH DEMAND RESPONSE–CASE A

	A1	A2	A3
6 DR Block Offers	10.53%	4.14%	0.1%
Fully Modelled Demand	36.63%	4.88%	11.36%

TABLE IV
COST REDUCTION WITH DEMAND RESPONSE–CASE B

	B1	B2	B3
2 DR Block Offers	9.54%	18.10%	19.70%
3 DR Block Offers	17.10%	23.42%	21.25%
4 DR Block Offers	20.81%	23.42%	25.13%
5 DR Block Offers	21.23%	23.43%	25.13%
6 DR Block Offers	21.43%	23.63%	26.00%
Fully Modelled Demand	36.78%	41.8%	43.44%
Limited Temperature Range	24.45%	28.72%	34.22%

saturation curve, which has an effective temperature range of approximately 50% of the full range using the absolute limits imposed by the supermarket operator. In comparison, the fully modeled demand resource is free to employ the full temperature range, resulting in greater overall flexibility. Imposing tighter temperature limitations on the fully modeled resource allows the comparison of the value of both the block definitions and the full model when they are operating with the same physical flexibility. This comparison is included in the last row of Table IV, where it is observed that the disparity between the two forms of demand response is significantly reduced. This indicates that a very limited representation of the demand response capabilities of this thermal system has comparable value to a fully described system. The cost of establishing, controlling, monitoring and operating a fully modeled system is very high, and this result indicates that such a cost may not be justified by the additional value it brings to system operation.

Comparison of Tables III and IV reveals that there is a greater disparity between the theoretical and practical values when the regulating power profiles vary slowly, as in Case A. Analysis of the behavior of the fully modeled units in Cases A1-A3 reveals that they tend to provide both response and rebound in the prevailing direction of the regulating power profile. In contrast, when the demand response behavior is limited to the asymmetric block offer structure, a rebound is necessary immediately

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following the response. This must be compensated for by conventional units if the rebound is in the opposite direction to the required regulating power. Consequently, scheduling blocks for slowly varying regulating profiles is either very costly, or the blocks are not scheduled at all. This is confirmed in Table III, where a larger difference between the theoretical and practical values is observed in case A1 than in any of the B cases, and in case A3 where the value of demand response described using blocks is negligible. In case A2, the demand response is incapable of bringing any significant value to the system, regardless of the resource description used. This is because the regulating power requirement is very high so the percentage contribution from demand response is lower than in the other cases.

Table IV presents the cost reductions for regulating power procurement when the demand response resource is represented with a varying number of blocks. For cases with less than 6 blocks, the blocks are taken in order from Table I. It can be concluded from Table IV that the value of the demand response resource when described using block offers approaches the value of the fully modeled resource as the numbers of block offers increases. In fact, if the flexibility of the demand response resource were described using an infinite number of block offers, it would be equivalent to the flexibility described by the fully modeled system.

It is shown in Table IV that in some cases, increasing the number of blocks has no impact on costs. This is because the additional block offer is not selected for dispatch, and can be understood to be unsuitable for the considered regulating power profile. The results of this analysis reveal that cost savings greater than 20% can be achieved with only four block offers. This demonstrates that even a very limited representation of the flexible demand resource facilitates significant cost savings.

Fig. 6 illustrates the aggregate dispatch of the generating and demand response units for case B1. The most beneficial behavior in terms of system dispatch cost would be for the demand response blocks to reduce the power provided by generating units. This behavior is observed for the majority of the dispatch horizon, however there are brief periods where the generating units are required to compensate for the rebound of the demand response units. This can be observed during the interval between minutes 145 and 160. During this interval, one of the demand response units is rebounding in the opposite direction to the required regulating power and the generating units must provide additional down-regulation. From minute 165, the second demand response unit begins providing down-regulation which partially compensates for the rebound of the first unit and reduces the over-provision from the generating units. Despite this need for compensation, the demand response blocks offer significant value to the system when optimized for cost minimization. In the case of a volume-based optimization, this form of demand response may not be attractive.

Fig. 7 illustrates the dispatch of the demand response blocks and the fully model resource for case B1. It is evident that the demand response blocks attempt to replicate the behavior of the fully modeled resource where they can. The key difference occurs between minutes 110 and 210 where the fully modeled system is capable of providing down regulation continually, whereas the demand response blocks have to alternate between

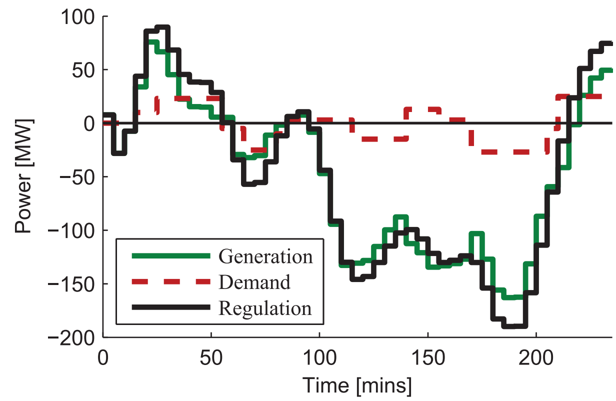

Fig. 6. System dispatch of conventional and demand response units for the provision of regulating power–Case B1.

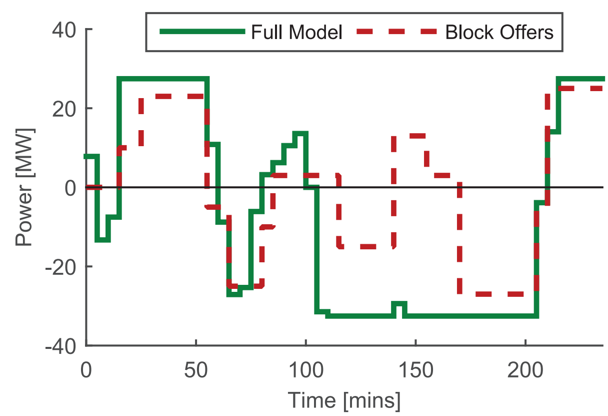

Fig. 7. Comparison of the dispatched aggregate demand response resource in case B1 when considering block bids and the fully modeled resource.

response and rebound. This is due to the wider effective temperature limits in the fully modeled case.

VII. Conclusion

This paper presents a method of representing the physical capabilities of flexible loads in the system dispatch algorithm at a comparable level of complexity to conventional generating units. A novel system dispatch algorithm is developed that schedules demand response units using asymmetric block offers that encompass both the response and rebound that are exhibited by flexible loads. Such block offers are limited in that they describe a subset of the capabilities of the demand response resource, but have the advantage that they are compatible with current system dispatch and market clearing algorithms.

Case studies have demonstrated that demand response from supermarket refrigeration systems, as described using a limited set of block offers, is capable of achieving substantial cost savings in the procurement of regulating power. The value of the demand response resource, as described using block offers, is compared to the theoretical value that could be achieved if it were possible to include a fully observable and controllable model of each flexible load within the system dispatch algorithm. The disparity between the theoretical and practical values is found to be relatively low, which indicates that significant costs involved in establishing the theoretical framework may

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not be justified by the additional value it may yield. It is important to note that this work is not intended to prove the value of demand response from supermarket refrigeration, or any other form of demand response. The objective rather, was to develop a methodology of scheduling demand response that is applicable to all forms of flexible loads capable of providing load-shifting. The flexibility of any thermal-electric load can be described in the form of a saturation curve, from which asymmetric block offers can be obtained, and scheduled in the manner described in this work.

In this work the characteristics of the demand response resource have been established through simulations, however going forward it would be advantageous to explore analytical approaches to this characterization. Further more, it will be beneficial to investigate methods to reduce the computational effort required to optimally dispatch demand response block offers, which require binary variables that are computationally burdensome for large scale implementation. A continuation of this research agenda should also consider uncertainty in both the achievable demand response, and the resource which it is providing, be that regulating power or another power system service.

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