Strategies for demand load control to reduce balancing costs

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***Abstract*—This paper addresses the problem of using demand load control to minimize balancing costs when extra generation is needed. The problem is formalized as an optimal control problem where the amount of load to be postponed at successive time instants is set with respect to constraints representing the balance between generation and demand at successive time instants. The paper presents three market designs, namely minimization of the system operators' cost over the peak period, successive independent merit orders, and successive predictive merit orders considering payback effect. It shows that actual practices such as successive independent merit orders may lead to significant extra costs, which can be strongly reduced by including mid-term implications in the decision-making.**

***Index Terms*—demand response, demand side management, direct load control, electricity market.**

I. Nomenclature

$P_D(k)$	Effective amount of power to be balanced at instant k
$\overline{P_D}(k)$	Original amount of power to be balanced at instant k
$P_{Gbase}(k)$	Base power generation at instant k
$P_{Gbase}^{\max}$	Maximum base power generation
$P_{Gpeak}(k)$	Peak power generation at instant k
$P_{Gpeak}^{\max}$	Maximum peak power generation
$P_{DLC}(k)$	Power demand avoided by direct load control at instant k
$P_{DLC}^{\max}$	Maximum amount of demand avoided by direct load control
$C_{Gpeak}(k)$	Cost of peak generation at instant k in €
α_{Gpeak}	Coefficient in the cost function of peak generation in €/MW²
β_{Gpeak}	Coefficient in the cost function of peak generation in €/MW
$C_{DLC}(k)$	Cost of direct load control at instant k in €
α_{DLC}	Coefficient in the cost function of direct load control in €/MW²
β_{DLC}	Coefficient in the cost function of direct load control in €/MW

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II. Introduction

BALANCING generation with demand is one of the prerogatives of transmission system operators (TSOs). In practice, to handle the difference between effective injections and those scheduled based on experience or weather, economic, and social forecasts [1], the TSOs request changes in generation and demand in the form of extra or less power injections. Balancing mechanisms are also used to manage congestions, when the scheduled transactions lead to a power flow that exceeds its respective available transfer capacity. Balancing mechanisms encompass significant costs, especially when the electric demand is higher than the available base generation. In this case, it usually relies on offers from peak generation units.

To lower balancing costs, some transmission utilities have thus developed specific tariffs for large consumers that reduce their demand during critical periods upon request from the transmission system operator. In addition, the development of direct load control opens new perspectives for demand response to balance the system when extra generation is needed [2]. Indeed, load demand in residential and commercial sectors for water-heaters and heating systems could be easily modulated. As emphasized in [3], these types of loads are capable of postponing their demand at a low rate, since they are more flexible than other loads, such as lighting or drives. New market participants, such as direct load control (DLC) suppliers already propose special tariffs for postponing demand for a few tens of minutes [4], which causes no significant disruption to customers. Although DLC is often presented as a mean for reducing the energy consumption [5]-[9], we will consider in this paper that it only postpones the demand. In this case, the payback effect that follows a load reduction has to be taken into consideration (i.e., the load demand is increased after a temporary reduction, so that the total energy consumption is not affected).

In the context of a large amount of DLC, such an offer could be valued by the balancing mechanisms [10]. However, the associated costs and benefits would then depend on the market strategies of both the demand response utilities and transmission system operator, which are directly related to the balancing regulation policy.

To assess the benefits of integrating DLC in a balancing mechanism, we have thus modeled balancing as an optimal control problem. Considering a given set of offers and electricity market rules, we have identified the optimal strategy to select offers during a period where extra generation is needed. Three scenarios are compared. The first scenario corresponds to the minimization of the balancing costs for the entire peak period. The second scenario corresponds to successive independent merit orders, where the system operator selects the least-cost solution regardless of its future implications. The third scenario corresponds to successive merit orders associated with a prediction of their future implications.

The paper is organized as follows. Section III describes the formalization of the problem. Section IV presents the problem with present practices and a new solution. Section V introduces the case study and presents numerical results. Finally, Section VII concludes and presents perspectives for further research.

III. Formalization of the Problem

This section proposes a theoretical formulation of the balancing problem with direct load control. After introducing the system architecture, it focuses on the cost functions and constraints of the system.

A. System modeling

The power system is represented as a single bus, where all generation units and loads are connected. The aggregated power demand is considered as a discrete parameter. We denote $P_D(k)$ the amount of power demand that needs to be balanced at instant *k*.

When $P_D(k)$ is positive, the transmission operator system can balance the system by calling extra generation or DLC. We will consider in this paper that balancing relies in priority on base power generation $P_{Gbase}(k)$, limited to $P_{Gbase}^{\max}$. If the demand to be balanced is higher than $P_{Gbase}^{\max}$, it can use either peak generation $P_{Gpeak}(k)$, limited to $P_{Gpeak}^{\max}$, or direct load control $P_{DLC}(k)$, limited to $P_{DLC}^{\max}$.

We will consider hereafter that this situation occurs during *T* consecutive time instants, as represented in Figure 1.

B. Cost functions

To balance the system, the transmission system operator calls for program changes from generation plants or loads, and values those changes.

On the one hand, we consider that $P_{Gbase}(k)$ has a low cost, which will be supposed zero from now on. On the other hand, peak generation units are supposed to formulate offers based on a time-invariant polynomial cost function,

$$C_{Gpeak}(k) = \alpha_{Gpeak} P_{Gpeak}(k)^2 + \beta_{Gpeak} P_{Gpeak}(k) \qquad (1)$$

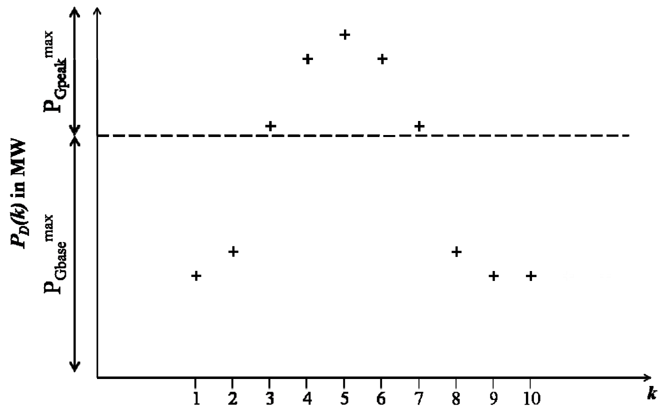

Figure. 1. Evolution of the amount of power to be balanced $P_D(k)$ exceeding $P_{Gbase}^{\max}$ during five consecutive time instants.

where α_{Gpeak} and β_{Gpeak} are constant parameters of the cost function for peak generation.

We also assume that direct load control suppliers also formulate offers based on a time-invariant cost function:

$$C_{DLC}(k) = \alpha_{DLC} P_{DLC}(k)^2 + \beta_{DLC} P_{DLC}(k) \qquad (2)$$

where α_{DLC} and β_{DLC} are constant parameters of the cost function for direct load control.

C. Constraints

The system operator must select offers so that the effective demand $P_D(k) - P_{DLC}(k)$ is equal to the effective production $P_{Gbase}(k) + P_{Gpeak}(k)$ at every time instant *k*.

$$P_{Gbase}(k) + P_{Gpeak}(k) + P_{DLC}(k) - P_D(k) = 0 \qquad (3)$$

The selected amount of base power generation, peak power generation and direct load control should be lower than their respective maximum limits.

$$P_{Gbase}(k) \le P_{Gbase}^{\max} \qquad (4)$$

$$P_{Gpeak}(k) \le P_{Gpeak}^{\max} \qquad (5)$$

$$P_{DLC}(k) \le P_{DLC}^{\max} \qquad (6)$$

In addition, DLC specific constraints are considered. First, as introduced in [11], it is assumed that the DLC selected at time instant *k*, cannot be used at the next time instant *k+1*.

$$P_{DLC}(k) \le P_{DLC}^{\max} - P_{DLC}(k-1) \qquad (7)$$

Second, the payback effect is modeled as a recursive constraint. Direct load control consists indeed of postponing demand to reduce operation costs, but we consider it different from energy saving. In this extent, a payback effect of 100% is considered, as in [11]-[12]. This implies that the energy saved at time instant *k* will be consumed during the next time instants. More specifically, we consider that the payback effect occurs during the two next time instants. This can be modeled as follows.

$$P_D(k) = \overline{P_D}(k) + \chi \cdot P_{DLC}(k-1) + (1-\chi) \cdot P_{DLC}(k-2) \quad (8)$$

where $\overline{P_D}(k)$ is the amount of balancing originally needed for instant *k*, χ is the share of the $P_{DLC}(k)$ that is effective at time instant *k+1*. Based on the observations on water heating systems reported in [13], and considering that a discrete time instant lasts half an hour, we will consider in this paper that χ is equal to 0.7.

IV. Policies for Balancing Mechanisms

Let us consider a period when extra generation (or less demand) is needed from instant 1 through *N*. Let us also consider that $P_D(k) \geq P_{Gbase}^{\max}$ from instant *P>2* through *T+P-1<N-1*. Then, the TSO must select for every instant *k* some of the offers formulated by base or peak generators, or DLC suppliers with respect to the constraints formulated in Section III.C. The way it will select the offers depends directly on the regulation policy for balancing mechanisms, which is often designed with no specific consideration for direct load control.

Three policies are presented in this section. They correspond to three sets of market rules to which the transmission system operator may be subject when balancing the system.

A. Minimization of the balancing cost for the entire period

When such a period of high balancing needs is scheduled, the TSO could minimize balancing costs for the entire period [14]. In this case, the balancing strategy would be elected by solving the following optimization problem

$$\min_{P_{Gbase}(k), P_{Gpeak}(k), P_{DLC}(k), \forall k \in [1,N]} \sum_{k=1}^{N} [C_{Gpeak}(k) + C_{DLC}(k)] \quad (9)$$

subject to Constraints (3)-(8).

The costs associated with the solution of this optimization problem will be denoted C_T^{OPT}.

B. Successive independent merit orders

The time-sequencing of electricity markets has usually imposed balancing mechanisms to be managed as successive independent merit orders. In this context, the system operator selects the cheapest offers at every instant *k* regardless of their impact on balancing mechanisms at instants *k+1*, *k+2*, etc. At each time instant *k*, the amount of $P_{Gbase}(k)$, $P_{Gpeak}(k)$, and $P_{DLC}(k)$ correspond to the solution of the following problem

$$\min_{P_{Gbase}(k), P_{Gpeak}(k), P_{DLC}(k)} [C_{Gpeak}(k) + C_{DLC}(k)] \quad (10)$$

subject to Constraints (3)-(8).

The costs associated with the solution of this optimization problem will be denoted C_T^{IMO}.

C. Successive predictive merit orders

As actual practices such as successive independent merit orders are likely to induce high balancing costs because they do not consider the payback effect in their objective, we present hereafter an alternative policy that could be used to obtain an efficient set of program changes while maintaining the principle of successive merit orders.

The proposed regulation is as follows. At every time instant *n*, the TSO selects the program changes $P_{Gbase}(n)$, $P_{Gpeak}(n)$, and $P_{DLC}(n)$ that would be applied if it were to minimize the balancing costs for the next three time instants.

$$\min_{P_{Gbase}(k), P_{Gpeak}(k), P_{DLC}(k), \forall k \in [n,n+2]} \sum_{k=n}^{n+2} [C_{Gpeak}(k) + C_{DLC}(k)] \quad (11)$$

subject to Constraints (3)-(8).

The costs associated with the solution of this optimization problem will be denoted C_T^{PMO}.

This method is derived from model predictive control approaches, where every decision is made while taking into consideration a prediction of its impact on a restricted time horizon, which considered three instants in this paper because it corresponds to the duration of the payback effect.

V. Simulation Results

A. Benchmark system

To evaluate the actual practices and proposed policy, the respective optimal control problems are solved in the context of the power system introduced in Section III. In addition, the following numerical figures are chosen.

- The amount of demand $\overline{P_D}(k)$ is as represented in Figure 2.
- The maximum amount of base generation $P_{Gbase}^{\max}$ and peak generation $P_{Gpeak}^{\max}$ are set to 500 MW and 200 MW, respectively.
- The maximum amount of direct load control $P_{DLC}^{\max}$ is set to 140 MW.
- The peak period lasts *T*=5 time instants and the period of study *N* is equal to 12 time instants.

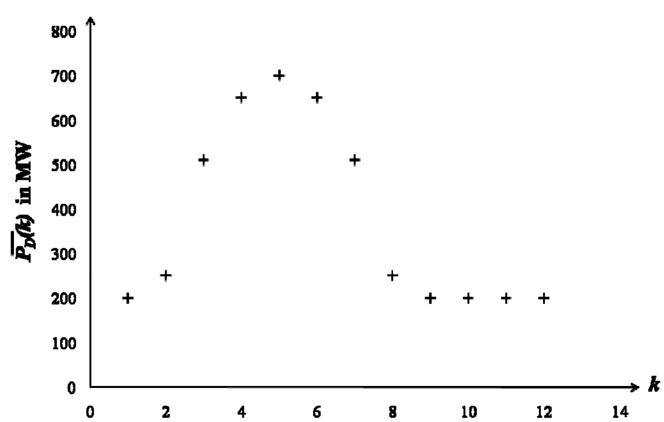

Figure 2. Evolution of the amount of power $\overline{P_D}(k)$ that needs to be balanced as a function of *k*.

- The cost coefficients for peak generation are $\alpha_{Gpeak} = 1€/MW^2$ and $\beta_{Gpeak} = 80€/MW$.
- The cost coefficients for direct load control are $\alpha_{DLC} = 0.75€/MW^2$ and $\beta_{DLC} = 80€/MW$.

The amounts of program changes are assessed by solving the optimization problems defined above using AMPL [15].

B. Simulation results

1) Minimization of the balancing cost for the entire period

Figure 3 depicts the effective demand obtained with the minimization of the balancing costs over the entire period. One can note that the TSO selects no offer from DLC suppliers at instant *3*, whereas $P_D(k) \geq P_{Gbase}^{\max}$. On the contrary, DLC is selected until the end of the peak period so that the payback effect operates when $P_D(k) < P_{Gbase}^{\max}$. Furthermore, the maximum of the effective demand is reached at instant *5*, but its value is close to the amount of effective demand at instants *4* and *6*.

The minimization of the balancing costs over the entire period yields program changes $P_{Gbase}(n)$, $P_{Gpeak}(n)$, and $P_{DLC}(n)$ whose associated costs are presented in Table I. The overall cost C_T^{OPT}=115.58 k€ corresponds to a minimum, but it can hardly be the result of system operation, as it relies on a perfect prediction of the needs for balancing. However, comparing it with the total cost C_T^{noDLC}=126.80 k€ that would be obtained with no direct load control emphasizes the potential benefits of DLC for balancing purposes.

2) Successive independent merit orders

Figure 4 depicts the evolution of the effective demand, when the balancing policy consists of successive independent merit orders. In this case, the system operator selects more DLC than peak generation as soon when needed and available. Consequently, as soon as $P_D(k) \geq P_{Gbase}^{\max}$, at instant *4*, direct load control is activated. This leads to a significant payback effect at instant *5*, when the effective demand is even higher than originally expected. This phenomenon reproduces at time instants *6* and *7*.

The costs related to the program changes induced by successive independent merit orders are depicted in Table II.

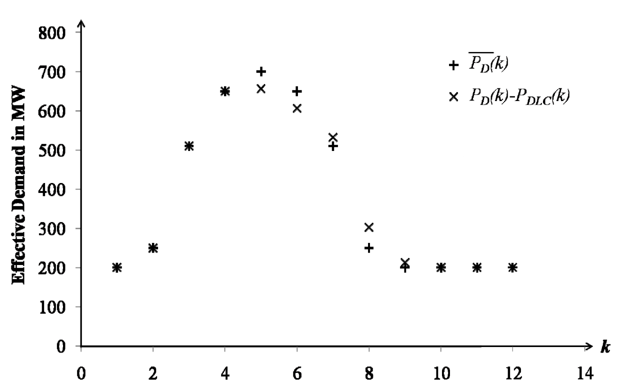

Figure 3. Evolution of the effective demand $P_D(k) - P_{DLC}(k)$ upon minimization of the balancing costs for the entire period.

The total cost C_T^{IMO}=181.07 k€ is significantly higher than C_T^{OPT}=115.58 k€, and even higher than C_T^{noDLC}=126.80 k€. This finding demonstrates that the successive independent merit order policy might induce significant extra-costs, and is indeed poorly appropriate to DLC.

TABLE I
EXTRA GENERATION AND DLC COSTS WITH A MINIMIZATION OF THE BALANCING COSTS FOR THE ENTIRE PERIOD.

k	$\overline{P_D}(k)$ *(MW)*	$P_{DLC}(k)$ *(MW)*	$C_{DLC}(k)$ *(k€)*	$P_{Gpeak}(k)$ *(MW)*	$C_{Gpeak}(k)$ *(k€)*
1	200	0	0	0	0
2	250	0	0	0	0
3	510	0	0	10	0.90
4	650	0	0	150	34.50
5	700	43	4.89	157	37.03
6	650	74	10.07	106	19.77
7	510	43	4.81	32	3.61
8	250	0	0	0	0
9	200	0	0	0	0
10	200	0	0	0	0
11	200	0	0	0	0
12	200	0	0	0	0

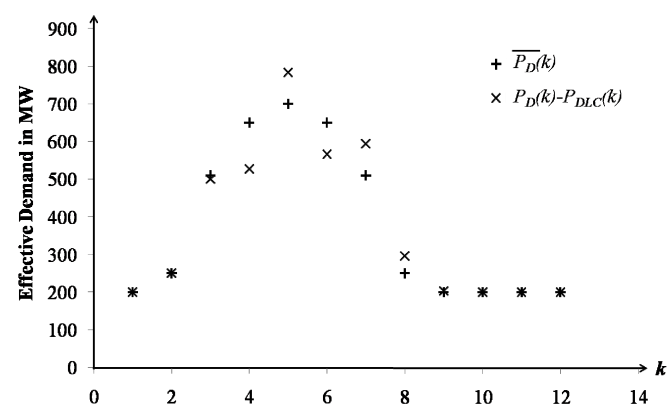

Figure 4. Evolution of the effective demand $P_D(k) - P_{DLC}(k)$ upon application of successive independent merit orders.

TABLE II
GENERATION AND DLC COSTS UPON APPLICATION OF SUCCESSIVE INDEPENDENT MERIT ORDERS.

k	$\overline{P_D}(k)$ *(MW)*	$P_{DLC}(k)$ *(MW)*	$C_{DLC}(k)$ *(k€)*	$P_{Gpeak}(k)$ *(MW)*	$C_{Gpeak}(k)$ *(k€)*
1	200	0	0	0	0
2	250	0	0	0	0
3	510	10	0.88	0	0
4	650	130	23.08	27	2.89
5	700	10	0.88	284	103.38
6	650	130	23.08	66	9.64
7	510	10	0.88	94	16.36
8	250	0	0	0	0
9	200	0	0	0	0
10	200	0	0	0	0
11	200	0	0	0	0
12	200	0	0	0	0

3) Successive predictive merit orders

Figure 5 depicts the evolution of the effective demand, when the balancing policy consists of successive predictive merit orders, as defined in Section IV.C. In this case, the system operator selects DLC or peak generation, while considering their expected effects for future time instants. It can be observed that DLC is not selected before instant *6*, when the amount of program changes required begins to decrease.

The costs related to the program changes induced by successive predictive merit orders are depicted in Table III. The total cost C_T^{PMO}=115.74 k€ is very close to C_T^{OPT}, which highlights the potential benefits of predictive merit orders in terms of balancing costs.

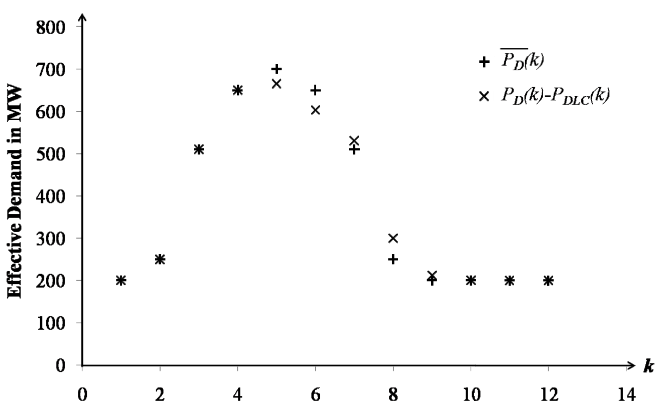

Figure 5. Evolution of the effective demand $P_D(k) - P_{DLC}(k)$ upon application of successive predictive merit orders.

TABLE III
GENERATION AND DLC COSTS UPON APPLICATION OF SUCCESSIVE PREDICTIVE MERIT ORDERS.

k	$\overline{P_D}(k)$ *(MW)*	$P_{DLC}(k)$ *(MW)*	$C_{DLC}(k)$ *(k€)*	$P_{Gpeak}(k)$ *(MW)*	$C_{Gpeak}(k)$ *(k€)*
1	200	0	0	0	0
2	250	0	0	0	0
3	510	0	0	10	0.90
4	650	0	0	150	34.50
5	700	35	3068	165	40.54
6	650	72	9.56	103	18.79
7	510	40	4.44	30	3.33
8	250	0	0	0	0
9	200	0	0	0	0
10	200	0	0	0	0
11	200	0	0	0	0
12	200	0	0	0	0

VI. CONCLUSION

This paper addresses the problem of integrating direct load control in balancing mechanisms. It proposes a formalization of direct load control as a discrete-time optimal control problem and introduces three formulations of the optimization problems that correspond to different market designs. Simulations have shown that actual practices may lead to significant extra-costs for balancing, which are mainly related to the payback effect. Furthermore, they show that including the predicted behavior of the system in the decision-making process could lead to close to optimal performance while maintaining the principle of a merit order.

While this finding highlights the potential of predictive decision-making for balancing purposes, it relies on several assumptions that could be discussed. First, a payback effect of 100% was considered, whereas some papers such as [4] advocate that the postponing load demand also induces energy savings. To get the most efficient balancing mechanism, the exact amount of energy saving needs to be determined.

Second, the cost functions are considered constant with time, and determined by polynomial functions of power. This model is probably close to reality for generators, whose program changes induce operational costs that bids are supposed to reflect. However, it is certainly approximate for demand load control, which has a zero marginal cost. Therefore, it would of great interest to consider the bidding strategy of demand load control suppliers. The problem formulation developed in this paper could be used to this extent, and the program would then elect the DLC offers that maximize the DLC supplier's income for a particular market design.

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