A Direct Load Control Model for Virtual Power Plant Management

Nerea Ruiz, Iñigo Cobelo, and José Oyarzabal

***Abstract*—In the framework of liberalized electricity markets, distributed generation and controllable demand have the opportunity to participate in the real-time operation of transmission and distribution networks. This may be done by using the virtual power plant (VPP) concept, which consists of aggregating the capacity of many distributed energy resources (DER) in order to make them more accessible and manageable across energy markets. This paper provides an optimization algorithm to manage a VPP composed of a large number of customers with thermostatically controlled appliances. The algorithm, based on a direct load control (DLC), determines the optimal control schedules that an aggregator should apply to the controllable devices of the VPP in order to optimize load reduction over a specified control period. The results define the load reduction bid that the aggregator can present in the electricity market, thus helping to minimize network congestion and deviations between generation and demand. The proposed model, which is valid for both transmission and distribution networks, is tested on a real power system to demonstrate its applicability.**

***Index Terms*—Air-conditioning, load management, optimal control.**

I. Introduction

THE progressive liberalization of the electricity sector and the subsequent transition to a decentralized system benefits the emergence of new ways of planning, managing and operating transmission and distribution networks. In this context, distributed generation and controllable demand can play an important role in participating in energy markets and providing ancillary services to system operators. However, the integration of these resources into power system operation is not simple: it requires a major change in the current network control structure. This challenge can be met by using the virtual power plant (VPP) concept, which is based on the idea of aggregating the capacity of many distributed energy resources (DER)—generation, storage, or demand—in order to create a single operating profile. In this way, individual DERs would gain visibility and manageability to system operators, optimizing their position and maximizing their revenue opportunities. Moreover, the system would benefit from an optimal use of the available resources and the efficiency of operation would be improved. A VPP is comparable to a conventional power plant with its own operating characteristics such as schedule of generation, generation limits, and operating costs.

This paper provides a tool for managing a VPP composed of a large number of end-users with controllable appliances. The developed algorithm is based on direct load control (DLC), and allows calculation of optimal control strategies to be applied to controllable devices in order to obtain the maximum load reduction over a specified control period. In this way, an aggregator can determine its load reduction capability so as to define the corresponding load reduction bid to be presented in the electricity market. The developed model is valid for both transmission and distribution systems. To check the applicability of the proposed algorithm, an application to the Spanish deviation management market is considered. This market is called by the transmission system operator (TSO) when deviations between generation and demand over 300 MW are expected between two intraday markets. When this occurs, market agents have 30 min to send their offers. Currently, only generators and pumped storage power stations can participate in this market. This case study seeks to demonstrate that a portfolio of controllable customers integrated into a VPP can contribute to real-time transmission system operation by participating in the deviation management market. In this paper, the terms "VPP" and "aggregator" are used indistinctly.

The study is focused on the aggregation of domestic and commercial customers with appliances that have thermal storage capabilities such as air-conditioning and electric space-heating systems. The possible control strategies are established by contract between the end-users and the aggregator and can consist of a temperature modification of the thermostat settings or a disconnection of the devices for a predetermined period. The algorithm developed is formulated using linear programming (LP).

In the literature, several DLC algorithms have been developed to determine the optimal load control schedules of groups of domestic devices [1]–[6]. Most of them are based on linear programming [1], [3],[4],[6], or dynamic programming [2],[5], and try to minimize peak load [1]–[6] or electricity production cost [1],[2] over a certain time period. Lee and Wilkins [1] present a methodology for scheduling the control actions of water heaters. The diversified water heater load demand is modeled based on data obtained by monitoring different uncontrolled residential water heaters. The payback or the shape of the controlled water heater demand for different control actions is also modeled. The method for the prediction of the diversified controlled water heater load shape is also based on empirical

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The authors are with LABEIN-Tecnalia, Parque Tecnológico de Bizkaia, 48160 Derio, Spain (e-mail: nruiz@labein.es; icobelo@labein.es; joseoyar@labein.es).

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data obtained from field tests. For a given number of total controllable water heaters, the number of water heaters that should be controlled following each control strategy is calculated.

Cohen and Wang [2] present an optimal control scheduling method based on dynamic programming. The advantage of the scheme presented is that the candidate control schedules are not prespecified. The algorithm calculates the ON and OFF cycles for a selected number of device groups. Each group can be controlled more than once during the control period. The size and composition of the groups is assumed to be known in advance. During the execution of the algorithm each group of devices is treated separately. The schedule for each group is calculated considering that the load consumption of the rest of the groups is fixed, and the obtained solution is suboptimal. This model can handle both peak reduction and production cost minimization.

Kurucz *et al.* [3] present another optimization method based on LP. The approach is similar to that of Lee and Wilkins [1] but the list of predetermined candidate control schedules is more flexible. Popovic [4] presents another optimization method based on LP. The main advantage of his approach compared to that of [3] is again the flexibility of the candidate control action list. The controllable devices are divided into two types: devices that can be turned off for a long period (water heaters) and devices that can be turned off for brief periods (air-conditioners). It assumes that water heaters can be controlled just once during the control period and that air-conditioners can undergo more than one control action during the control period. The objective is to reduce system peak load.

A similar approach to [2] is presented by Chu *et al.* [5]. They target commercial buildings with air-conditioning and apply dynamic programming techniques to schedule the OFF/ON cycles of groups of loads. The difference is that their objective is to reduce peak load while minimizing the amount of load controlled. The reasons for minimizing the amount of load controlled are loss of income and customer satisfaction.

Hoe-Ng and Sheblé [6] present a LP optimization technique that looks not for peak reduction or energy production cost reduction but rather for the maximization of utility profit over the control period.

The contribution of this work to the previous studies lies in the approach developed for modeling the behavior of loads with thermal inertia. For this purpose, the building energy simulation tool EnergyPlus [8] is employed. Through the definition of a model building for each customer type and its subsequent simulation with EnergyPlus software, the thermal consumption curves of air-conditioning and space-heating systems under the different possible control actions are accurately obtained. In this way, the dynamics of the house are included in the model. The developed methodology has the advantage of calculating the generated "payback," which represents the extra amount of energy that must be supplied to the devices when the control actions are released in order to bring them back to the initial set-point. This procedure allows the definition of control strategies based not only on ON/OFF cycles but also on modifications of the temperature settings of the thermostats. The proposed algorithm is flexible on the selection of the start time and the duration of the control actions as long as they fall within the specified control period.

The paper is divided into five main sections. Section II describes the methodology developed for simulating the load consumption curves of controllable devices. Section III presents the mathematical formulation of the DLC algorithm. Section IV applies the model to a real power system. Section V describes the general requirements for implementing the proposed model. Finally, Section VI summarizes the main conclusions drawn from the study.

II. Controllable Load Modeling

The first step in the DLC algorithm developed is to perform a study of the loads in order to determine their nature and type and, consequently, establish their usual consumption patterns. Then the changes that the different control actions cause in these typical profiles must be analyzed. In this way, the reduction in demand that can be achieved through the application of each control strategy can be determined. This analysis is performed by the aggregator every time it presents a load reduction bid in the electricity market.

Calculation of these consumption curves is influenced by many variables, such as building characteristics (dimensions, construction materials, etc.), local climate conditions (temperature, humidity, radiation, etc.), comfort settings, and existing HVAC equipment. For this reason, the building energy simulation tool EnergyPlus is employed.

The followed methodology consists of defining a model building that represents the average behavior of each customer type and simulating their thermal behavior with the aforementioned software. The results of these simulations provide thermal demand curves of controllable devices for a base case, that is, when no control actions are applied.

Taking the model building for the base case as a reference and modifying the schedule of the controllable loads according to the control strategy considered, a new consumption curve that represents the influence of such control action is obtained. Control strategies can consist of complete disconnection of the appliance for a set time period or modification of the thermostat settings. It is considered that only one control strategy can be applied to each device during the control interval. However, it can start at any time-step inside it as long as the duration of the control action does not extend beyond the end time of the control interval. This process is repeated for all possible control actions that the aggregator can apply to each customer type. The results represent input data for the algorithm formulated in the following section.

Next, an application of the described methodology to the modeling of a domestic air-conditioner is presented. The model building considered is a 90 m^2 flat sited in a block of apartments. It is represented in EnergyPlus as an orthogonal parallelepiped with dimensions $9\ \mathrm{m} \times 10\ \mathrm{m} \times 3\ \mathrm{m}$. It is west oriented and the construction materials fulfill the actual Spanish regulation in relation to edification [9]. The 30% of the façade is glazed. Regarding the mode of operation of the air-conditioning system it is assumed to be switched on throughout the day, being the temperature setting of the thermostat 23°C. The EnergyPlus simulations are performed considering that the conditioning equipment is the "Purchased Air Component"

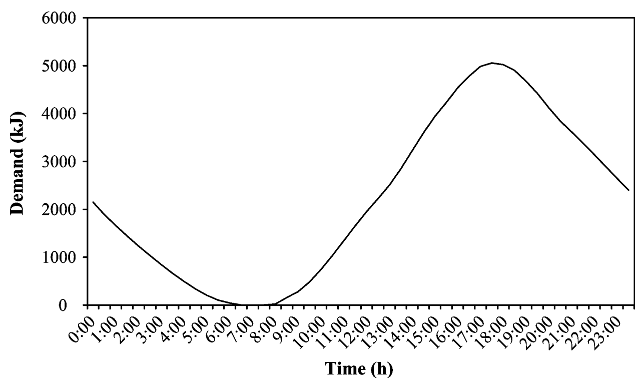

Fig. 1. Thermal load consumption curve for a domestic air-conditioner (flat).

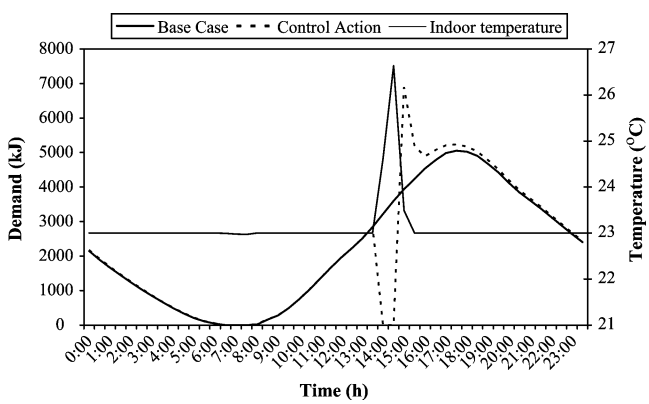

Fig. 2. Thermal load consumption curves of a residential air-conditioner in the base case and when it is switched off for 60 min starting at 14:00.

which is used when the performance of the building with an ideal system is wanted to be studied [8].

Taking into consideration the described model and the forecasted local climatic conditions relative to the building for the control period (temperature, relative humidity, atmospheric pressure, radiation, and wind speed), the aggregator runs the EnergyPlus simulations in order to estimate the thermal load demand or the domestic air-conditioner. Fig. 1 shows an example curve obtained for a particular summer weekday in the north of Spain area.

The previous curve represents the consumption of the air-conditioner for the base case, that is, when no control actions are applied. The next step consists of calculating the load demand curves under all possible control actions. For this purpose, the EnergyPlus simulations are performed again by modifying the scheduling of the controllable loads according to the considered control strategies. Fig. 2 shows the obtained load consumption for the previous domestic air-conditioner when it is switched off during 60 min starting at 14:00. It can be observed the impact of such control action on the temperature inside the building that reaches almost 27°C and the demand peak occurred just after the control period.

III. Algorithm Formulation

This section presents the mathematical formulation of the DLC algorithm. The objective of the optimization is to maximize load reduction over a specified control period through the selection of the optimal control strategies to be applied to a group of controllable devices. It is intended to be run by an aggregator managing a portfolio of controllable customers so as to determine its load reduction capability over a specified control interval. These customers are operated as a VPP taking part in the electricity market by offering load reduction bids to the system operator (SO).

Required inputs can be grouped into dynamic and static parameters. The dynamic parameters are the forecast load demand of the aggregator portfolio, existing customer types that have controllable devices and the number of controllable devices within each customer type; start and end time-steps of the control period and the length of each time-step. In addition, the forecast uncontrolled consumption pattern for each kind of controllable appliance and load consumption curves of controllable devices under the effect of all possible control actions are required. This information is obtained with the methodology presented in Section II. The static parameters include information on control strategies that can potentially be applied to the controllable devices of each customer type and the duration of each such strategy.

The results provide the optimal control strategies, their start times and the number of devices that must be controlled with each of them in order to achieve the maximum possible load reduction over the control period while constraints are fulfilled.

A. Mathematical Formulation

The input parameters and the decision variables involved in the optimization problem are listed below.

Input parameters:

z_i	initial time-step of the control period;
z_f	final time-step of the control period;
Δz	time-step duration;
$forecLoad_z$	forecast load demand of the aggregator at time-step z;
k	customer type (e.g., domestic customers, supermarkets and offices). This is an integer that varies from 1 to the number of customer types;
$nDev_k$	number of controllable devices within the group of customers of type k (e.g., 1900 domestic air-conditioners);
$d_{k0}(z)$	expected consumption at time-step z of the devices of the type k customer when no control actions are applied (base case). This information is obtained with the methodology presented in Section II;

s possible control actions. Each strategy has two components: action (e.g., switch off the device) and duration of the action (e.g., 30 min). The strategies can vary for the different customer types;

$d_{kst}(z)$ expected consumption at time-step z of the devices of the type k customer when the strategy s is applied at time-step z. This information is obtained with the methodology presented in Section II.

Decision variables:

Y_{kst} number of devices of the type k customer which are controlled after the optimization with strategy s starting at time-step t;

Y_{k0} number of devices of the type k customer not controlled after the optimization. The total number of variables Y_{k0} coincides with the number of customer types, that is, there are k variables of this type.

The aim of the optimization problem is to maximize load reduction over the control interval or to minimize final demand over that period. The objective function, based on integer LP, can be written as follows:

$$\text{Min} \sum_{z=z_i}^{z_f} load_z \tag{1}$$

where $load_z$ is the final demand obtained at time-step z after applying the control strategies calculated with the optimization algorithm.

The values of the final load at each time-step are obtained with the following formula:

$$load_z = forecLoad_z + \Delta Load_z \tag{2}$$

where $forecLoad_z$ is an input data representing the expected demand at time-step z and $\Delta Load_z$ is the variation in load that occurs at that time-step when the control actions are applied. This term can be divided into two parts: 1) load variation at time-step z due to control actions starting at z and 2) load variation at time-step z due to control actions starting before z. $\Delta Load_z$ can be formulated as follows:

$$\Delta Load_z = \sum_{l=1}^{k} \sum_{v=1}^{n_z} Y_{ksz} \cdot e_{ksz}(z) + \sum_{l=1}^{k} \sum_{t=z_i}^{z-\Delta z} \sum_{v=1}^{n_t} Y_{kst} \cdot e_{kst}(z) \tag{3}$$

where

$e_{kst}(z)$ load consumption variation in relation to the base case of the devices of the type k customer at time-step z when strategy s is applied at time-step t. This is obtained with the following formula:

$$e_{kst}(z) = d_{kst}(z) - d_{ko}(z). \tag{4}$$

Consequently, $e_{ksz}(z)$ represents the variation in the load consumption of the devices of a type k customer at time-step z when strategy s is applied at time-step z;

n_z number of Y_{kst} variables in which the control action starts at time-step z. That is, the total number of Y_{ksz} in the problem. Consequently, n_t is the number of variables in which the control action starts at time-step t.

The final formulation of the optimization problem is obtained by substituting (2) and (3) in (1)

$$\text{Min} \sum_{z=z_i}^{z_f} \left[forecLoad_z + \sum_{l=1}^{k} \sum_{n=1}^{n_z} Y_{ksz} e_{ksz}(z) + \sum_{l=1}^{k} \sum_{t=z_i}^{z-\Delta z} \sum_{n=1}^{n_t} Y_{kst} e_{kst}(z) \right] \tag{5}$$

subject to the following constraints:

1) The number of devices controlled cannot be negative:

$$Y_{kst} \geq 0, \quad \forall k, s, t. \tag{6}$$

2) The total number of devices connected during the control period for each customer type is the sum of the number of devices controlled and the number of devices not controlled:

$$nDev_k = Y_{k0} + \sum_{n=1}^{nVar} Y_{kst}, \quad \forall k \tag{7}$$

where $nVar$ defines the total number of control variables in the problem, that is, the number of Y_{kst}:

$$nVar = \sum_{t=z_i}^{z_f} n_z. \tag{8}$$

3) The values obtained for Y_{kst} and Y_{k0} must be integers.

4) Demand after the control period must be below a specified maximum limit. This limit is optional and is considered as set by the aggregator in order to ensure that the generated payback is within acceptable limits:

$$load_z \leq loadLimit, \quad \forall z. \tag{9}$$

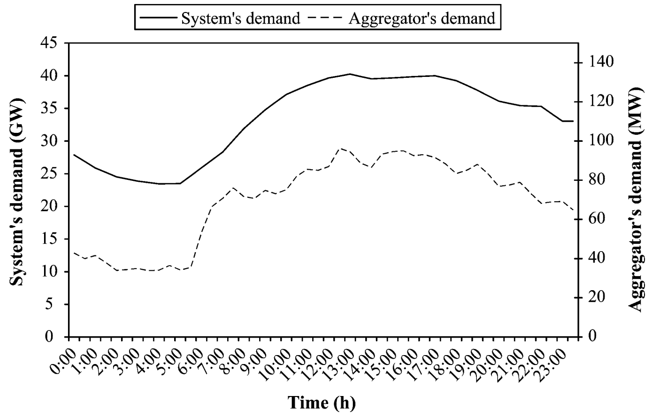

Fig. 3. System's and aggregator's total load demand.

B. Solution

The solution to the algorithm provides the optimal values of the variables Y_{kst} that represent the optimal combination of control strategies and the number of devices that should be controlled with each of them in order to maximize system load reduction during the control interval.

The final step consists of calculating the resulting daily load demand curve via (2).

IV. Case Study

The DLC algorithm developed was tested on an actual power system in northern Spain. The analysis considers a particular power system area characterized as having a significant number of domestic and commercial buildings connected. It is assumed that an aggregator operates in the region, offering DLC contracts to end-users with controllable devices in order to obtain a significant load reduction capacity that can be offered in the market. The aim of this case study is to test the applicability of the proposed DLC algorithm for managing the participation of a VPP in the deviation management market. The study is performed in a summer scenario where air-conditioning system control is considered. The same methodology could be employed for the control of space-heaters in a winter scenario.

A. Input Data

It is considered that the TSO calls the deviation management market for a period running from 14:00 to 16:00. From the time of notification, market agents have thirty minutes to submit their bids. Consequently, the aggregator runs the algorithm to generate the load reduction bid corresponding for that control interval. In the calculation, the time-steps are set as 30 min long.

The daily load curve of the aggregator is shown in Fig. 3. These data correspond to the registered consumption on a particular summer weekday in the considered area resulting from both controllable and noncontrollable loads.

In this graph, the total demand of the transmission system for the considered day is also represented. It can be observed that peak demands of both curves do not occur at the same time. It can also be seen that the control period, which runs from 14:00 to 16:00, is posterior to the peak demand of the system. This is because the objective of the developed control system is not the reduction of system peak but to provide a mechanism allowing the participation of demand side management into the ancillary services markets.

TABLE I
NUMBER OF CONTROLLABLE DEVICES

Customer type	Number
domestic customers	6295
supermarkets	12
offices	197

TABLE II
BREAKDOWN OF CONTROL ACTIONS

Action	Duration	Start time
OFF	30 min.	14:00
OFF	30 min.	14:30
OFF	30 min.	15:00
OFF	30 min.	15:30
OFF	60 min.	14:00
OFF	60 min.	14:30
OFF	60 min.	15:00

Three different customer types are taken into consideration in the study: domestic customers, supermarkets and offices. Table I shows the number of air-conditioners that the aggregator can control within each group.

The control strategies that the aggregator can potentially apply to the controllable devices, which have been agreed in advance with the end-users, are the same for all customer types and consist of: 1) disconnecting the air-conditioner for a maximum of 1 h; 2) increasing the temperature setting by a maximum of 2°C for a maximum of 2 h; 3) increasing the temperature setting by a maximum of 3°C for a maximum of 1.5 h; and 4) increasing the temperature setting by a maximum of 4°C for a maximum of 1 h. This information needs to be processed so as to break it down into all control possibilities. For example, the first option would lead to the seven different options that are presented in Table II.

As a result, 44 different control possibilities for each customer type are obtained.

Daily consumption curves for controllable devices are provided in Fig. 4. These curves represent the expected uncontrolled consumption of a domestic air-conditioner, a supermarket air-conditioner, and an office air-conditioner, respectively (base case). They are obtained via the methodology explained in Section II, i.e., building modeling and simulation. To convert the thermal demand curves resulting from the EnergyPlus simulations into electrical ones, it is assumed that the air-conditioning systems considered in the study comply with the U.S. regulation that establishes a seasonal energy efficiency ratio (SEER) of 10 or higher.

Domestic air-conditioners are assumed to be connected throughout the day, while supermarket and office conditioners are only switched on at the times when the buildings are occupied.

It can be observed that the domestic air-conditioner is disconnected in the morning between 6:30 and 8:30, because at that time the temperature inside the building is below the temperature setting. Peak demand in commercial appliances occurs just

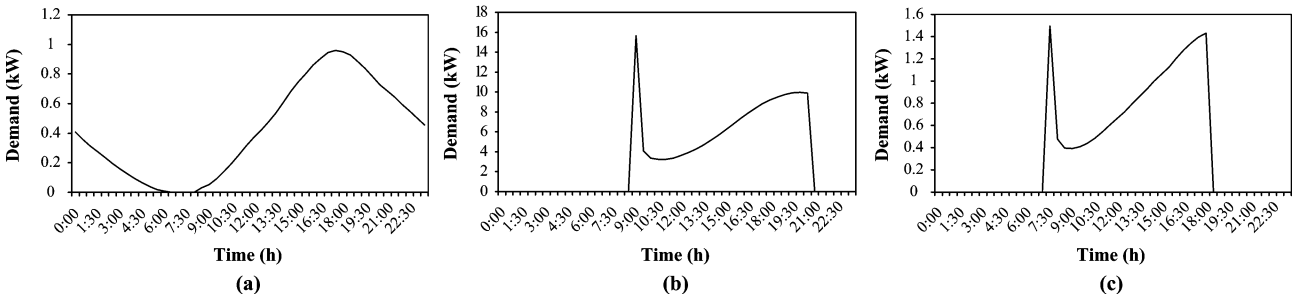

Fig. 4. Uncontrolled electrical load consumption curves. (a) Domestic air-conditioner. (b) Supermarket air-conditioner. (c) Office air-conditioner.

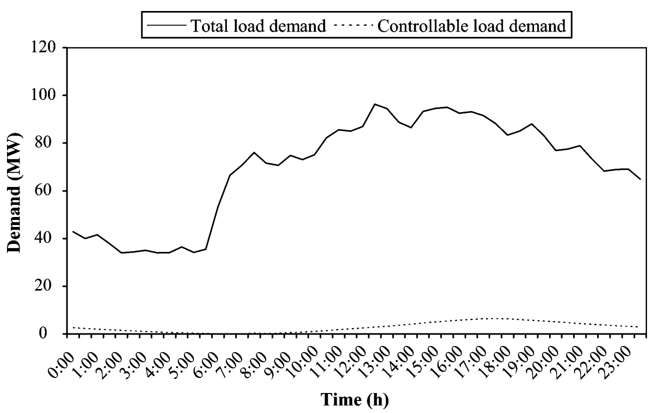

Fig. 5. Total and controllable load demand curves.

when the air-conditioning systems are turned on because that is when the biggest input of energy is required to reach the temperature setting, which is 23°C for all customer types.

It is assumed that all controllable devices belonging to the same customer type have the same load consumption patterns. Aggregating the above curves for all customers in the considered region, the controllable fraction of the demand in relation to the total can be obtained (see Fig. 5). The resulting hourly average controllable load is 3.7%.

The consumption curves of the controllable devices under the effect of the control actions defined above are also inputs to the algorithm. An example curve was provided in Fig. 2. This curve represents the load consumption obtained for a domestic customer when the air-conditioning system is switched off for 60 min starting at 14:00. The load consumption curve corresponding to the base case when no control strategies are applied is also shown, as well as the temperature variation inside the building. It can be observed that the set temperature (23°C) is maintained throughout the day excepting the period when the control action is applied. During that interval, the air-conditioning system is disconnected and the temperature inside the building rises to almost 27°C. The same calculation is performed by the aggregator for all possible control actions and customer types.

Finally, it is assumed that the aggregator constrains final demand to below 96 MW, which represents the forecast peak consumption for the day. In this way, it limits the payback generated after the control period in order to ensure that it is within acceptable limits.

TABLE III
OPTIMAL CONTROL ACTIONS

Type	Action	Duration	Start time	Number of customers
Domestic	OFF	60 min.	14:00	1544
customers	+ 2ºC	120 min.	14:00	1830
	+ 3ºC	90 min.	14:30	2917
	+ 4ºC	30 min.	15:30	3
Supermarkets	+ 3ºC	90 min.	14:30	12
Offices	+ 3ºC	90 min.	14:00	197

TABLE IV
LOAD REDUCTION CAPACITY OF THE VPP

Time-step	Load reduction (kW)	Reduction (%)
14:00 – 14:30	2128	2.46
14:30 – 15:00	1864	2.00
15:00 – 15:30	1940	2.06
15:30 – 16:00	2123	2.24

B. Results

Table III shows the results of the implementation of the DLC algorithm. It includes the optimal control actions and their durations, the initial time and the number of devices that must be controlled with each action so as to obtain the maximum load reductions over the control interval, which runs from 14:00 to 16:00.

By applying the above control actions, the aggregator can attain the load reductions presented in Table IV. This table also includes the percentage of forecast demand represented by those variations.

The load reductions achieved are practically constant for all time-steps in the control period, and average 2 MW. This represents a drop of 2.2% in relation to the expected demand and a potential energy reduction of 4 MWh for the whole control period.

Fig. 6 shows a graphic representation of the load reduction achieved.

Fig. 7 is an enlargement of the part of the graph that runs from 14:00 to 18:00. It can be observed that consumption drops for the two hours of the control period, but rises in the subsequent time-steps. This is the payback effect that represents the extra amount of energy that the air-conditioning systems demand in order to restore their temperature settings. The values of the payback generated are provided in Table V.

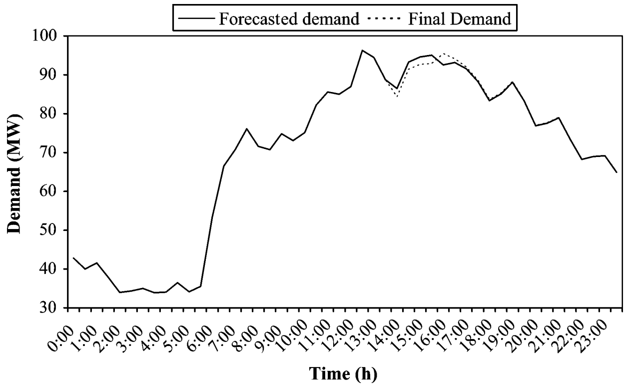

Fig. 6. Final load demand curve.

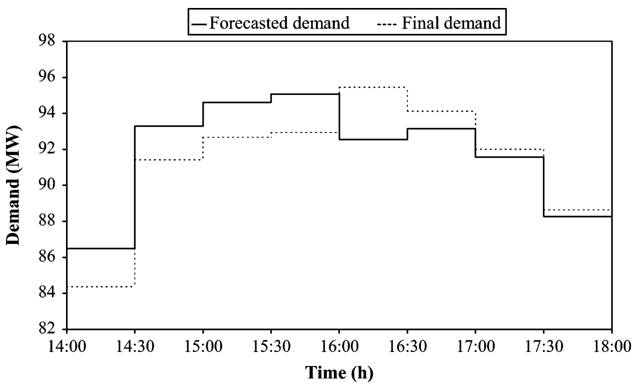

Fig. 7. Detail of the load variation obtained.

TABLE V
PAYBACK VALUES

Time-step	Load Increment (kW)
16:00 – 16:30	2897
16:30 – 17:00	978
17:00 – 17:30	442
17:30 – 18:00	362

It can be observed from Fig. 7 that maximum demand occurs from 16:00 to 16:30, when the value is 96 MW. This coincides exactly with the maximum admissible limit established by the aggregator, so the solution provided by the optimization algorithm fulfills the imposed constraint. If the calculation had been performed without taking that constraint into account, the load demand curve provided in Fig. 8 would have been obtained. The difference in the energy reduction is 1.2 MWh for the whole control period, with an average power reduction for each time-step of 2.6 MW.

Finally, Table VI shows the load reduction bid that the aggregator would send to the TSO (constrained scenario). For this purpose, the operation procedures for the Spanish transmission system have been taken as in [12].

The planning periods considered are 1 h long, coinciding with the current characteristics of the Spanish market. The bid formulated is upward because consumption reduction is similar to generation increase. The bid includes the energy offered for each planning period and the corresponding price. These prices

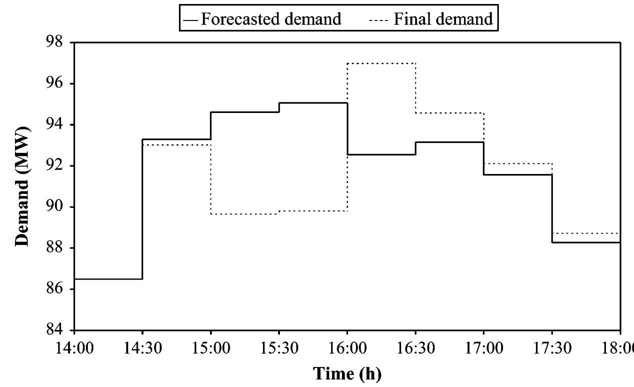

Fig. 8. Final load demand curve—no constraint.

TABLE VI
LOAD REDUCTION BID

Bid Data		
	14:00-15:00	15:00-16:00
Energy (MWh)	1.996	2.032
Price (€/MWh)	P1	P2

should be set by the aggregator taking into consideration financial compensation for customers and its own costs and profit. In addition, the complex condition that establishes the indivisibility of the bid is defined.

V. PRACTICAL IMPLEMENTATION

Implementation of the proposed DLC model would require two different communication stages: 1) the communication between the SO and the aggregator, and 2) the communication between the aggregator and the controllable appliances.

The SO performs communication with the aggregator in the same conditions as it does with the remaining agents involved in the electricity market (generators, suppliers). In this way, the number of agents the SO interacts with is minimized.

The aggregator is responsible of the physical communication with the controllable loads in order to ensure that the contracted load reduction service is delivered. For this purpose, it makes use of a central controller whose main functions are the following ones: 1) maintaining a database that stores information on the contracted control possibilities of each customer; 2) running the optimization algorithm; 3) submitting the resulting load reduction bids on the market; and 4) sending the calculated control signals to the controllable appliances. These appliances would require an intelligent thermostat that receives the corresponding temperature setting. Such devices are fairly common on today's market.

To check whether the target load reduction has been achieved smart meters with communication capabilities should preferably be installed at all controllable customers. However, the cost of the metering infrastructure could be reduced. The aggregate load consumption could be accurately estimated using a statistically valid number of metered customers [13], [14].

The most suitable communication technology should be selected according to the preexisting infrastructure and the costs of installation and operation. Radio signals, Internet, or power line communication systems could be used.

VI. Conclusion and Future Work

In this paper, a DLC algorithm based on LP is developed with the aim of operating a VPP composed of a large number of customers with load reduction capabilities. It is intended as a tool to enable aggregators managing portfolios of controllable customers to provide load reduction bids to the TSO/DSO and consequently participate in electricity markets. The algorithm is able to obtain the maximum load reduction over a considered control period by determining the optimal control strategies to be applied to a group of controllable customers. These control actions act on domestic and commercial appliances which offer some thermal inertia such as air-conditioning and space-heating systems, and can consist of disconnecting the device for a set time or modifying the temperature settings of the thermostats.

One advantage of the proposed model lies in the method used to model controllable loads, which are calculated by setting up a building model for each customer type and then simulating it with the building energy simulation tool EnergyPlus. In this way the thermal behavior of air-conditioners and space-heaters under the effect of the different control actions can be accurately obtained and introduced into the algorithm.

The applicability of the optimization algorithm is tested on an actual power system in northern Spain, where the control of air-conditioning systems is considered. Results show that the developed model provides an effective approach for generating load reduction bids of a VPP, thus allowing the participation of a group of controllable customers in transmission system operation markets.

Future work will improve the flexibility of the VPP by removing the indivisibility condition from the load reduction bid. To that end a new optimization algorithm capable of determining the control actions to be applied to the controllable devices of the VPP in order to obtain the load reduction schedule finally accepted will be developed.

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Nerea Ruiz was born in Orduña, Spain, in 1977. She received the B.Sc. degree in industrial engineering and the M.Sc. degree in electrical engineering from the School of Engineering, University of the Basque Country, Bilbao, Spain, in 1999 and 2002, respectively.

Since 2003, she has worked at the Energy Unit of LABEIN-Tecnalia, Derio, Spain, on European research projects regarding demand response, microgrids, and distributed generation integration.

Iñigo Cobelo was born in Bilbao, Spain, in 1977. He received the M.Sc. degree in industrial engineering from the University of the Basque Country, Bilbao, in 2001 and the Ph.D. degree in electrical engineering from the University of Manchester, Manchester, U.K., in 2006.

He joined the Energy Unit of LABEIN-Tecnalia, Derio, Spain, in 2002 where he is currently a Project Manager. He works in the fields of demand response, the impact of distributed generation, and active distribution networks.

José Oyarzabal was born in Bilbao, Spain, in 1967. He received the B.Sc. degree in industrial engineering and the M.Sc. degree in electric engineering from the School of Engineering, University of the Basque Country, Bilbao, in 1989 and 1992, respectively.

Since 1994, he has been working at LABEIN-Tecnalia, Derio, Spain, on several applications related to power transmission and distribution control systems as well as protective relays. His specialist field includes the application of information and communication technology standards to energy management systems. Since 2006, he has been a Lecturer in the Faculty of Engineering of the University of Deusto, Bilbao.

Mr. Oyarzabal is a member of CIGRE SC6 and the Association of Industrial Engineers of Bilbao.