Approach to Multivariable Predictive Control Applications in Residential HVAC Direct Load Control

A. Molina A. Gabaldón, Member, IEEE J. A. Fuentes Fco. J. Cánovas
Department of Electrical Engineering
Polytechnic University of Cartagena
30202 Cartagena (Murcia – SPAIN)

Abstract: The purpose of this paper is to describe a new constrained multivariable predictive control strategy applied in Residential HVAC Direct Load Control. In this way, starting from a target load profile prefixed by the utility in order to achieve several objectives – economic, technical- and taking into account customer constraints – minimum comfort levels, HVAC limits- this control algorithm provides, in a multiobjective framework, the most suitable HVAC load control strategy to minimize the discrepancies between the controlled load curve and the predefined target load curve. The control system has a close-loop behavior with a proper and consistent treatment of modeling errors and other disturbances. It is allowed a dynamic modification of the target load curve according to the real-time system behavior. In order to demonstrate its qualities widely, this control system has been applied to modify a real load curve profile under different operating conditions.

Keywords: Direct Load Control (DLC), Load Management Systems (LMS), Constrained Multivariable Control

I. INTRODUCTION

At this moment, the number of implementations of Load Management Systems (LMS) is increasing more and more. This is mainly due to the rise in demand peak values in comparison with the average demand values, and the difficulties encountered by the utilities –economical as well as technical- to expand their generation and/or transmission capacities in order to assure a future and present supply of quality. On the other hand, the important advances related to communications and computing tools have helped to develop LMS more suitable and complex.

Generally, the LMS can be divided into the following groups: Direct Load Control (DLC) in which the utilities realize a remote control over some of customer loads –HVAC mainly- taking into account several constraints fixed previously between the customer and the utility; Indirect Load Control (ILC) in which the own customers connect or disconnect their loads depending on price signals; and Local Energy Storage which is jointly used by customers and utilities in order to store energy during the low cost periods and consume it during the high cost periods (Peak Demand Periods). The most common LMS is Direct Load Control, which is also known as End-use equipment control [1]. The main purpose of this kind of programs is to modify the global demand profile by means of forced switching cycles applied to controllable load groups to achieve maximum cost profits, improve the load factor and control the demand growth as many as it is possible. These forced duty-cycles have to be calculated taking into account minimum comfort levels for the customers. These levels depend on the kind of contract between the utility and the own customer.

This paper describes a DLC algorithm, which has been developed to shape the global load demand in accordance with a predefined target load curve using constrained multivariable predictive control. The global load demand is modified by means of controlling residential HVAC groups. The system constraints are taking into account by including them in the control algorithm with real-time optimization using sequential quadratic programming (SQP). These constraints are directly related to the minimum comfort levels of the customers, the residential HVAC load characteristics, avoiding payback periods after controlling and decreasing secondary peaks. The predictive control technique has been widely suggested like a possibility to develop DLC programs and it is also used to solve other engineering control problems –Fossil power plant operation, Boiler control system-.

PWM technique has also been applied to solve the same problem, [3], however customer minimum comfort levels are not initially taking into account to calculate the forced duty-cycles, and then it is possible to obtain a load control strategy which rouses people dissatisfied. Besides, it is necessary to define a partial target curve (Modulating Wave) associated only with the controllable demand part and not with the global demand curve. Linear and Dynamic Programming have widely been used to develop algorithms in order to reduce the demand peaks and maximize profits, [2] [5-7]. One of their disadvantage is that candidate schedules have to be prespecificied, and besides they do not allow to modify the demand profile according to a target load curve. On the other hand, most of them have a series of simplifications and hypothesis that are avoided in our control algorithm in order to obtain a more flexible and adaptive tool. So, most of them assume a constant controllable load during the control period, [2] [4] [6], take into account only a few of possible control strategies but not all possibilities, [5], and/or fix specific patterns for payback phenomenon, [2]. Moreover, the developed algorithm includes all benefits of others previously indexed and improves those aspects in which, from our point of view, they present problems or deficiencies which would have to be made better.

The rest of the paper consists of the following parts: In the Section II, the proposed control algorithm is described together with its main objectives, assumptions and constraints. The control strategy as well as its implementation is given in Section III, a block diagram is used in order to symbolize schematically the proposed model control strategy. The nomenclature and all mathematical expressions –model and constraints- are also showed in this section. In Section IV, an example is analyzed in order to evaluate the suitability of this control algorithm. This example is based on load demand data of the Polytechnic University of Cartagena, which were collected during the last summer. In Section V, conclusions of this control algorithm are expounded as well as future improvements in which we are now studying.

II. THE CONTROL PROBLEM

First of all, it is necessary to classify the customers in different sets in order to form load groups which have residential HVAC with similar characteristics –power demand, geographic distribution, thermal characteristics, similar use patterns-. The type of contract between the utility and customer is also taking into account to set up these groups, since important DLC values would have to be reflected in this contract -as maximum OFF periods or minimum ON periods-. Then, a target load curve is defined according to the objectives pursued by the utility, for example to maximize distribution network efficiency, control the demand growth, minimize losses and/or increase profits. It is important to take into account that is possible to find an optimum load curve profile for each distribution network in order to achieve these objectives. There are several Spanish utilities which have just defined these profiles for their distribution networks.

The control problem here is to optimally control the residential HVAC demand to modify the global load curve according to this target load curve prefixed previously. Therefore, the output variables are the control actions over each residential HVAC group at the following control period, that is to say, the forced duty-cycle for each residential HVCA group during each control period stage. The global control period usually lasts between four to ten hours per day, depending on the load demand curve characteristics and the utility objectives. This global control period is divided into several periods, which are usually between 10 and 15 minutes. Therefore, the control actions, which are generated for each one of these periods or stages, are directly related to the control actions applied during the period before and, of course, the required minimum comfort levels.

In this kind of analysis is usual to assume that the demanded global energy with and without control is practically equal, [2-5]. This hypothesis is also considered in the present control algorithm, though it is possible to modify it and define energy rates as a function of forced duty-cycles, time of day or season of the year.

Several constraints are taking into account in order to avoid typical problems related to DLC programs. So, it is possible to fix a maximum of cumulative energy deferred per group for each control period stage in order to assure minimum customer comfort levels and avoid payback problems after controlling. In fact, the cumulative energy deferred values are normally close to zero for the last control period stage in order to minimize payback. Another important constraint is related to the peak values for each load group. So, it is possible to limit these secondary peaks to avoid values higher than without control, in spite of the maximum global load curve can be lower.

Disturbances or interfering variables are divided into two groups: One group is related to the errors associated with the input variables - expected demand curves, controllable load for the next control period stage, maximum cumulative energy deferred- and the other is related to the errors between the output signals generated from the control algorithm and the real actions that are realized on each residential HVAC load group. On the other hand, the target load curve has been implemented using a First-order system. By means of this implementation is possible to control the rapidity that is desired for the answer in close-loop of our system. Besides, it is allowed to modify the target load curve during the control period. This is necessary because the load reduction levels depend on the controllable load and the control actions before. Therefore it is possible to fix a target load curve which can not be achieved at that moment and it would be very convenient to modify it.

III. THE CONTROL STRATEGY

The proposed model control strategy is showed in the block diagram given in figure 1. It is basically formed by the simulated distribution network that contains the residential HVAC loads on which the control is applied, and the algorithm to calculate these control actions. The simulation process is based on models provided in [9], external parameters and the control actions constitute the simulation input variables; and then, the forecasting load curve is obtained according to these values. These external parameters are related to the main variables that can have some influence on the load demand curve, for example external temperature, hour, season or month.

Although the predictive control is based on a receding horizon, only the control actions for the next period are implemented. So, the optimization process is performed again during the next interval in order to obtain the new control actions.

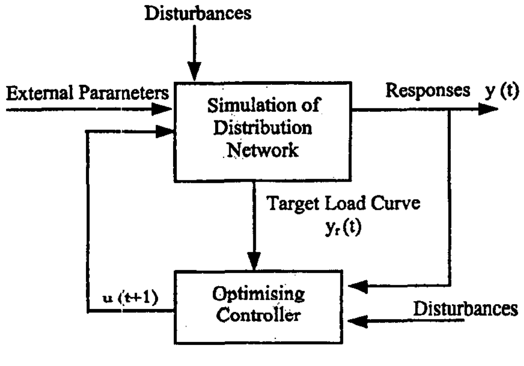

Fig. 1. The model-based control strategy

A. Nomenclature

a: Parameter which controls the answer rapidity in the close-loop behavior

CL_{ij}: Residential HVAC Controllable Load of group i at period j

CLD_{ij}: Cumulative Load demand Deferred by the DLC group i at period j

CT_j: Total Load with Control at period j

m: Number of periods of control projection horizon

MCD_{ij}: Maximum Cumulative Load demand Deferred of group i at period j

MCL_{ij}: Maximum Controllable Load that is possible to consume of group i at period j

MPb_i: Maximum Payback value that is allowed of group i after control

MPl_i: Maximum Peak Load value that is allowed of group i during control period

N: Number of residential HVAC controllable load groups

NL_{ij}: Non controllable Load of group i at period j

Pb_i: Payback of group i after controlling

RC_j: Reference Curve implemented at period j

u_{ij}: Control actions on group i at period j

Wc_{ij}: Weighting Matrix to apply graded penalties to step changes in the control actions of group i at period j

Wf_j: Weighting Vector for prioritizing the future control actions

y_j: Total Load with control at period j

y_{r_j}: Target Load Curve at period j

B. Controller Formulation and Implementation

Taking into account the nomenclature showed above, the formulation of this control problem is as follows.

$$Min\left[\sum_{j=1}^{m} Wf_j\left(CT_j - RC_j\right)^2 + \sum_{j=1}^{m}\left(\sum_{i=1}^{N} Wc_{ij}\left(u_{ij} - u_{ij-1}\right)^2\right)\right] \quad (1)$$

Where:

$$RC_j = a \cdot RC_{j-1} + (1-a) \cdot y_{r_j} \quad (2)$$

$$CT_j = \sum_{i=1}^{N}\left(NL_{ij} + u_{ij} Min\left\{MCL_{ij}; CL_{ij} + CLD_{ij-1}\right\}\right) \quad (3)$$

$$\begin{aligned} CLD_{ij} = {} & CLD_{ij-1} + CL_{ij} - \\ & - u_{ij} \cdot Min\left\{MCL_{ij}; CL_{ij} + CLD_{ij-1}\right\} \end{aligned} \quad (4)$$

Subject to:

$$0 \le a \le 1 \quad (5)$$

$$0 \le u_{ij} \le 1 \quad (6)$$

$$0 \le CLD_{ij} \le MCD_{ij} \quad (7)$$

$$0 \le Pb_i = CLD_{im} \le MPb_i \quad (8)$$

$$0 \le NL_{ij} + u_{ij} Min\left\{MCL_{ij}; CL_{ij} + CLD_{ij-1}\right\} \le MPl_i \quad (9)$$

$$CLD_{i0} = 0; u_{i0} = 1 \quad (10)$$

The design and implementation of the controller involves different phases which are mainly the following: First, a correct formulation of procedure for computation of multi-step-ahead prediction of the outputs as well as constraints, objective function and the iterative determination of optimal values for controller tuning parameters –Weighting vectors, receding horizon-. After, the definition of an iterative method to fix the target loads curve and the implemented reference curve. These curves are directly associated by means of a First-order system. Finally, the development of a routine to implement the controller using an optimization algorithm. In this case, the Sequential Quadratic Programming algorithm, available in MATLAB optimization toolbox, has been used. This method approaches the solution of a Non-Linear Problem (NLP) by simply replacing the nonlinear function by its local quadratic approximation and solving the resulting series of approximating subproblems. Therefore, each function is replaced by the following expression, [8]:

$$\begin{aligned} q(x;x^0) = {} & f(x^0) + \nabla f(x^0)^T (x - x^0) + \\ & + \frac{1}{2}(x - x^0)^T \nabla^2 f(x^0)(x - x^0) \end{aligned} \quad (11)$$

Here, the objective function is a nonlinear, discrete and recursive function, this makes more difficult to find simple analytical expressions for the Gradient and Hessian functions, and therefore the process is more complicated than others cases. However, a more flexible and adaptive tool is obtained.

IV. EXAMPLE

An example of control strategy is considered in order to illustrate the proposed methodology. The load data have been collected from the Polytechnic University of Cartagena demand curve, from June 1, to October 31, 1998. These loads have been divided into four groups, depending on the installed HVAC characteristics -power demand and using patterns mainly-. Another load group has been implemented in order to take into account the global disturbances and errors of the system, in this group has been supposed a typical percentage of HVAC load which has been obtained from the other load groups.

It has been studied the impact on the load demand curve due to the control actions on each group by means of the models given in [9]. The following figure shows schematically the complete system. The dotted line shows the connections between the control system and the rest of the system. Its output signals are the control actions for each control period stage applied on HVAC loads.

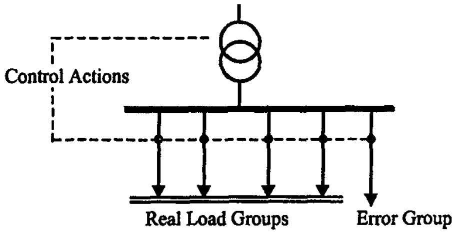

Fig. 2. Scheme of System

In this case, the control actions constitute a vector formed by five values. These values are the forced duty-cycles for the HVAC loads per group during a concrete control period stage. A random day has been selected in order to apply the algorithm control. The considered control duration is 7 hours; it begins at 10 a.m. and ends at 5 p.m. During these hours the system achieves its peak value and minimum load demand. The control actions are recalculated every 12 minutes and sent again to the respective HVAC load groups. The load curve for this day as well as the target load curve are showed at figure 3. The power values are given per unit, referred to average demand peak obtained from the collected data. The load factor is initially close to 0.45 and the load peak is about 250% of the valley load demand.

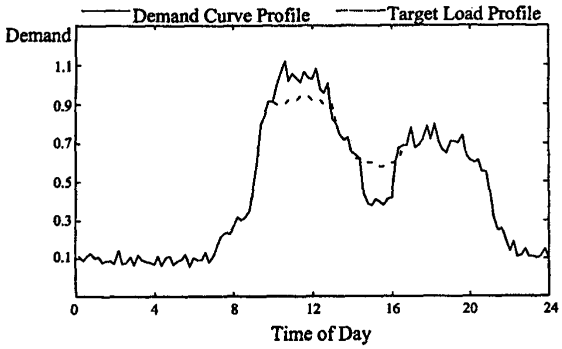

Fig. 3. Load Curve Profile

The proposed control algorithm has just been implemented and its main parameters and constraints are the following:

$$RC_j = 0.2\cdot RC_{j-1} + (1-0.2)\cdot y_{r_j} \qquad (12)$$

$$0 \le Pb_i \le MPb_i = 0.05\cdot\sum_{j=1}^{N}\left(NL_{ij} + CL_{ij}\right) \qquad (13)$$

$$MPl_i = 0.95\cdot Max\left\{NL_{ij} + CL_{ij}; 1 \le j \le m\right\} \qquad (14)$$

The maximum cumulative load deferred per group is a matrix that depends on the internal temperature evolution and is directly related to the models used to simulate, [9]. The following figure shows the load demand curve with control, the load demand curve before controlling and the reference profile, equation (12). The load peak has decreased about a 11% and now this is about 190% of the new valley load demand.

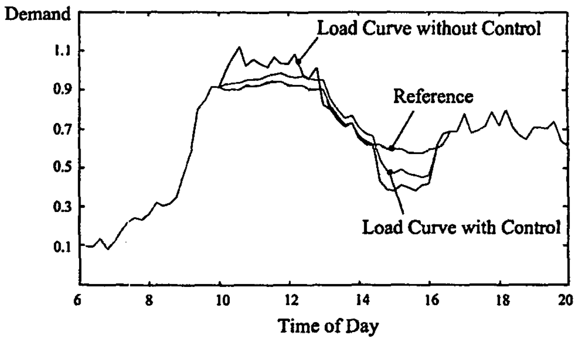

Fig. 4. Control Action Results on Load Demand Profile

It is important to take into account that the total energy associated to the target load profile is similar to the total energy demanded without control, this is convenient in order to minimize the payback after controlling. The following figure shows the control actions implemented for each control period stage and group. These control actions are close to 1 during the last control period stages. This is due to the limit of payback value that has been implemented per group.

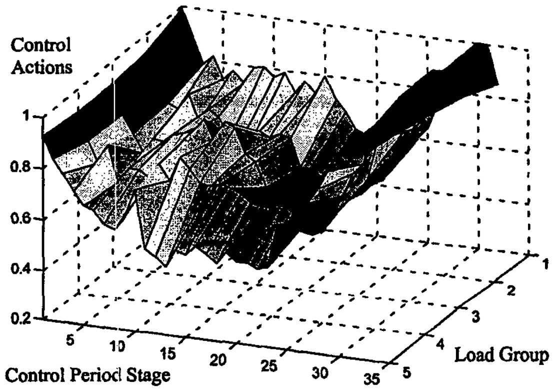

Fig. 5. Control Actions during the Control Period

The load groups from 1 to 4 are related to the real load groups, controllable and non-controllable, which are schematically showed at Figure 2. The last load group is logically related to the modeling error load group.

In reference to the implemented weighting matrix, the controller is not found to be very sensitive. On the other hand, as expected the controller activity increases and deviations in the controlled variables decrease when the receding horizon is increased.

The load demand curves for each individual load group with and without control are showed at Figure 6. Each load demand curve is referred to the average peak value per group. As evident this figure, the new load peaks are less than the load peaks without control, therefore it has been avoided any overload on load groups during the control period stages and after these stages. As seen in this figure, the controller gives excellent performance in regulating all the five controllable HVAC groups within the available range of variation. The last load curve profiles are again related to the modeling error load group.

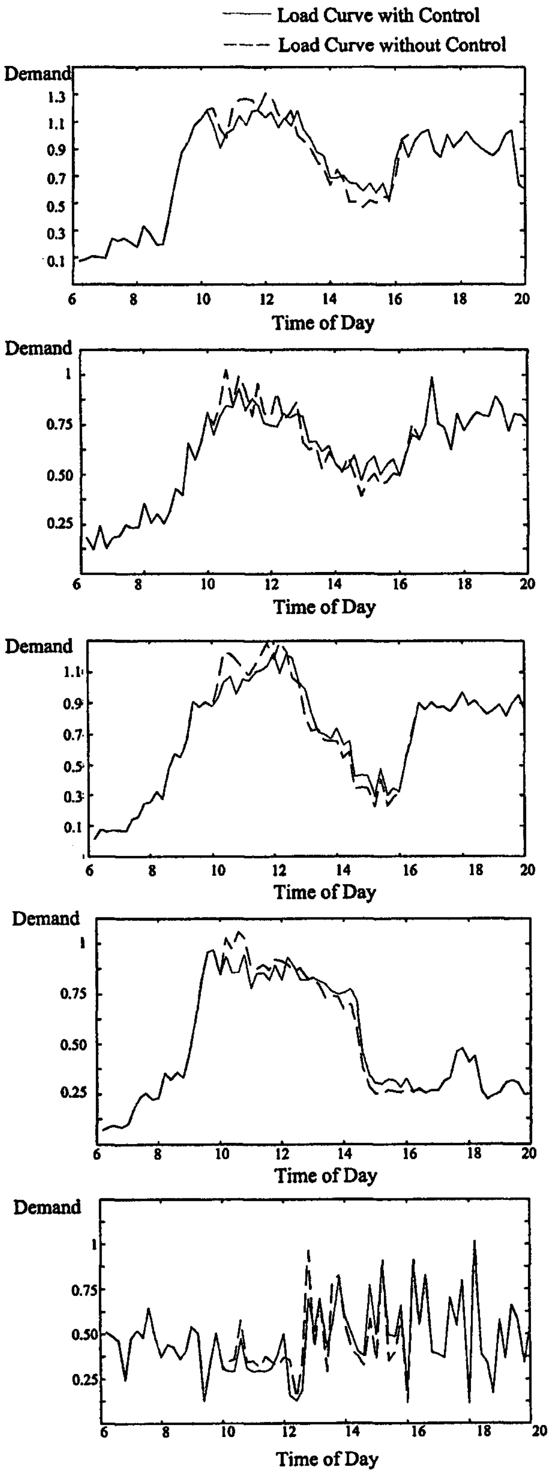

Fig. 6. Load Curve Profiles per Group with and without Control

Finally, the following figure shows the cumulative load demand deferred per group. Its values are directly related to the control actions along the total control period. So, the maximum cumulative load demand deferred values coincide with the lowest control values. Besides, they are close to zero for the last control period stages. All values showed at this figure are also referred to the average peak demand per group.

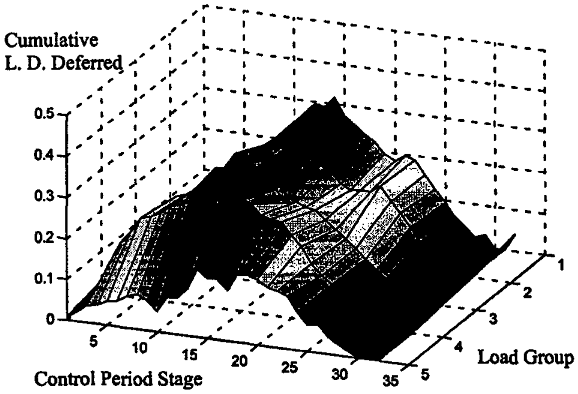

Fig. 7. Cumulative Load Demand Deferred per Load Group

V. CONCLUSIONS

An algorithm based on constrained multivariable predictive control has been developed in order to obtain a new DLC program. The proposed method is applied to residential HVAC and determines the forced duty-cycles for these devices in order to modify the global load curve according to a prefixed target load curve. A distribution network is simulated taking into account the models given in [9]. The system constraints have also been considered and they are mainly related to the minimum comfort levels of the customers. All the mathematical expressions are included in this paper as well as the main assumptions. The control algorithm has been tested on a real load curve which has been collected from the University of Cartagena demand. Most of test results are presented to illustrate the algorithm performance and its improvements in comparison with other methodologies.

At this moment, we are working on other possible routines to implement this control algorithm. The main objective is to increase the calculation speed and allow the use of this control algorithm with other kind of loads, for example, residential heat storage or electric water heating loads. On the other hand, we are also improving our individual load models as well as the aggregated demand models to achieve a more realistic simulation. Mainly, we are developing physically based load modeling which is very suitable to assess the effects associated with the control actions for each control period stage and the payback periods after controlling. We are collecting load demand data from residential zones in order to test the developed models and find their possible deficiencies.

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VII. BIOGRAPHIES

A. Molina García was born in Cieza, Spain. He received his Industrial Engineering degree from Polytechnic University of Valencia, Spain in 1998. Currently, he is working towards his Ph.D. at Department of Electrical Engineering of Polytechnic University of Cartagena, Spain. His research interests include DSM, Adaptive Predictive Control, as well as optimization theory and its DLC applications.
Angel.molina@upct.es

A. Gabaldón Marín (M'97) was born in Cieza, Spain. He received his Industrial Engineering degree from Polytechnic University of Valencia, Spain in 1988, and his Ph.D. degree from the same University in 1991. Currently, he is working at Department of Electrical Engineering of Polytechnic University of Cartagena, Spain. His research interests include Demand-Side Management, End-Use Efficiency, Modelling and Distribution Automation.

J.A. Fuentes Moreno was born in Murcia, Spain. He received his Industrial Engineering degree from the University of Zaragoza in 1994. He is currently working towards his Ph.D. at the Department of Electrical Engineering of the Polytechnic University of Cartagena, where he is a lecturer since 1996. His research interests include Load modeling, control and optimization.

F. J. Cánovas Rodríguez was born in Cartagena, Spain. He received his Industrial Engineering degree from the University of Murcia in 1994. He is working towards his Ph.D. at the Department of Electrical Engineering of the Polytechnic University of Cartagena. His areas of interest include power quality, power system harmonics and power system analysis.