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Electrical Thermal Storage Modeling: a Tool to Evaluate New Opportunities and Bids for Residential Users in a Deregulated Market

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Abstract-- **The purpose of this paper is to describe a useful tool for the initial analysis to assess the possibilities of residential Electric Thermal Storage (ETS), taking into account heat storage and cool storage devices. These load models are based on an energy balance between the indoor environment, the dwelling constructive parameters, the ETS device and the internal mass through a discrete state-space equation system. The main application of this load model has been oriented towards the simulation of ETS performance in order to evaluate the possibilities of Load Management in the new de-regulated structures of Electrical Power Systems.**

The proposed model has been implemented and validated for heat storage, using real data collected during the last years in residential areas to evaluate its accuracy and flexibility. Finally, a simulation case study is presented to show the possibilities of modifying the actual residential demand profile through a storage period re-scheduling proposed by the authors, taking into account the customer minimum comfort levels and avoiding program rejection.

Index Terms— **Demand-side bidding, residential load modeling, Electrical Thermal Storage**

I. INTRODUCTION

TWO different approaches have been used to solve the continuous growth experienced in the demand of Electrical Energy Systems. The first one is focused on adding new resources and expanding the Power System so that the new energy requirements can be met −Supply Side Management (SSM)−. The second one is to try to influence on customers in order to reduce their demand peaks and/or modify their habits. Thus, Demand-Side Management (DSM) technologies −and specifically Load Management (LM) programs− have been applied in the United States and the European Union countries for over the last two decades. The main objective is to manage the timing, magnitude and sharpness of daily and seasonal load curves to provide, economically and technically mechanisms matching load to supply. Nowadays, and throughout the world, the electric power industry is moving toward a deregulated framework in which consumers *will* have a choice among competing providers of electric energy. In this change to a deregulated (or re-regulated) market, the first casualty of utility restructuring is the demise of utility founded DSM programs. For example, in the USA, capital expenses on DSM programs fell from $1.65 in 1993 to $0.91 billion in 1998. Deregulations should benefit the environment and the economy as well as the security of supply; since, the new electricity market will not be complete before full economic and environmental efficiency is achieved, including end-use energy efficiency, fuel switching, LM and *new tools* as *Demand Side Bidding* (DSB), *which* fulfill these conditions. DSB should enable consumers to actively participate in electricity trading by offering changes in their normal pattern of consumption, in return for a specified income. These concepts are oriented, as some DSM policies, towards controlling or rescheduling of electrical loads; maintaining the balance between energy supply and demand, and they can also help to improve the quality and security of supply. Thus, Demand Side technologies are ahead from their full potential in deregulated markets.

In Spain and other EU countries, around 20-25 percent of the annual electric energy demand is attributable to residential loads. Specifically, over 75 percent of the residential electric energy use is for air conditioner, space heating and water heater loads. Moreover, these loads have a great responsibility on the Power System peaks −winter or summer peak−. Direct Load Control (DLC) and other technologies such as heat/cool storage have one of the greatest potential for meeting DSM and DSB objectives, as well as utility and customer needs. Finally, the number of electric energy storage devices and programs in residential and commercial sectors has grown considerably during the last years, [1]. In this way, cool storage is a well established alternative for larger buildings. Despite this fast growth, the total number of installations is still a small percentage of the market potential −less than 10%, even for large customers, [2]−.

The purpose of this paper is to describe and assess a physically-based load model of residential Electric Thermal Storage (ETS) device, analyzing the possibilities of modifying the customer demand, allowing retailers or energy service companies (ESCOs) to provide energy bids in the wholesale market, but maintaining their comfort levels and improving the efficiency of electrical delivery network.

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II. ENERGY STORAGE FOR RESIDENTIAL CUSTOMER

A. Potential of Energy Storage

According to the previous section, the number of electric energy storage devices and programs in residential and commercial sectors has grown considerably during the last years. This way, it is reasonable to believe that in the near future, ETS will be bright. The premises, which support this optimistic point of view, are mainly based on the following:

- *Technological maturity.* Nowadays, thermal and cool storage is a straightforward and proven technology, which offers users substantial savings and business opportunities; not only for ESCOs and retailers, but also for manufacturer projects differentiated from those of others.
- *Technological progress.* There is an increasing interest in ceramics, rare earths and non ferrous elements as heat storage materials, since both have suitable thermal characteristics and high density. In cool storage, eutectic salts and phase-change materials are one of the most promising alternatives. For example, these salts are being developed to achieve and profit phase-change energy (liquid to solid and vice versa) at temperatures as high as 6-8°C. At these temperatures, chillers can work with higher efficiency than at the low temperatures required by ice storage –at this moment, the less expensive alternative for residential cool storage, due to lower tank capacity requirements–.
- *For DSB opportunities.* It is expected an important growth in the use of ETS devices for this decade, which will suppose an increase in generation, transmission and distribution load factors. For example, in Finland about 600.000 small houses have electric heating, [3]. Many customers have a supply contract that allows the supplier to interrupt the energy to the heating circuits during short periods –less than two hours–. Therefore, suppliers can interrupt the load directly without any notice, and manage the demand during peak periods, assisting the System Operator (ISO) to maintain quality of supply. In this scenario, ETS would help to avoid user complains when the control is exerted –one of main drawbacks of DLC–.
- *Customer satisfaction level.* It is very interesting to provide several service options which offer customers, for example, the opportunity to achieve more control over theirs electricity bills. Moreover, information is always welcome by the users and, jointly with DLC, could be an opportunity to allow users to access the market prices and benefits.

B. Energy Storage for Valley-Filling: Concepts and Opportunities

Traditionally, DLC policies applied to electric water heaters have been one of the most usual DSM policies for valley-filling in the United States and EU countries, [4], [5], [6]. These devices are switched *on* at least for periods from six to eight hours (valley hours) and switched *off* during peak periods, and perhaps in flat–hours demand periods.

Therefore, ETS devices have a great interest for the, so-called, winter-peak systems. These devices store energy in thermal storage reservoirs –ceramic, water– during off-peak periods and this energy is later used to cover the user necessities along the utility peak periods. This set of loads could be remotely controlled by retailers or individually controlled by the own users. The bulk of interest in ETS is focused on ceramic storage, water and slab-storage. In Europe, individual ceramic units are the most suitable and receive more attention than central units. In reference to summer-peaks systems, the supply-side interest is focused on Storage Air Conditioner (SAC) technologies. Application of cool storage appears to be lagging from its maximum potential in buildings. For residential uses, the technology has been developed, but its applicability is limited to prototypes and small-scale testing (1994, Sacramento Municipal Utility District), due to the difficulty to overcome cost economies of scale in this market. SAC systems typically generate and store ice or chilled water during off-peak periods.

Finally, it is interesting to note that cool storage technology –widely used in industrial processes to reduce capital and operative costs- presents an opportunity for equipment vendors and engineering companies, since it is a partial but important alternative to decrease annual summer-peak demand growth –technologies used in industrial applications a decade ago, as electronic drives, are now fully developed for residential uses–.

C. Technical Problems and Environmental Concerns for Energy Storage

Energy storage presents an exciting potential for utilities and users, but also some problems arise in practical uses for valley filling.

- *Technology and cost for DLC.* Technology for controlling ETS devices is not significantly different of air conditioner, heat pump or electric water heating loads, since all of them require a two-way communication system with an adequate architecture, [7]. However, the operating procedures should be quite different, due to the *payback* phenomenon –water heater and air conditioner load profiles are exerted after a DLC period, and they usually show an important energy demand. Two methods could be used to mitigate this effect: using larger storage capacities, or improving load models together with suitable control strategies to predict and correct the load demand after DLC periods. The first one is preferred by supply side, but it is considerably more expensive for the customers.
- *Cost of energy storage loads.* Despite the important growth of residential storage installations, the percentage of market penetration is very low, even for ceramic ETS –which is the most common and reliable technology–. Due to this fact, the total costs of ETS loads are normally from eight to ten times the electric heating conventional costs. An estimated price of a standard 3kW dynamic ETS device could be between 400 and 600 €, mainly due to the costs of the ceramic bricks, included to meet the necessary heat

storage capacity during peak-off periods. For cool storage, some disadvantages are also found, as the cost of HVAC system, the more complicated design, or the cost of maintenance; but, specially, the volume required for storage, considerably larger than for heat storage.

- *Environmental concerns*. This is a very important objective for developed countries in the 21st century. For example, European Commission has a target of saving 1% per year of the total electricity and gas demand in EU. Over ten years, it would suppose an economic saving of 10% in the energy sector, equivalent to 100 million toe/year of primary energy savings, about 70 million toe/year of final energy savings of which electricity savings would amount to 260 TWh/year –and a CO_2 reduction of around 230 million tonnes/year–. Generation companies (GENCOs) will increasingly be the targets of regulations to reduce emissions, because they are regarded as major contributors to heat-trapping gasses to the atmosphere. ETS devices can help to mitigate this problem.

III. PHYSICALLY BASED LOAD MODELING

A. General Description

Physically-based load modeling methodologies are one of the most promising approaches for the load modeling problem applied to DSM purposes, [8], [9], [10]. In [11], an improved physically-based load model has also been presented by the authors. In this section, a model of ETS devices is proposed. This model has been integrated in the thermal model of [11], in order to simulate its global behaviour when external action inputs are considered over this system.

The proposed elemental model is focused on residential individual houses with ETS devices. An energy balance analysis has been applied to the system integrated by the housing, the external environment –outdoor temperature and radiation– and the ETS device, obtaining a discrete state–space equation system, . The load model response relies on information about physical load characteristics, internal control mechanisms –thermostat performance–, usage and environmental parameters.

Two kinds of ETS devices have been studied: Static and Dynamic Electric Thermal Storage loads (SETS, DETS); and Cool Storage Loads (CSL). While SETS devices have a thinner insulation layer and their discharge regulation is based on the opening/closing of a vent driven by a bimetallic mechanism; DETS devices have a wider insulation layer and an internal fan to circulate the stored energy by means of forced convection, and helping to maintain the indoor temperature around the thermostat set point. Therefore, two control mechanisms are needed: an internal thermostat which controls the ceramic brick charge periods and the electric demand, and an external thermostat which is related to the target indoor temperature. Fig. 1 show the internal structure of a typical ETS device.

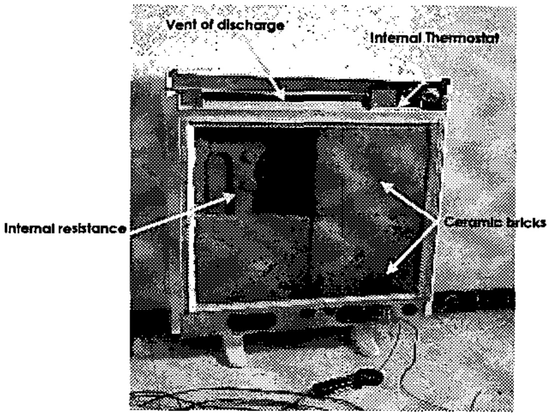

Fig. 1. ETS internal components

B. Mathematical Model

The analogy between the heat transmission processes and the electrical circuit theory has been used. The elemental model consists of a discrete state-space equation system which comprises continuous states –temperatures– as well as discrete states –thermostat performances–. A simplified ETS model was previously proposed in [13], and now it has been improved in order to achieve more accurate results. Fig. 2 shows this equivalent circuit in which the indoor temperature node has been explicitly indicated.

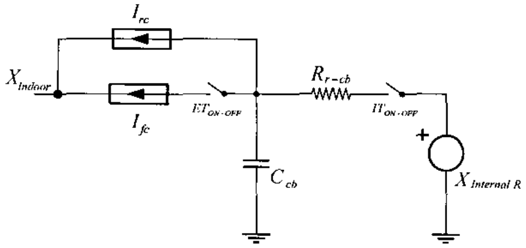

Fig. 2. System equivalent electrical subcircuit

Where:

C_{cb} : Ceramic brick thermal capacity

ET_{ON-OFF} : External thermostat –indoor temperature control–

IT_{ON-OFF} : Internal thermostat –ceramic brick temperature control–

I_{fc} : Heat flux by forced convection from the ceramic bricks to the indoor –controlled by the external thermostat–.

I_{rc} : Equivalent heat flux by radiation and natural convection from the ETS external surface to the indoor

R_{r-cb} : Thermal resistance of ceramic bricks during the charge periods

$X_{Internal-R}$: Temperature of internal charge resistances

It is possible to know the evolution of several variables related with the ETS performance from this equivalent electrical subcircuit: Ceramic brick average temperature; loss heat flux during the charge period –due to natural convection and radiation through the ETS external surface–, and electric consumption related to the power of $X_{Internal\text{-}R}$.

C. *Appliance Model for Cool Storage*

Nowadays, we are beginning to study a real CSL in order to validate our model. From our point of view, it is relatively easy to obtain model parameters from the main SETS parameters and energy needs, through the water thermodynamic data. Solving these equations we can obtain an energy storage capacity for a 20 kWh residential demand. TABLE I shows several examples according to different storage possibilities:

TABLE I
ENERGY STORAGE CAPACITY EXAMPLE

Storage capacity	kJ/kg	BTU/pound	Volume (litres)
Chilled water	40-50	18-20	1500-2000
Ice	300-350	140-150	250-290

Thus, ice storage is the most promising alternative for residential uses, since it represents about one-seventh the capacity per pound of chilled water.

Basically, our elemental model remains the same in order to simulate cool storage devices, except for two differences. The first one is that equivalent heat flux by radiation and natural convection from the indoor tank to the external surface is practically negligible, due to the small temperature difference between ice or chilled water and air, perhaps 20-30°C and the low internal temperature –near to 0°C–. The second one is related to the electrical power demanded by heat pump, since this power depends on the Energy Efficiency Ratio (EER) or Coefficient of Performance (COP), a parameter that varies with the internal and evaporator temperatures. In this way, it is necessary to be noted that night time operation at lower evaporator temperatures improves EER and COP, and it improves the overall efficiency, reducing the impact of tank heat losses during the storage period. Fig. 3 shows the electric power as well as the internal temperature evolution during a starting process until the steady-state is achieved. In this case, the electrical power variations can clearly be recognized.

D. *Model Implementation*

The state-space equation system has been implemented by means of *Matlab-Simulink*. In reference to the thermostats, they both include a hysteresis control around their setpoints. The external thermostat setpoint is fixed by the user, and it depends on his lifestyle, desired comfort level and several subjective parameters; whereas the internal thermostat setpoint is closely connected with the selected charge level and the last discharge periods. The system equations and theirs implementation for SETS and DETS devices are approximately the same, even though they have some differences related with the way they exchange energy with the indoor environment.

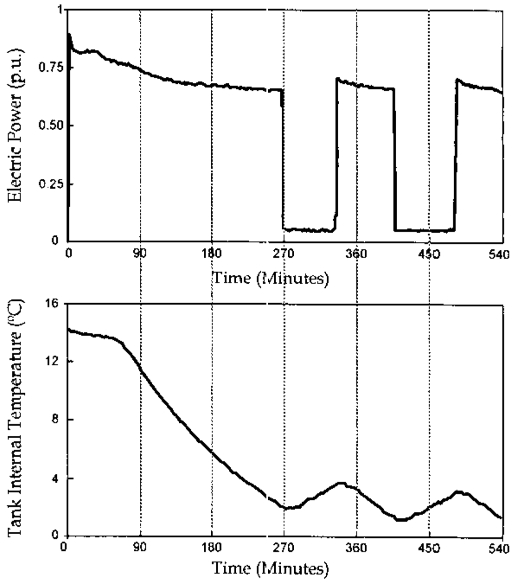

Fig. 3. Power demand evolution. Cool storage device example

IV. ELEMENTAL LOAD MODEL VALIDATION

This physically based elemental model has been tested using data obtained from houses with different orientations, lifestyles and situated in several cities with various outdoor temperature profiles. The data have been collected during several years, being compared with the simulated results to assess this load model. The main outputs of the implemented system are: ETS heater electric consumption, indoor and ceramic bricks temperature evolution along charge and discharge periods.

The system inputs are basically: weather data –outdoor temperature and radiation levels– and time of day. If radiation data would be not available, it has been developed and implemented a subsystem which would allows us to estimate the radiation levels according to the solar hour, the external wall orientation and the day of the year. Fig. 4 to Fig. 6 present a brief example about the validation process of this elemental load residential model.

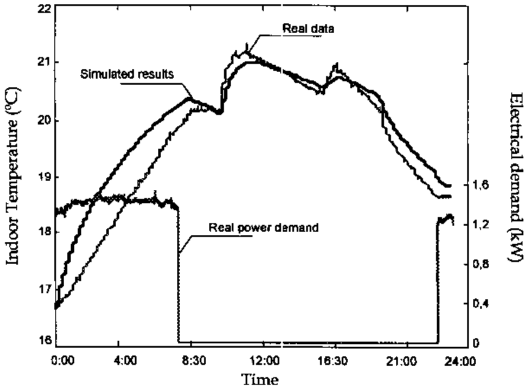

Fig. 4. Static Electric Thermal Storage load validation

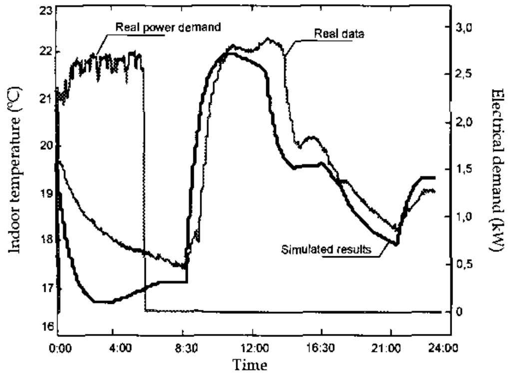

Fig. 5. Dynamic Electric Thermal Storage load validation

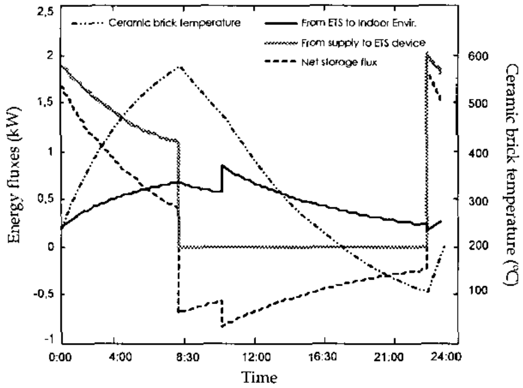

Fig. 6. Main energy fluxes of Static ETS device

V. SIMULATION CASE EXAMPLE

A large number of correlations between the HVAC demand and the outdoor temperature evolution have been widely developed in the technical literature. In all cases, the maximum values of HVAC demand have been related with harsh outdoor temperatures. So, summer and winter peaks normally take place in days with extreme weather conditions. In reference to the winter peak, it could be possible to decrease its maximum value by using ETS devices together with a correctly chosen LM program. In this way, the authors propose to introduce an intermediate recharge phase, between 13:30 and 17:30, which takes into account the decrease in the residential demand during this time interval, in order to recharge partially the ceramic bricks and maintain the customer minimum comfort levels, without using any secondary heating system which could increase the load peak.

This kind of solutions also allows us to reduce the device thermal capacity, decreasing its volume and increasing its mobility. Fig. 7 shows the simulated results and the advantages of implementing the proposed strategy in reference to maintaining comfort levels, shifting the load demand from on-peak to off-peak periods and limiting the peak value.

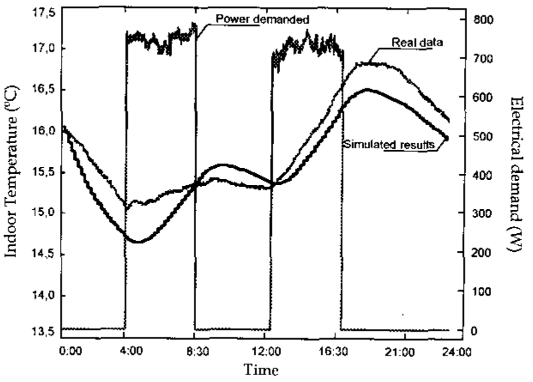

Fig. 7. Partial storage period. Indoor temperature evolution

In order to compare the indoor temperature evolution when this partial storage is applied, Fig. 8 shows both cases. It can be seen the discomfort degree introduced by these two storage periods through the indoor temperature differences. Nevertheless, these differences are less than 10 per cent, and therefore, the proposed solution could be right from a thermal point of view.

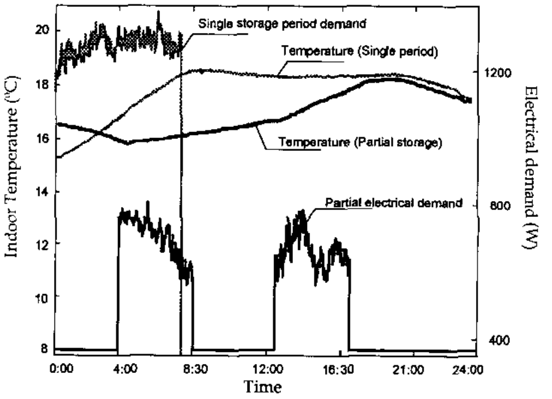

Fig. 8. Indoor temperature evolution comparison

VI. CONCLUSIONS

A physically-based load model of ETS devices has been described and assessed. This model is focused on the simulation of ETS steady-state performance as well as its behaviour under external control actions. The main advantages of this model are a high accuracy and wide information about the ETS physical magnitudes –electric consumption, ceramic brick temperature...– and the indoor temperature–.

Also, it has been implemented by means of Matlab-Simulink, obtaining a friendly graphical interface in spite of its complex mathematical representation. In our opinion, through this model it is possible to choose the most suitable control strategies, taking into account utilities and customers needs.

VII. ACKNOWLEDGMENT

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