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Simple rule for management of thermal loads with real-time prices

J. Agüero-Rubio [a,*], A. Giménez-Fernández [a,b], A.J. Callejón-Ferre [a], J. López-Martínez [a,b]

[a] Department of Engineering, University of Almería, Almería, Spain
[b] Automatic Control, Electronics & Robotics Research Group, University of Almería, Spain

ABSTRACT

The integration of renewable energies, and therefore the generation of a clean and sustainable energy, is a current demand by society. The use of real-time pricing offers advantages for integrating renewable resources into the electrical grid. This is because users enhance the flexibility of their own energy demand thanks to planning loads with accumulation capacity. The aim of the present work is to equip users to manage their energy demands with simple planning systems. For this, a simple rule is proposed to help a greater number of users to gain the capacity to manage their demand. The new rule, based on a geometric progression of real-time pricing of energy and intrinsic characteristics of the load, provides valuable information for the user to decide whether or not to accumulate energy in the load. This rule provides good results by the simulation of a simple thermal load.

1. Introduction

The so-called green energies (hydraulic, wind, geothermal, solar, and biomass), based on clean production systems and environ-mentally friendly, are in demand, especially in industrialized soci-eties (Martin, 2012; Manzano-Agugliaro et al., 2013). These, faced with problems such as climatic change, the rising price of petro-leum, doubts about the safety of nuclear energy, and excessive emissions (carbon dioxide, methane, nitrous oxide, etc.), among others, demand governmental measures and/or actions to advance towards complete sustainability (Callejón-Ferre et al., 2014). In this context, the good use and control of energy (energy efficiency) is critical, because, together with the "green and clean" origin of this energy are the responses that societies expect of their governments (Vincenzo-Giorgio et al., 2009).

The European Union seeks to reach the goal of 20% use of renewable energies by 2020 (European Parliament, 2009). In Spain, this would increase their contribution to the total energy consumption from 10.5% in 2008 to 22.7% by 2020 (Ministry of Industry, 2011). It has been affirmed (Ghassan, 2011) that the option of expanding solar as well as wind energy is viable in Spain, as the former could rise 30% and the latter 15% with reasonable costs between 2020 and 2030. Also, the making use of biomass can be seen in many studies (Panepinto and Genon, 2012; Penepinto et al., 2013, 2014).

Along this line, it has been emphasized that if Europe is serious about achieving its target to keep the global mean temperature increase below 2 °C, it has to strive for a 100% renewable electricity system by 2050 (Battaglini et al., 2009).

Therefore, the integration of RES and the appropriate indoor energy use are being widely studied from technical as well as scientific standpoints (Jay and Swarup, 2011; Xu et al., 2011). However, due to the random nature of RES (Moura and de Almeida, 2010; Yuanxiong et al., 2012), it is necessary to develop energy-demand management strategies which enable the final user to participate actively in the electricity market and thereby achieve more flexible energy demand (Pratt, 2004; Schleicher-Tappeser, 2012). This will provide approaches that are ecologically and economically appro-priate for the short- and long-term future of society (Dovi et al., 2009).

The integration of RES has been studied by several authors who approach it in terms of domestic loads (Jay and Swarup, 2011; Samarakoon and Ekanayake, 2009; Xu et al., 2011). Hanane et al.

(2012) undertook a study on a smart building with hybrid systems based on: RES, different technological alternatives to satisfy the different demands, the possibility of integrating energy storage (thermal or electric), and strategies to improve efficiency in defining the energy supply (smart buildings are called “green buildings”). The smart-building concept has been extended to smart homes (Zang et al., 2013), which share the common DERs (Distributed Energy Resources) from a microgrid. Both the operations of the DER and the domestic appliances with their specific energy-consumption profiles are scheduled based on real-time electricity prices at each interval, and therefore by their forecasting. Hybrid systems are also studied to establish synergies from different technologies, such as fuel cells and cogeneration (Rivarolo et al., 2013; Wakui et al., 2012).

More specifically, it has been established that any load with energy accumulation can be regulated, as in the case of thermal loads, which can aid in the management of systems with a high use of renewable energies by means of a flexible demand (Jorge et al., 2000). In addition, this requires developing an incentive system, since there are conflicting goals between consumers and energy distributors, such as users’ comfort, the reduction of energy-grid losses, and the economic benefits (Jorge et al., 2000).

The use of real-time pricing (RTP) offers certain advantages for the integration of RES. Local energy markets with adequate energy-management systems offer the cheapest prices while maximizing the utilization of RES (Marzband et al., 2013). Also, RTP can provide more flexibility in the energy demand (Allcott, 2009; Berger and Schweppe, 1989), and in Greensfelder et al. (2011) RTP is applied directly to thermal loads with thermal-energy accumulation. However, the main disadvantage is the lack of knowledge among consumers concerning how to make use of this system (Pratt, 2004).

The present work develops a system of evaluation and control of thermal loads with power regulation and energy accumulation based on day-ahead pricing (DAP) (Conejo et al., 2010; Lujano-Rojas et al., 2012) and the characteristics of the load. It has been tested by simulation and it is made specifically for a load of air conditioning of a typical office in a research building of the University of Almería (SE Spain) (Rosiek and Batlles, 2009). This rule can be applied to other loads, whether domestic or not, that have accumulation ca-pacity, offering promising preliminary results that can be extrap-olated to any room with a network of sensors and an HVAC system.

The ultimate aim of this study is to provide the user a rule to manage thermal loads and thereby participate in an electric-energy market with RTP through the DAP modality. And therefore, un-specialized users can have a variable that provides information on the potential savings that any given load has with a forecast of the prices available.

The present paper is structured according as follows: Section 2 describes the management rule for thermal loads, based on a geometric progression of DAP; Section 3 shows the results; and Section 4 presents the conclusions.

2. Energy management of thermal loads

As stated in the previous section, the intent is to enable the user to manage loads with electric-energy consumption and accumulation of thermal energy in a context of real-time pricing (RTP). For this, the RTP modality, defined as DAP, has been selected, this consisting of an hourly forecast of the electric energy price for the following day (Conejo et al., 2010; Lujano-Rojas et al., 2012). The user gains information on the economic state of the load and therefore of the most financially advantageous action. All this is through the rule defined in Section 2.2 and applied to simple load model described below in Section 2.1.

2.1. Description of the model

A first-order model in discrete time has been proposed for an HVAC load (Constantopoulos et al., 1991), which has been used as the model in the present work, Eq. (1).

$$T(k) = E \cdot T(k-1) + (1-E) \cdot \left(T_o \pm \frac{P(k-1)}{A} \mp \frac{Q}{A} \right) \tag{1}$$

where $T(k)$ is the indoor temperature, k is the interval of the sample corresponding to the current instant in time, E is the thermal inertia defined in Eq. (2), T_O is the outdoor reference temperature, P is the HVAC system power, Q represents the thermal loads and A is a coefficient of thermal losses. The upper sign indicates the cooling and the lower sign the heating.

$$E = e^{\left(\frac{-t_S}{\tau}\right)} \tag{2}$$

where τ is time constant of process and according to reference (Calloway and Brice, 1982) is easy to fulfil; t_S is the sample time.

This case is applied to an air-conditioning load, the temperature is used as a thermal-comfort index (ISO7730, 1994) and the user comfort zone being defined according to a previous study (ASHRAE55, 1992).

2.2. Function, gain of accumulation

One part of the energy (power per time interval) that a thermal load consumes is proportional to the difference in temperature of that load, i.e. losses. The action of accumulating energy in the current time interval (in the form of a temperature difference) to compensate for losses in the future implies a degradation of this energy over time. The accumulation of energy is determined by the intrinsic characteristics of the load (accumulation capacity and coefficient of losses) and by the energy prices from the current instant until disconnection of the load.

Fig. 1 represents an energy accumulation as a temperature difference corresponding to an air-conditioning load (cold).

At the instant k_0 the user stores a quantity of energy $P_{Ac}(k_0) \cdot t_S$ (Fig. 1c), under a variation in the temperature difference $T(k_0) - T_D$ (Fig. 1a). In this example, this action is made because the price at this instant is more reduced than at the next one (Fig. 1b). Where P_{Ac} is the power capable of bringing about temperature changes in the load, P_0 is the power that maintains the temperature at a constant value T_D, which represents the desired comfort of the user (ASHRAE55, 1992; ISO7730, 1994), t_S is the sampling time, and $T(k_0)$ is the temperature in the load at the end of the time interval k_0.

Accumulated energy at an initial instant k_0 is lost over time in such a way that, at instant k, only the quantity of energy given by Eq. (3) remains accumulated in form of temperature difference (see Fig. 1a).

$$P_{AC}(k) = P_{AC}(k_0) \cdot E^{k-k_0} \tag{3}$$

where $P_{Ac}(k)$ is the energy that remains accumulated until the time interval k (in the form of temperature differences); $P_{Ac}(k_0)$ is a power step that is added at the instant k_0 (see Fig. 1c); and E is the thermal inertia of the load defined in Eq. (2).

Given that the energy accumulated is degraded according to Eq. (3), i.e. curve ABC (Fig. 1a), the gain of accumulating energy at any instant k_0 is given by Eq. (4), generalized for any k.

$$g_{acc}(k) = \sum_{i=1}^{N_T-k} [c(k+i) - c(k)] \cdot E^i \tag{4}$$

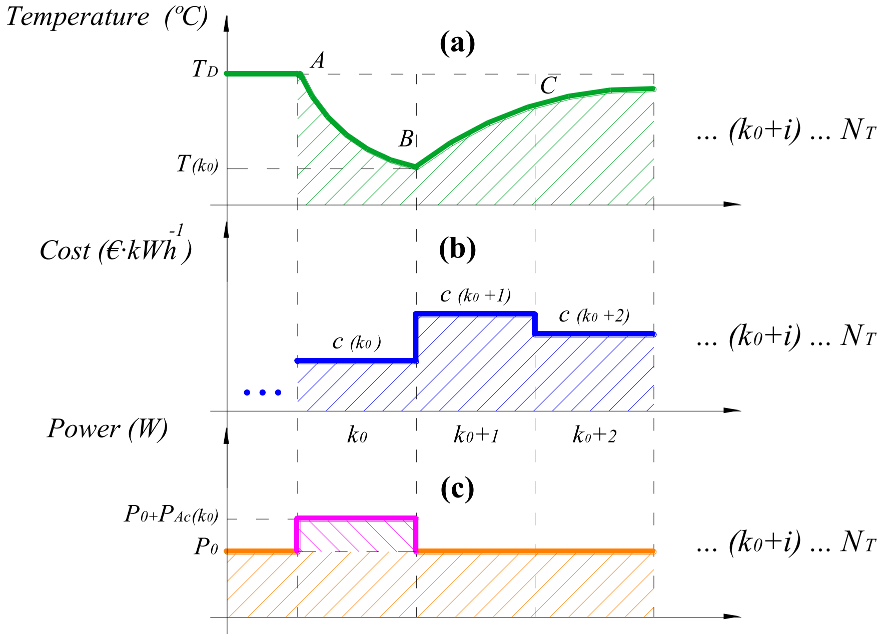


Fig. 1. Energy accumulation in the load: (a) Temperature, (b) Cost and (c) Power.

where $g_{acc}(k)$ is the gain of accumulating energy at the instant corresponding to the time interval k in € kWh^{-1}, N_T is the number of time intervals that the load connection lasts, $c(k)$ is the price forecast according to DAP in € kWh^{-1}, and E is the thermal inertia.

Fig. 2 plots the curve corresponding to Eq. (4) for a sample price forecast. Eq. (4) is represented by a broken red line and the DAP is represented in a solid blue line. The beginning hour will be considered to be 10:00 h and the ending hour 20:00 h.

2.3. Control rule

The rule of control consists of accumulating energy or not by using the gain function of accumulation defined in Section 2.2. This rule is applied only between intervals in which the gain function of accumulation is continuous and positive. The function is continuous between instants at which the cost remains constant, Fig. 2. Eq. (5) defines the time intervals in which the control rule is applied.

$$\forall\ k;\quad k_h \le k \le k_{h+1} \Leftrightarrow g_{acc}(k) \ge 0 \qquad (5)$$

k_h and k_{h+1} are the first and last instant (just before changing to the next hour) of each hour. According to Fig. 2, all the action periods correspond to one hour, except for 12–14 h, which are two hours and, since the gain of accumulation is negative in this interval, it is not considered in the present work.

The control intervals defined in Eq. (5) are considered independent of each other. For this, the following hypothesis is admitted, Eq. (6):

$$T(k_h) = T(k_{h+1}) \qquad (6)$$

The accumulated energy, and therefore the temperature in the load, is equal to the beginning and end of the complete action period (each hour in this work).

The gain function of accumulation, Eq. (4), facilitates the control decision in the intervals that fulfil Eq. (5). A simple rule for the

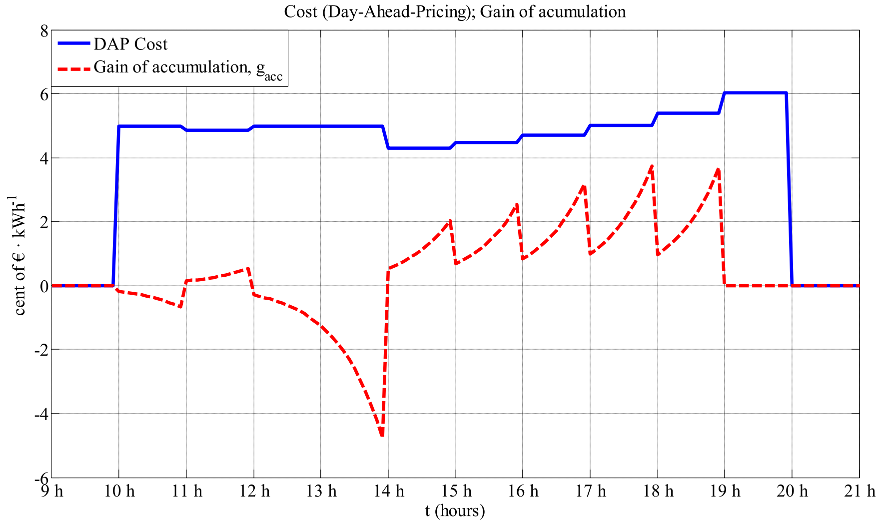


Fig. 2. Day-Ahead-Pricing cost and gain of accumulation.

Table 1
Load characteristics (room).

Parameter name	Symbol and value
Loss coefficient	$A = 0.022$ kW °C^{-1}
Time constant	$\tau = 41$ min
Sampling time	$t_S = 5$ min
Thermal-comfort zone	22 to 26 °C
Desired temperature	$T_D = 24$ °C

control consists of balancing the power variations and the varia-tions of the function, Eq. (7):

$$\forall\ k;\ k_h \le k \le k_{h+1} \Leftrightarrow g_{acc}(k) \ge 0$$

$$\frac{\Delta P(k)}{P_o} = \frac{\Delta g_{acc}(k)}{g_{acc}(k_N)} \rightarrow \begin{cases} \Delta g_{acc}(k) = g_{acc}(k) - g_{acc}(k_N) \\ \Delta P(k) = P_{Ac}(k) \end{cases} \qquad (7)$$

where $P_{Ac}(k)$ is the power capable of bringing about changes in the load temperature (to accumulate energy), P_0 is the power that maintains the temperature at a constant value, k_h and k_{h+1} are the instants between which the function gain of accumulation $g_{acc}(k)$ is continuous, and $g_{acc}(k_N)$ is the function value to the instant of not acting k_N (Null), described below.

Eq. (8) indicates the part of the power that, being accumulated at any instant k between the instants k_h and k_{h+1}, arrives “alive” at instant k_{h+1} (just an instant before the change occurs in cost of the next hour).

$$\forall\ k;\quad k_h \le k \le k_{h+1} \Leftrightarrow g_{acc}(k) \ge 0$$

$$\sum_{k=k_h}^{k=k_{h+1}} P_{Ac}(k) \cdot E^{(k_{h+1}-k)} \qquad (8)$$

Substituting Eq. (7) in Eq. (8) and making it equal to zero to fulfil the condition of Eq. (8), gives the value of the function of not acting $g_{acc}(k_N)$, Eq. (9).

$$g_{acc}(k_N) = \frac{\sum_{k=k_h}^{k=k_{h+1}} \left[g_{acc}(k) \cdot E^{(k_{h+1}-k)} \right]}{\sum_{k=k_h}^{k=k_{h+1}} E^{(k_{h+1}-k)}} \qquad (9)$$

Finally, with Eq. (9), all the elements of Eq. (7) are defined and the rule of control is posed.

Table 2
Results.

% Cost reduction	MSE (°C)	$\Delta T_{Max}/\Delta T_{min}$ (°C)
8.48	0.78	+1.51/−0.02

2.4. *Description of the load and the simulation conditions*

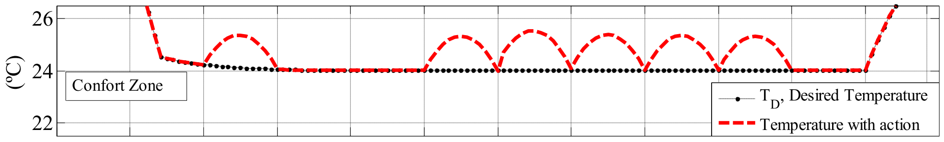
For cooling in summer, thermal comfort can be reached at a temperature of 24 °C with a tolerance of ±2 °C (ISO7730, 1994; ASHRAE55, 1992). The results are from simulating the air conditioning of a characteristic room in a research building of the University of Almería (SE Spain) (Rosiek and Batlles, 2009), (http://www.ciesol.es).

The above criterion is applied in the simulation of a thermal load for which the main parameters according to the first-order model given in Eq. (1) are indicated in Table 1. These parameters are established by comparing the first-order model proposed in Castilla et al. (2010) with the model proposed in Constantopoulos et al.(1991).

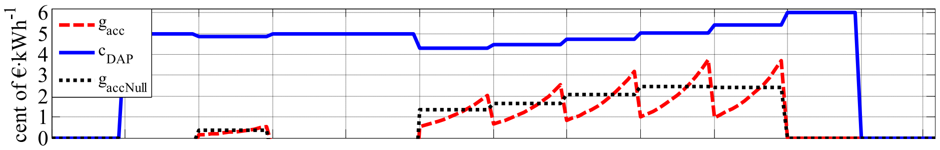
The simulation conditions are:

1. The load starts at 10:00 h and ends at 20:00 h, and therefore for a sampling time of 5 min, N_T takes a value of 120.
2. Baseline. This is the desired curve and consists of reaching the value of the indoor temperature $T_D = 24$ °C, through the power needed to achieve it, P_0. This provides the background to make comparisons.
3. Both for the baseline case as well for the study case, only the thermal loads due to temperature differences are considered; this is equivalent to nullifying Q in Eq. (1).
4. It is necessary to know the outdoor reference temperature T_O according Eq. (1). The data used for T_O correspond to the room temperature for one day of holiday for the same period and similar weather conditions with the HVAC disconnected.
5. This is an air-conditioning load and therefore the data of the above parameter are for a summer day in the province of Almería (SE Spain).
6. For all cases, the price forecast (DAP) is adjusted to the one made by the operator of the Spanish electrical market (www.omel.es).

(a): Indoor Room Temperature



(b): Costs



(c): Power

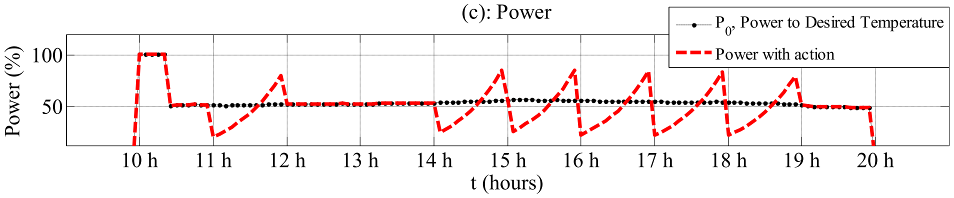


Fig. 3. Results of the control rule applied: (a) Indoor Room Temperature, (b) Costs and (c) Power.

3. Results and discussion

The first and third graphs of Fig. 3 plot the temperature and power of the HVAC, (Fig. 3a and c respectively). In black is the optimum desired temperature T_D, and the power necessary to achieve it, P_0, the baseline. The broken red line represents temperature and power resulting from applying the rule described. Fig. 3b shows the predicted cost (DAP) plotted in a solid blue line, gain of accumulation in a broken red line, and the gain of accu-mulation corresponding to a null action or of not acting according to the definition in Eq. (9), along a dotted black line.

By the application of the rule posed in Section 2.3, the power of the load follows the time course of the gain of accumulation (curved broken red lines in Fig. 3c and b respectively).

The action intervals are independent of each other as defined by the hypothesis, see Eq. (6). Thus the temperature of the load at the beginning and end of each hour, the action period defined since the gain of accumulating is continuous, is the same. Therefore, the action that takes place, for example, between 14 and 15 h is independent of the action that takes place just afterwards, between 15 and 16 h or in any other action period. This aspect is useful in terms of the unforeseen in planning the load; for example, if the load instead of being connected at 10 h is connected at 14 h the application rule from 14 h to 20 h does not change, as the application is over complete hours.

In addition, within the hour (or period of action), the user knows the null instant of acting and thus its gain of accumulation $g_{\mathrm{acc}}(k_N)$, for each hour. This, in the case of imbalances, enables knowing the starting point from which to reverse the action made up to that time.

Table 2 shows the cost reduction achieved, the mean square error of the temperature of the load and the maximum and minimum variations over the baseline case. Given that it was selected that T_h and T_{h+1} would be equal to T_D, the variation of temperature is positive in almost all hours of action (Fig. 3a). This can be improved by selecting temperature with a value lower than T_D in such a way that the maximum and minimum variations given in Table 2 are equal. Nevertheless, this improvement will be left for future works, as the present study focuses primarily on verifying how the power is modulated according to the function defined (Fig. 3b and c).

Many works (e.g. Berger and Schweppe, 1989; Jorge et al., 2000; Greensfelder et al., 2011) have applied RTP in thermal loads with energy accumulation, and specifically to air-conditioning loads. These have used approaches of multi-objective control that achieve similar cost reductions. Nevertheless, these approaches require the optimisation of opposing aims, such as the cost of the energy and the comfort of the user. Also, to evaluate the second objective, they use weighted coefficients adjusted by the user.

Agüero et al. (2013), in a bibliographic review of the above multi-objective approach, functions for evaluation of comforts against cost are proposed. Finally, it is up to the user to decide which of the two aims is preferable.

The latter justifies the importance and need of having simple rules as opposed to the multi-objective approach. The reason is that finally the user makes the adjustments through the corresponding weighting coefficients. Therefore, as the goal is to encourage an increase in the number of users participating in the management of the demand and thus foment the incorporation of renewable resources, it would be advisable to establish simple rules to apply with the greatest amount of information possible.

4. Conclusions

The new rule based on a geometric progression of day-ahead pricing (DAP) and intrinsic characteristics of the load, through evaluation and control of one simple thermal load, gives good results in simulation. The main advantage of the strategy proposed is that the user has an action criterion at all times. The rule requires little mathematical complexity for its execution, as it is of interest to reach the point of no action (no accumulation), after which the action on the power changes sign. Given the simplicity of the rule, this can be applied even to domestic loads and/or to unspecialized users. This could enable an increase in the management of the demand, in this case according to the profit function of the accumulation presented, encouraging the real penetration of renewable energies and contributing to the generation of clean and sustainable energy.

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