THERMO-ELECTRICAL LOAD MODELLING OF BUILDINGS FOR ASSESSMENT OF DEMAND RESPONSE BASED ON HEATING VENTILATION AND AIR CONDITIONING (HVAC) DEVICES

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ABSTRACT

This paper presents a thermo-electrical modelling approach for demand response services through Heating Ventilation and Air Conditioning (HVAC) systems.

The starting point of the approach is to gain insights on the heating and cooling energy required to keep a building at predefined temperature settings. These studies are supported by the simulation engine EnergyPlus, which is used to generate base-case (uncontrolled) consumption scenarios. Then, a number of different control actions are simulated to study how the energy demand and the indoor temperature profile of different buildings react to such control actions. In particular, the relations between user's comfort levels and temperature setting point variations and durations of the control are explored for different types of buildings.

In order to move from thermal loads to electrical loads, synthetic and general models of reversible HVAC devices are developed through a so-called black-box approach, whereby input-output functions are generated to link the equipment performance to indoor and, more important, outdoor temperatures in both heating and cooling operation. A mathematical formulation of these performance functions is developed from real data available in table form from manufacturers' catalogues.

A demand side management (DSM) scheduling algorithm is finally presented. It allows selection of an optimal combination of control strategies for the different devices involved in the analysis. In particular, the algorithm is able to select type, number, and duration of operation of the HVAC systems so as to maximise the sought benefits, e.g., support of system balancing task, network constraint management, and so on. This can ultimately lead to facilitate efficient integration of intermittent generation and enhance the utilization of existing network assets.

INTRODUCTION

Power systems are typically operated so that the amount of available generation capacity that can be called upon in relatively short time is always greater than demand. This is to ensure that, should any unforeseen events such as loss of a power line or of a generator occur, there is enough spare generation capacity available to meet the demand. In times when power demand is high, relatively inefficient fossil fuelled power plants are fired up and kept running at low utilization (and efficiency) to provide spare capacity. This spare capacity (reserve) is used to "balance" the system for unforeseen changes in load or generation and is a traded commodity in the system balancing market. With increasing penetration of wind power, then, additional reserve capacity is envisaged to be needed to manage the uncertainty due to wind forecast, with further decrease in the system operational performance and utilization.

It is now widely accepted that Demand Side Management (DSM) – whereby a portion of power system load is modulated to change the overall demand according to specific needs – can offer a viable alternative to increasing generation power needed for short and long term system balancing. This can contribute to offsetting a large amount of carbon emissions relevant to reserve plant operation and to decrease installed capacity of peaking plants that could be substituted by demand reduction measures. In particular, DSM is foreseen to be able to offer relevant flexibility needed to manage the variability associated with intermittent renewable generation such as wind, solar and marine power. This aspect will become increasingly important in the context of the European and UK targets of CO_2 emission reduction.

Among possible options and technologies for DSM, electro-thermal loads such as Heating Ventilation and Air Conditioning (HVAC) devices could represent important players in the market. In fact, owing to the thermal inertia intrinsic in the building fabric, it is possible to change the thermal generation (and then electrical consumption) of HVAC devices for a certain amount of time without affecting significantly the users' comfort level. Such control actions could be deployed to provide system services such a reserve or peak management. Hence, although an increase in demand for air conditioning systems, even in mild climates, and the perspective of shifting from fuel-based heating to cleaner electric heating (for instance, based on heat pumps) would lead to higher energy demand, it would also give an opportunity to better manage the system through DSM.

Characterisation of the electro-thermal load flexibility for given users, building types and weather conditions consists of establishing the relationship between extent and duration of control actions and acceptable comfort level modifications (which represents the main constraint to flexibility). On these premises, this paper presents the general approach to electro-thermal characterization and modeling of HVAC devices for DSM applications. The analysis of energy consumption and power/comfort level relations for different control actions is based on utilization of the EnergyPlus software tool for building thermal simulation. A black-box approach is then presented that models the performance characteristics of HVAC devices in both heating and cooling operation. A DSM scheduling algorithm is finally presented, with specific application to peak lopping.

THERMAL LOAD MODELLING

Thermal loads of buildings are modelled in terms of the energy consumption required to keep buildings at prescribed temperature settings. This modelling is based on simulation programmes that solve classical heat balance equations from heat transfer theory. In particular, the studies carried out here deploy the software EnergyPlus [1], supported by a user-friendly interface called DesignBuilder [2]. These well-proven software tools have the ability to model building thermal behaviour in a number of conditions. More specifically, besides assessing the steady-state thermal requirements of a given building, which is a common characteristic of several commercial tools, the software package used is able to simulate thermal dynamic response to different control actions (particularly, temperature setting change and on-off operation of the HVAC system) carried out on the HVAC system. Specific aspects that can be adequately captured by the software regard the assessment of the peak thermal requirements when the HVAC system picks up the load (typically in the morning), as well as of the energy pay-back phenomenon when given control actions are released. In addition, while simulating the various control actions, it is borne in mind not to breach minimum comfort levels required by the user. The correct understanding and modelling of these phenomena is crucial to guarantee the appropriate use and appraisal of DSM.

BUILDING CHARACTERISTICS

General information on UK dwelling dimension and construction types can be found in [3]. Statistical data [4] provides the number of building and building type. Typical occupancy periods and construction of UK buildings are taken from DesignBuilder template [2]. Likewise for domestic buildings, for illustrative purposes the number and the total floor space of office buildings and retail stores are available from statistical data [4]. These average models worked out have been drawn in DesignBuilder and used as EnergyPlus inputs to derive base cases of buildings. Average characteristics for the city of London are shown in Table 1.The three building types in table 1 have been implemented in DesignBuilder and EnergyPlus software to generate typical thermal load characteristics. The simulations are set up from a designated day of minimum and maximum temperatures. London Gatwick weather data is used for the simulation. The typical heating and cooling energy demand profiles of all buildings in the low- and high- temperature designated days are given in figure 1 and 2. The cooling system load patterns exhibit different shape from the heating load patterns. More specifically, the heating load profiles have a peak at the morning when the outdoor temperature tends to be the lowest. On the other hand, the cooling load profiles are peaky at the early afternoon when the outdoor temperature is the highest. In addition, for different buildings different cooling and heating set-points of each building type result in different amplitude of the thermal load profiles. Besides this, the amplitudes of all load profiles are dependent on the building floor areas and physical construction. In particular, the major factor driving heating and cooling energy demands is related to the size of the building: with the same building construction: the larger is the building size, the greater is the energy consumption. Figure 1 and 2 show that offices consume the highest energy demand in winter following by retail stores and houses respectively.

Table 1 Typical London building characteristics.

Type	Detached-House	Office	Retail store
Number of storey	2	4	1
Floor area (m^2)	85	341	163
Dimension of each storey (m)	8.5 x 5 x 3	8.5 x10 x 3.5	12.7 x 12.7 x 3
Heating setpoint (°C)	20	22	20
Heating setback (°C)	14	12	12
Cooling setpoint (°C)	25	24	23
Cooling setback (°C)	28	-	-
Setpoint period	6am - 11.30pm	6am - 7pm	7am - 7pm
People density (people/m^2)	0.03	0.11	0.11
Construction type	Reference Medium weight		
Glazing type	Double glazing		

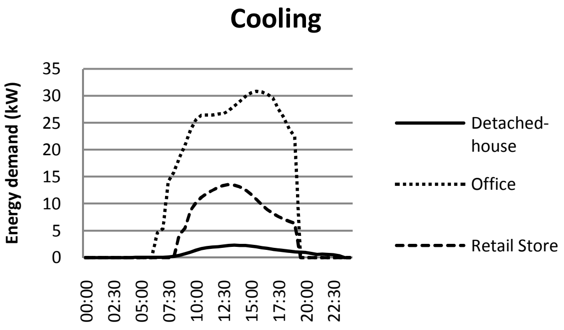

Figure 1: Cooling load profiles of different buildings in London summer design day

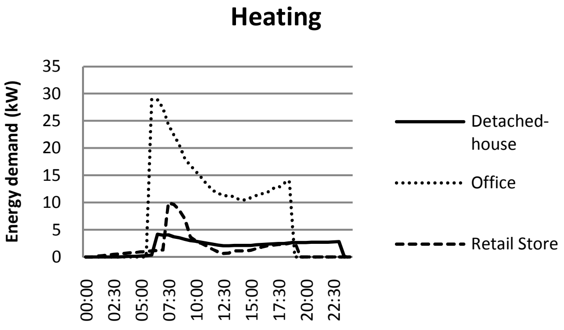

Figure 2: Heating load profiles of different buildings in London winter design day

GENERIC MODEL OF HVAC DEVICES USING A BLACK-BOX MODEL APPROACH

A relatively simple (but effective for system-level studies) approach to model an Electric Heat Pump (EHP) is based on having, starting from internal thermal requirements and temperature conditions, a simplified model of the Coefficient of Performance (*COP*) as a function of outdoor temperature and load as shown in figure 3. More specifically, *Wt* and *Wc* represent electrical energy demands for heating and cooling, *Q* and *R* are the thermal and cooling energy required by the building, *T* generally indicates outdoor and indoor temperatures, *COPt* and *COPc* are the coefficients of performance of the EHP for heating and cooling modes, respectively. A straightforward input/output backward approach is then adopted whereby, starting from the required output (thermal energy demand – the load as given in output by EnergyPlus simulations, for instance) and temperature characteristics (indoor and outdoor), it is possible to calculate the energy input (electrical energy required by the EHP to generate the needed thermal energy, whether for cooling or for heating).

In order to endeavour to develop generic and synthetic black-box models without drifting from the real behaviour of devices, real data from existing equipment has been used. In particular, from real data available from manufacturers' catalogues it is possible to create a black-box model based on the given curves or tables of *COP* and capacity as a function of outdoor and indoor temperature.

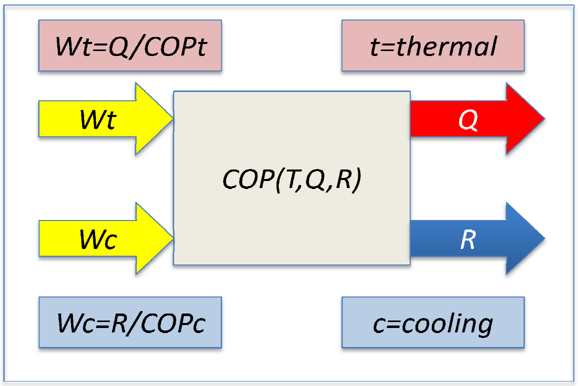

Figure 3: Black-box approach for HVAC performance modelling

Cooling and heating *COP* black-box models have been derived here by applying a multiple linear regression technique. More specifically, multiple linear regressions are used to find the relation between indoor temperatures, T_i, outdoor temperatures, T_o, and cooling and heating *COP*. The multiple linear regression relations can be written in the form:

$$COP_{cooling}(T_i,T_o) = C_0 + (C_1*T_i) + (C_2*T_o) \quad (1)$$

$$COP_{heating}(T_i,T_o) = H_0 + (H_1*T_i) + (H_2*T_o) \quad (2)$$

where $H_{[0,1,2]}$ and $C_{[0,1,2]}$ represent the characteristic coefficients found from the regression exercise.

DSM MODEL

A DSM algorithm has been developed to determine the optimal load control schedules of groups of building HVAC devices. More specifically, Cobelo's formulation optimization problem [5] is implemented using a linear program, and specific modifications have been carried out to adapt the problem and the solution to maximum peak demand reduction over a certain time period. Crucial inputs to the algorithm are a possible control action set to be applied to the HVAC devices of the buildings. In this respect, variation in the thermostat temperature setting is a typical and straightforward control action that could be implemented while keeping track directly of the comfort level of the building's occupants. As mentioned above, the relationship between the comfort level and the temperature setting, the duration of the control, and the building insulation level, are thus investigated by EnergyPlus simulations.

By giving the original electrical demand profile in a region, electrical demand profiles of HVAC devices with and without possible control actions of each building groups, and the number of buildings in each groups as inputs, the algorithm is able to select the optimal number of each control action type for each building group to achieve maximum peak reduction. The outputs of the model are the after controlled electrical demand profile of HVAC devices and their optimal control action set.

CASE STUDY EXAMPLE

Offices have a high potential to benefit from the installation of control equipment and air-conditioning systems. Therefore, a case study of control actions for offices is investigated. All the offices in this case study are assumed to have the same characteristics as shown in table 1. The control actions for cooling and heating for all office buildings consist of:

1) Increasing (for cooling)/Decreasing (for heating) the temperature setting by 3°C for 1 hour,

2) Increasing (for cooling)/Decreasing (for heating) the temperature setting by 2°C for 1.5 hours; and

3) Increasing (for cooling)/Decreasing (for heating) the temperature setting by 1°C for 2 hours.

This information needs to be processed so as to break it down into all control possibilities. The control action period is 10.30 – 12.30 and 16.30 – 18.30 for the summer and the winter peak loads, respectively. Electrical consumption of an office cooling/heating when control strategies are performed, and the energy pay-back phenomenon when given control actions are released are highlighted in figure 4 and figure 5.

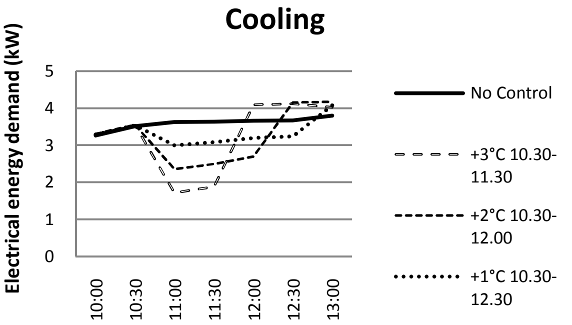

Figure 4: Electrical consumption of an office with and without control strategies (cooling)

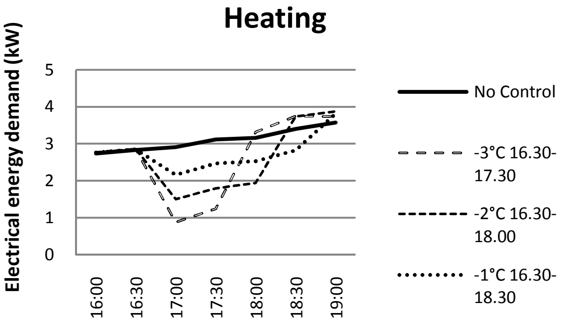

Figure 5: Electrical consumption of an office with and without control strategies (heating)

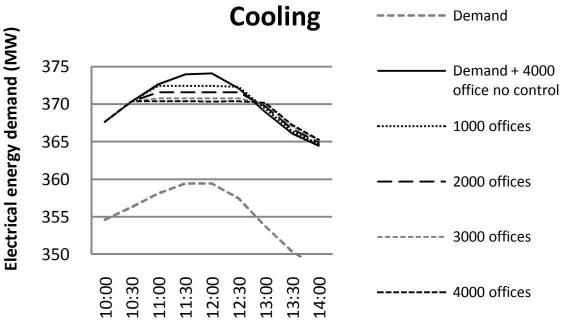

Figure 6: Regional electrical demand with and without control strategies (cooling)

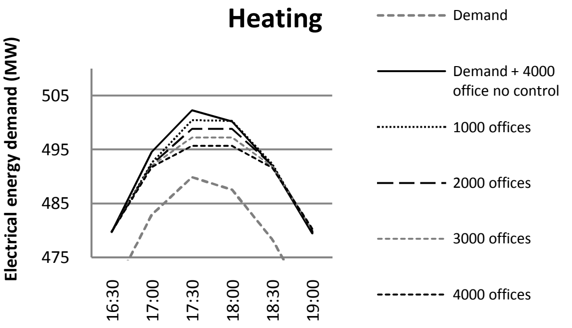

Figure 7: Regional electrical demand with and without control strategies (heating)

Figures 6 and 7 show the effect of adding the HVAC demand of 4000 offices on top of a regional summer and winter electrical base demand, respectively. In addition, the peak reduction effect from performing control strategies when 1000, 2000, 3000 and 4000 offices can be controlled is shown. As it could be expected, a higher number of offices that can be controlled leads to higher peak demand reduction. However, a saturation effect, particularly for cooling, can be noticed, meaning that incremental addition of controllable devices bring smaller benefits.

CONCLUSIONS

In this paper, detailed modelling of the thermal energy consumption (heating and cooling) required to keep a building at predefined temperature settings has been shown. The study is supported by the well-proven software tools EnergyPlus and DesignBuilder, which have the ability to model building thermal behaviour under various steady-state and dynamic situations.

Based on numerical simulations, thermal loads for different typical building types (residential and commercial premises, particularly) have been modelled. The thermal behaviour of heating and cooling systems and the building response under different nominal and DSM-controlled conditions have been analysed, with the specific aim of getting insights in the change in the comfort level and the energy payback phenomenon. A generic model of heating and cooling devices has been developed to characterize the performance of HVAC plants. Real data available from manufacturers' catalogues have been used to tune the model parameters. Finally, in a case study application it has been shown how, through a specifically developed algorithm, a large set of HVAC devices could be controlled to provide peak minimization services at a local level, while keeping track of the indoor comfort level in office buildings, Starting from the model shown in this paper, works in progress are aimed at estimating the potential of HVAC devices to provide other system services, particularly for frequency regulation and balancing.

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