INVESTIGATION OF THERMOSTAT-SET CONTROL AS A NEW DIRECT LOAD CONTROL METHOD

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Abstract

The goal of Direct Load Control is to reduce daily peak demand and to maximise the utility profit with least reduction of discomfort caused to consumers served. In this paper, a new Direct Load Control method called Thermostat-set control is presented. Thermostat-Set Control method is based on the direct access to the thermostat of consumer's load from the distribution management center or dispatch center. Controlled consumer's load is usually a heater or an air conditioner. This new control method is simulated by using a physically based load model, which accounts the behaviour of the thermostatically controlled loads in the distribution system. Thermostat-Set Control method is compared to Load Cycling Control method and conclusions are presented.

Keywords: Demand-Side Management, Direct Load Control, Load Modelling, Load Cycling Control method, Thermostat-Set Control method.

I. INTRODUCTION

Demand-Side Management could be defined as planning and implementation of the utility activities, which are designed to influence customer use of electricity, in ways that will produce desired changes in the magnitude and shape of utility's load. Change of load shape may be needed to meet peak demand or to respond flexibly to the price change in the deregulated power markets without constructing new power plants.

Load Control is an application of Demand-Side Management. Load Control has different aspects such as reducing peak demand, maximising utility profits and minimising discomfort caused to customers. Load control programs are being developed to help utilities use their generation facilities more efficiently. These systems will shift load to off-peak times or actually reduce the amount of electric energy required. Load control can be classified into two groups; indirect load control and Direct Load Control (DLC). Indirect load control is applied upon a contract between the customer and the electric utility company; which offers customers different time-of-day tariffs for the use of electricity. Many works have been done in the literature dealing with the demand side management [1-6].

There are two different groups of individual loads in distribution systems; thermostatically controlled and manually controlled loads. Thermostatically controlled loads are switched to on state or to off state depending on the set values and dead bands of their thermostats. Manually controlled loads are switched on and off by occupants of the house in undetermined fashion. The lifestyle of the occupants of the house has a significant influence on the contribution of these loads to the total load of the house.

In DLC, thermostatically controlled loads are preferred because these loads could be interrupted for a short duration without leading to a significant decrease in the comfort level of customers. There are many studies on modelling these types of loads [7-12]. The concept of load model is important because it enables to estimate the possible effects before control is applied on a real system. Therefore, the load model should be expected to reliably reflect the dynamics of the devices. Load models can be categorised into two groups; statistically based and physically based load models. Load models based on statistical analysis of historical data may not reflect the effects of load control applications. But, physically based load models may reveal the effects of load control actions in a distribution system. Another feature of physically based load models is that, the effect of model parameters on the aggregated load could also be analysed easily.

In this paper, a new DLC method called Thermostat-Set Control (TSC) method is presented. First, the first-order time-varying differential equation model is adapted. Then, the first-order time-varying load model is converted to a discrete time model and simulated by using Monte

Carlo method developed with C programming language [13]. Also, Load Cycling Control (LCC) method is simulated and compared to TSC method. The results of the study are summarised in the conclusion part of the paper.

II. DYNAMIC OF AN AIR CONDITIONER

The load model presented by Ihara and Schweppe [12], as a first order hybrid differential equation, is given in Equation 1 below.

$$\frac{d\theta(t)}{dt} = -\frac{1}{\tau}\left[\theta(t) - \theta_a + w(t)\theta_g\right] \qquad (1)$$

Here, the parameters are as follows; $\theta(t)$ (^{o} C) is the inside temperature of the house, θ_a (^{o} C) is the ambient temperature, θ_g (^{o} C) is the temperature gain of air conditioner, and τ (hr) is the time constant of the house. The variable $w(t)$ is a binary variable denoting the state of the air conditioner. When the air conditioner is off its value is zero and when it is on its value is one. The state of an air conditioner changes when the temperature of the house reaches the thermostat upper or lower limit, given by $\theta_s + \Delta/2$ and $\theta_s - \Delta/2$, respectively. When the inside temperature of the house reaches the upper limit, air conditioner state changes from zero to one, and when the lower limit is reached, the state changes from one to zero. Figure 1 shows the state of thermostat and the house temperature as a function of time when the ambient temperature is constant.

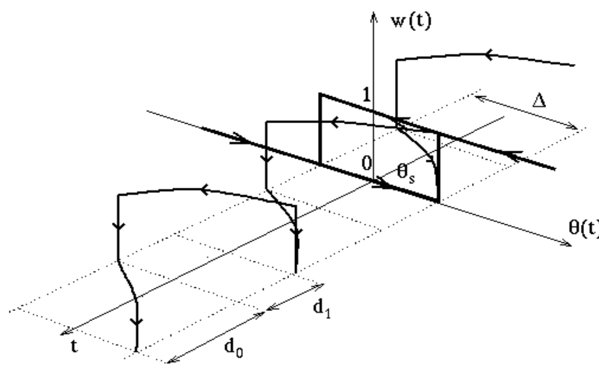

Figure 1. The state of thermostat and house temperature as a function of time during steady state ([14], page 15).

In Figure 1, a three dimensional picture of an air conditioner dynamic is shown for steady state. The hysteresis loop of thermostat state can be seen when it is looked to the figure from the time axis direction and the change of temperature of the house can be seen when it is looked from the direction of $w(t)$ axis.

III. STOCHASTIC DIFFERENCE EQUATION MODEL

There are many different load models that can be used to account for the behaviour of thermostatically controlled loads starting from a very simple first order differential equation model to much more complex higher order models, statistical aggregated load models, or stochastic difference equation model. Stochastic difference equation model is derived from the first order hybrid differential equation given by Equation 1. The significant difference of stochastic difference equation model from the other types of load models is that it is suitable for the computer analysis. Thus, in Monte Carlo simulation houses are modelled with stochastic difference equation shown in Equation 2 and Equation 3, below. Equation 3 models the thermostat state change when the temperature of the house reaches the upper and lower limit of the dead band. The assumption is that the thermostat always switches exactly at sampling instants. Time, *t*, is made discrete by using a sampling period *h* with the notation $a = e^{-h/\tau}$ and $b = 1 - a$ as in reference [11], the difference equation for air conditioner load will be

$$\theta[(n+1)h] = a\theta(nh) + b\left[\theta_a - c(nh)w(nh)\theta_g\right] + V(nh) \qquad (2)$$

$$w[(n+1)h] = \begin{cases} 0, & if\ \theta(nh) < \theta_s - \Delta/2 \\ 1, & if\ \theta(nh) > \theta_s + \Delta/2 \\ w(nh) & Otherwise \end{cases} \qquad (3)$$

In Equation 2, *V(nh)* is a Gaussian white noise discrete time process with zero mean. DLC actions can be incorporated to Equation 2 and Equation 3. For LCC control action, the term $c(nh)$, which is a binary variable, can be used to simulate the control action send from the distribution management center or dispatch center. Also TSC action can be simulated by changing the thermostat set value θ_s in Equation 3.

IV. LOAD CYCLING CONTROL AND THERMOSTAT-SET CONTROL METHODS

LCC method is a commonly used method to reduce daily peak demand. The cycling is accomplished by the signal sent from the control center to the groups of thermostatically controlled loads. The principle of LCC method is first grouping the devices and then switching one group of devices to off state for certain duration. All groups are switched off in different time intervals. For example, if four groups are exist, each group will be switched off for 15 minutes, that is, the period of cycling is one hour so that each group will be off 15 minutes and will be left alone for 45 minutes to continue its natural cycle. In the following 15 minutes, the next group will be switched off and this cycle will continue until to the end time of control period. Figure 2 shows the LCC Method applied to one thermostatically controlled device. When the device is forced to switch off then there will be a payback duration to recover the interrupted energy as shown in Figure 2. One of the successful studies on application of DLC in distribution systems had been done by South California Edison Company [1]. In this study, controlling 100,000 air conditioner from the center, by offering 50%, 67%, and 100% control alternatives to the customers had reduced the peak in the system. The consumer air conditioners were interrupted in-groups at different times.

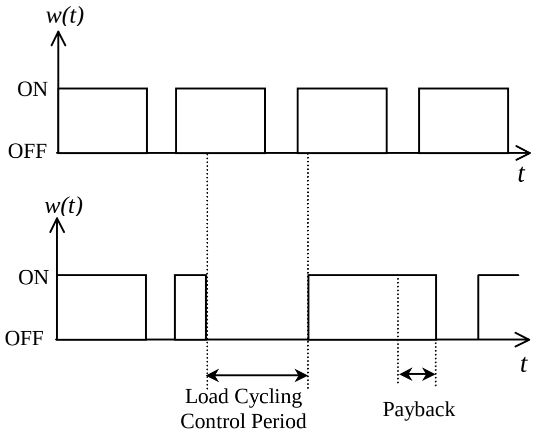

Figure 2. Principle of LCC method.

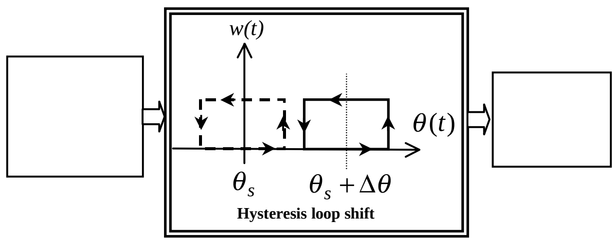

Figure 3. Principle of TSC method.

Termostat-Set Control method introduced in this paper is also a DLC method. The principle of the method hides behind the adjustment of the temperature set value of the thermostat of the controlled devices. To achieve this, it is assumed that the thermostat set values of thermostatically controlled devices can be adjusted from control center. The adjustment of the temperature set value is sent as a signal from the electric utility, to all of the controlled air conditioners, that is, the devices allow their set values to be changed from a remote center. Figure 3 shows the principle of TSC method. In Figure 3, a signal from the distribution center is sent to the air conditioner to increase its temperature set value by $\Delta\theta$. The new temperature set value will be equal to $\theta_s + \Delta\theta$ and hysteresis loop will shift to the left as shown in Figure 3. This will result with the reduction of consumed power of air conditioner. In this study, air conditioners, which are thermostatically controlled loads, have been chosen as the controlled loads in a distribution region. Control signal sent from the center to increase the temperature set values of air conditioners will reduce the aggregated load in the system. Objective of TSC method is to achieve a significant reduction in daily peak load while minimising the decreased comfort levels of customers caused by the control action. Comfort level of customers is important in today's utilities because of the competition introduced as a result of deregulation. The competition among the electricity suppliers and providers are tough, therefore the electric utilities now pay more attention to their customer's needs.

V. MONTE CARLO SIMULATION

Temperature histograms and graphs of total power change had been analysed using Matlab and it had been observed that the temperature-set control method is effective in reducing peak power as well as maintaining the comfort level of customers [13]. But, these results can not be accepted for getting a statistical conclusion about this method since the simulations are made for only forty houses. Therefore, there had been a need for a larger system to be studied. Thus, Monte Carlo simulation had been studied for 10,000 houses.

Monte Carlo simulation had been done using C programming language. 10,000 houses had been simulated with this program. Each house is modelled with stochastic difference equation as given in Equation 2 and Equation 3. LCC and TSC methods had been simulated for the parameters given in Table 1. In Table 1, the mean and the variance of the parameters are shown. The mean and the variance are used in a gauss random generator to generate parameter values, specific for each house to account for the diversity of the system. That is, 10,000 houses will have different values for their parameters.

Table 1. Parameters of stochastic difference equations for 10,000 houses.

Parameters	μ	σ
V	$0\ ^{o}C/min$	0.1
θ_s	$20^{o}C$	1.41
θ_g	$20^{o}C$	6.00
Δ	$2^{o}C$	0.3
τ	120 min	20

LCC method, which the applications to a true system exist in some utilities, and new TSC method are compared in Figure 4. Both LCC method and TSC method are applied between the times 11:00 and 23:00. In

Figure 4, the normalised load change without any control action is shown as NoC to have as a reference for the controlled cases.

In LCC method, 10,000 houses are divided to four groups of each having 2500 houses. Each group are controlled for 15 minutes in consecutive time segments and released for 45 minutes to continue to their natural cycle. The normalised load change for the control action is shown in Figure 4 as CycC. With this LCC method the peak load has been reduced by 15% approximately. There is load deep at the beginning and payback at the end of entire control period. But, these load transients are not very significant and especially they do not exceed the peak load during the control period.

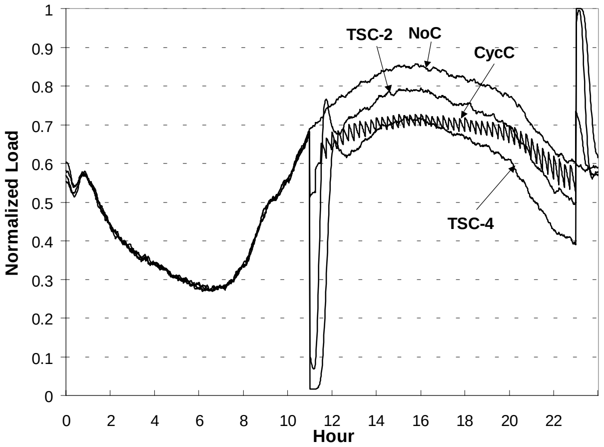

Figure 4. Normalised load change when LCC and TSC methods are applied.

TSC method is simulated for two different thermostat-set values. The first one is when the thermostat-set values of the houses are increased by 2 ^{o}C. The resulting load change is shown in Figure 4 as TSC-2. With 2 ^{o}C control, approximately 5% load reduction is achieved. The second simulation for TSC method is done with 4 ^{o}C increase in thermostat-set values of the houses. In this case, the normalised load change is decreased around 5% more during the entire control period as shown in Figure 4 with legend TSC-4. The LCC method (shown as CycC) and TSC method (shown as TSC-4) give approximately the same peak value in the control period considered. Especially, the normalised load change between the times 14:00 and 16:00 is comparable for both of the control actions. In TSC method, the load deep at the beginning and the payback at the end of the control action are more than those of the LCC case. When the control is applied, the aggregated load approximately becomes zero and when the control is finished, the payback magnitude reaches the maximum value of 1. The reason for that is because the thermostat-set values of whole air conditioners increased by 4 ^{o}C and this caused the house temperature values to be less than the upper limit of the dead band in the beginning of the control duration. Thus, air conditioner's states for the most of the houses became zero. Also, similar conclusion can be drawn for the payback magnitude. Grouping the air conditioners as it is done in LCC method can reduce these unwanted high magnitudes. In this paper, customer comfort level is considered, therefore methods which deal with the reduction of magnitudes are not studied.

Application of load control to the customers will affect their house temperatures. In the air conditioner case, it will increase the average temperature inside the house. Thus, the comfort level of the customers will be reduced accordingly. For 10,000 houses, it will be interesting to see the distribution of the house temperatures when the control methods are applied. This will give an indication of how much the temperature distribution has shifted and changed when the control is applied. Causing too much increase in the house temperatures results with many unsatisfied customers and it could danger the load management program. The distribution of house temperatures of the 10,000 houses is shown in Figure 5 for uncontrolled (NoC), LCC (CycC), and TSC cases. The distribution of house temperatures shown in Figure 5 can be closely represented with Gamma distribution. The distribution of TSC of 4 ^{o}C is similar to that of the uncontrolled case with approximately 4 ^{o}C shift to the left. The distribution of temperatures in LCC method is wider and it has more houses with higher temperatures over 26 ^{o}C when it is compared to the TSC-4. The number of houses with lower temperatures is also higher in LCC method compared to that of TSC case. The success of load management program is more affected by the higher temperature region because customers with higher temperatures will complain more and may give up to participate in load management program. Thus, utilities should be careful on deciding what type of control action must be performed to keep customers satisfied.

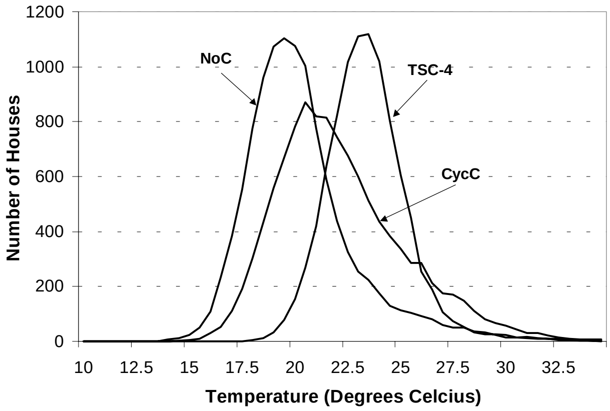

Figure 5. Temperature distribution of 10,000 houses at 4 pm when LCC and TSC methods are applied.

Both TSC and LCC methods reduce the peak load when control is applied. The magnitude of load reduction depends on both to the system parameters and to the control strategies applied. In LCC method, the number of houses with higher temperatures may be larger than TSC method. Therefore, it may cause more customer related problems to the utilities. A utility should carefully examine the options for DLC to reduce the number of unsatisfied customers as an outcome of the load management program.

Application of TSC action may result over-reduction of the load in the beginning and high payback at the end of the control duration as it is mentioned before. Two solutions to this problem may be used. First solution may be the application of TSC in a whole day that prevents the payback that leads to a severe peak as stated above. But this is not a suitable solution because the customer's would be facing higher temperatures as a result of the load control application even at the night times. Although load control is not needed at night times of a day, as the temperature is not as high as the daytime, control would lower the comfort level of customers. The other solution may be grouping of the houses. Grouping would lower the number of interrupted houses in certain intervals of time and this will result with the smaller over-reduction and payback.

VI. CONCLUSION

It is observed that new Thermostat-Set Control method is effective in reducing peak power in noticeable rates. The study pointed out that TSC application can be better than the LCC case in higher temperature range. In other words, the number of houses with higher temperatures is less than that of LCC. This is an important result because the success of DLC depends on the number of satisfied customers. Load management procedures must reduce the number of unsatisfied customers to be able to use the peak load reduction methods. Customers can tolerate the increases in lower temperature region, this may not cause an uncomfortable situation, whereas the increases of temperature in higher temperature region may become intolerable for customers and they may reject the DLC to their appliances. Thus, the paper concludes that TSC method reduces (compared to LCC method) the number of houses at higher temperature region when the DLC action is applied to the customers.

The work is continuing to incorporate TSC and LCC. A better control strategy is searched both to reduce the load deep and payback magnitudes and to minimise the comfort level reduction caused to the customers.

Acknowledgment:
This study is sponsored by the Graduate Thesis Support Program of Institute of Science and Technology, Istanbul Technical University.

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