

Safe Control of Thermostatically Controlled Loads with Installed Timers for Demand Side Management

by

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Abstract

Motivated in part by the expanded use of renewable power generation, which are often non-dispatchable and intermittent, we examine the role of electric loads in providing ancillary services for demand side management. A large ensemble of thermostatically controlled loads (TCLs) can provide ancillary services and help balance generation and demand.

In this thesis we model and control the aggregated power consumed by a large ensemble of TCLs like air-conditioners. We develop safe protocols for thermostatically controlled loads (TCLs) to provide power pulses to the grid without a subsequent oscillatory response. Such pulses can alleviate power fluctuations by intermittent resources and maintain balance between generation and demand. A power pulse in either upward (rise) or downward (drop) direction can be generated by signaling the TCLs to turn on or off. The width of the pulse depends on the time for which the fluctuation occurs and the magnitude of the pulse depends on the size of the ensemble. Thus, by generating pulses of varying magnitudes and widths we can offset fast time scale fluctuations in the power grid.

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In loving memory of

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Also dedicated to my brothers and sisters

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Introduction

With the increase in global population, the demand for energy is also increasing. Most of the electrical energy is supplied from fossil fuels, predominately by coal and natural gas. These sources of energy do generate power in bulk but also lead to carbon emissions and emit other pollutants. Alternative sources of energy to generate electricity are being developed and a lot of research has been carried out since past few decades on integration of renewable energy sources like wind and solar power with the power grid.

With increasing penetration of intermittent sources of energy, the most important issue is Grid Reliability. If generators fail to match sudden fluctuations in demand, it can lead to loss in synchronism and hence frequency will deviate from 60 Hz, which can result in cascading failure. Due to several supply side issues, controlling electric loads on demand side to balance generation and demand is currently being investigated. Various demand side management (DSM) programs have been implemented in recent years to motivate the customers to participate and use energy efficiently by consuming less power during peak demand. Although, these programs have not been successful on a large scale, but their implementation have helped gain some insights on problems and scope of improvement in implementing them. Ensuring cost-effectiveness and the ability to control peak energy demand are most important factors that can guarantee successful implementation of DSM programs. For reference, various demand side management alternatives have been explained in [1].

DSM alternatives not only provide functions to the utilities like peak shaving and load filling but can also benefit customers by giving them more control over their electric costs. Load Management is a DSM technique which offers an alternative to control the power consumed by

large group of electrical loads. One such class of electrical loads are thermostatically controlled loads (TCLs). Thermostatically controlled loads are ON/OFF loads [2–23]. The turn on and turn off of TCLs depends on their duty cycle. Air-conditioners, refrigerators, space heaters and water heaters are thermostatically controlled and can provide ancillary services to balance generation and demand [1], [10], [18], [22], [24–34].

TCLs are considered as appropriate candidates to provide ancillary services for two main reasons: 1) around 50% of electricity in United States is consumed by TCLs like air-conditioners and water heaters, 2) their inherent ability to store thermal energy [17]. According to US Energy Information Administration [35], the American household units that have air-conditioners has increased from 68% in 1993 to 87% in 2009 with 65.1% of all occupied homes in US having central air-conditioning units. In China alone, over 50 million of air conditioners are sold annually [36]. When the power response of millions of air-conditioners is aggregated over a large city, the available power that can be controlled can be of the order of gigawatts [12], [17], [19]. Thus, it is evident that there exists a huge potential to control power of the order of hundreds of megawatts to gigawatts.

It is imperative to understand the dynamics on the time scales of seconds to minutes for analyzing the stability of the system. As TCLs are able to respond to control signals faster than spinning reserves [32], [34], [37–39], they can help to stabilize the power balance in the grid by offsetting sharp power fluctuations at time scales of minutes [19], [34]. The potential of TCLs to assist in controlling the power grid by varying their temperature set points has been discussed in a number of publications [5], [14], [16], [17], [20], [21].

A major challenge to achieving control over a large ensemble of TCLs is the wide distribution of parameters such as thermal resistance, thermal capacitance, set-point, ambient temperature, duty cycle and the power consumed when an air-conditioner is in the ON state. It was discovered in numerical studies that, because of the lack of complete information, it is hard to avoid unwanted power oscillations lasting for several hours [17], [20], due to synchronization of TCLs by the external control signals. A number of possible solutions have been proposed such as stabilizing feedback signals [34] and randomization [40]. It seems, however, that such strategies are limited by the requirement of having the ability to obtain and process considerable information about all TCLs available.

Recently, new strategies, referred to as the safe protocols (SPs), were shown to effectively resolve the problem of unwanted power oscillations [12], [19]. The idea of a SP is to add additional memory and instructions to the endpoint TCL temperature controllers so that TCLs are able to identify specific states and produce some of the operations, such as switching between ON and OFF, autonomously, i.e. without waiting for a specific external signal. The focus of research on SPs has been on strategies to shift temperature set points of TCLs. However, the idea of SPs is not restricted by instructions for temperature shifts.

The aim of this thesis is to explore alternative approaches to constructing safe protocols such as adding timers at the endpoint TCL temperature controllers in order to generate on-demand power outputs by TCL ensembles while having minimal information about the aggregate TCL ensemble parameters. Specifically, we will (i) propose a safe protocol not discussed in the previous papers [12], [19], that generates a power pulse using a timer, (ii) we perform simulations to demonstrate that timer-based safe protocols can be used to successfully eliminate

strong and short power fluctuations in the power grid and (iii) we explore the application of a safe protocol beyond the simple framework of a steady state equilibrated ensemble of TCLs.

The rest of the thesis is organized as follows. Chapter 1 illustrates the literature review. Chapter 2 describes the mathematical modeling of TCL and demonstrates the '*Unsafe*' set point change method to control the aggregated power. Chapter 3 describes '*Safe Protocols*' to generate power pulses. Chapter 4 demonstrates the versatility of safe protocols in offsetting fast time scale fluctuations. Chapter 5 explains the role of heterogeneity where ambient temperature is varying throughout the day, and the last section concludes the thesis.

Chapter 1: Literature Review

Author Goran Strbac in [30] explains several benefits and challenges of demand side management (DSM) identifying its potential role in improving efficiency of operation and investment in the system. Ageing assets, increased penetration of renewables, low-carbon generation technologies and an efficient and stable system operation are main reasons that have triggered research on DSM technologies. DSM not only helps reduce generation capacity by shifting loads from peak to off-peak but also helps maintain system stability on occurrence of a credible contingency. On the distribution side, DSM can help relieve voltage-constrained power transfer problems and congestion in distribution substations and allow increased integration of distributed generation. DSM will also enable customers to have a better control over their electricity consumption if some form of real-time pricing arrangements are made. However, this would require complex architecture that would allow trading energy online leading to a creation of electronic energy market system.

DSM changes the natural diversity of loads. As a result of which, the total load of the group of controlled devices will increase during the load recovery period. Thus, the corrective action provided by DSM tends to increase the complexity of system operation when compared with traditional solutions. DSM has not yet been fully integrated into the operation of electricity markets. Lack of metering, information and communication infrastructure, lack of understanding the benefits of DSM and the complexity involved in understanding the competitiveness of DSM when compared to traditional approaches are main challenges in successful implementation of DSM technologies.

In [17], authors explain modeling and control of homogeneous population of loads. Due to homogeneity, parameters like thermal resistance 'R', thermal capacitance 'C' and ON state power consumed 'P' by the TCLs, the duty ratio and the time period are same for all TCLs. The set point and the ambient temperature θ_{amb} is assumed to be constant. As noise is not modeled into the system, the TCL dynamics are constrained within the hysteresis band $[\theta_-, \theta_+]$ where θ_- and θ_+ are the lower and upper temperature dead band limits respectively and the set point temperature is set at the midpoint of the hysteresis band. The power consumed by individual TCL is cyclic in nature. The power consumed by a large ensemble of TCLs depends on the percentage of TCLs on at a particular instant. In steady state the number of TCLs in the ON and OFF state will be proportional to their respective cooling and heating time periods.

The paper explains the variation in aggregated power consumed by a large ensemble of homogeneous population of TCLs when a small change in set point is applied. On changing the set point the dead band is also shifted to new values $[\theta_{n-}, \theta_{n+}]$. After the set point change is applied, the TCLs that are in OFF state will continue in OFF state till the temperature of the room has reached to θ_{n+} , while the TCLs that are ON and having temperature greater than that of θ_{n-} will continue to be in the ON state till the temperature of the room has reached θ_{n-} at which point TCL will turn OFF and will then operate according to the new dead band limits. However, TCLs that are in ON state and have temperatures between θ_- and θ_{n-} will turn OFF at the instant the change in temperature set point has been applied.

If the set point temperature is increased by a small amount, it can lead to a sudden and a sharp drop in aggregated power consumed due to sudden switching of TCLs from ON to OFF state where as a decrease in set point temperature will lead to an increase in power consumption

due to sudden switching of TCLs from OFF to ON state. As the population is homogeneous, oscillations are observed and lasts for a longer time. A large set point change can not only lead to large power oscillations but can also lead to consumer dissatisfaction. Such 'unsafe' control strategies should be avoided to ensure grid stability.

The paper also derives the transfer function for the aggregated power response when a set point change is applied. The response is linearized and linear quadratic regulator (LQR) is designed. Thus, having TCL set point as the control input, the LQR enables aggregated power to track reference signals. If the train of short width pulses that cause a temperature set point change is applied, it is observed that the energy consumed by the TCLs is negative implying that the energy is delivered by TCLs. This property can be used to compensate for any unbalance in generation.

The paper by Wei Zhang et.al [20], proposes a method to develop aggregated model of heterogeneous population of TCLs. As the population is heterogeneous, the parameters R , C and P are different for different loads. However, for a very large population, we can assume there can be several TCLs with similar parameters. The aim of the paper is to understand the aggregated behavior under demand response. This is accomplished by capturing the dynamic behavior accurately by considering the second order effects. The paper considers an Equivalent Thermal Parameter (ETP) model of home heating/cooling system and models the second order dynamics by considering the influence of temperature of the solid mass inside the room on the room temperature. Parameters like inner mass temperature, conduction between inner air and inner solid mass, heat flux into the interior air and solid mass are considered to incorporate second order dynamics in the model.

The model developed is able to capture oscillations that are introduced by a set point change and can effectively account for both steady state and dynamic behavior. The air and mass temperature range are divided into equal number of bins. Every bin has a (normalized) density function associated with it that tells us the probability of the load population whose air and mass temperature are within a particular interval. The rate of transportation of population in some bin 'l' to bin 'k' is then calculated. In order to account for the effect of heterogeneity, different parameter vectors θ are formed. Then using k-means algorithm, these parameters are classified into ' N_c ' clusters, each having a centroid C_i such that all similar parameters are grouped together in one cluster. Thus, a fixed constant parameter is the centroid parameter for each cluster which is used for the simulation of ETP model.

The aggregated model is tested and validated against GridLAB-D, an open source tool that can simulate large number of buildings using the ETP model. It is observed that as number of bins and cluster increases, the aggregated model accurately tracks the GridLAB-D simulations and is also able to capture dynamic behavior accurately. However, there are limitations to this approach: 1) Model is more complex as second order effects have been considered, 2) design of feedback control strategies is difficult due to complexity, 3) frequent change in set point setting can lead to customer dissatisfaction, 4) frequent switching of TCL is not recommended, 5) more number of bins and clusters increases computational time and costs, 6) Both first and second order model exhibit strong oscillations for homogeneous population and damped and stable aggregated response for heterogeneous loads. Hence considering second order effects makes the model more complex.

In [5] Duncan S. Callaway explains controlling aggregated power consumed by thermostatically controlled loads using the set point change method. In cases where wind plants

are located far from other generation, TCLs in the vicinity can provide ancillary services. However, advanced metering infrastructure and programmable communicating thermostats (PCTs) would be required to change thermostat set points. Given the fact that tracking the state of each TCL is extremely difficult, probability of a TCL in a particular state can be calculated accurately. Only the TCLs that are approaching their dead band limits can be turned ON or OFF. This results in partial synchronization of TCLs producing desired aggregated power demand. Thus, short time scale responses can be produced by changing the thermostat set points.

In [12] S. Kundu and N. Sinitsyn explain light version of ‘safe protocol’ for controlling power consumption by heterogeneous population of loads. A large heterogeneous population of TCL can be grouped such that TCLs in a particular group have almost identical parameters. The control method shifts the dead band limits for all the TCLs by equal amounts. But it does so in a manner that parasitic oscillations are avoided. If the change in dead band shift is much lower than the difference between the ambient and the set point temperature, the change in time period after the shift is applied is within the range of 1% to 2% as compared to the case before the shift is applied. Such small variation should not introduce significant fluctuations in the system. This control method is suitable for producing strong changes in power consumption for a longer duration of the order of TCL’s time period. We require a simple local controller capable of changing the dead band limits as required, avoiding any use of complex smart functions.

In [19] we come across different safe protocol methods to generate power pulses. These protocols are designed to avoid unwanted oscillations associated with temporary synchronization of individual states of TCLs. Few basic instructions and small amount of intelligence needs to be added to instruct the TCLs to turn ON or OFF. The main advantage of the control methods is the reduction from two-way to one-way communication thus eliminating consumer privacy

issues. Also, arbitrary shapes of power pulses can be generated by combination of various safe protocols. This control methodology not only avoids unwanted oscillations but also gives us additional flexibility to generate pulses of varying magnitudes and duration.

Chapter 2: Set Point Change Control

We model heterogeneous population of TCLs by first order differential equation in the same way as that shown in [12], [17]. By considering first order dynamics, designing feedback control strategies is easier. The TCL is controlling the room temperature $\theta(t)$. When the air-conditioner is in the ON state, $\theta(t)$ decreases and TCL consumes power. When the air-conditioner is in OFF state, $\theta(t)$ increases and the TCL does not consume any power.

2.1: Mathematical Modeling of TCL

The differential equation that describes the evolution of $\theta(t)$ within the dead band limits $[\theta_-, \theta_+]$, where θ_- and θ_+ being the lower and upper dead band limits respectively, are as follows:

$$\dot{\theta} = \begin{cases} \frac{-1}{CR} (\theta - \theta_{\text{amb}} + PR) & \text{ON state} \\ \frac{-1}{CR} (\theta - \theta_{\text{amb}}) & \text{OFF state} \end{cases} \quad (1)$$

The dynamics of TCL and the power consumed is as shown:

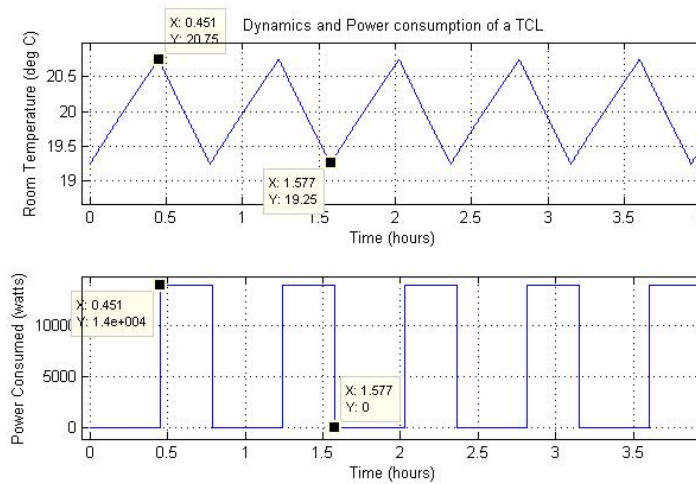


Figure 1: Dynamics of temperature (up) and power (down) consumption of a single TCL

From Figure 1 we observe that, the power consumed by TCL when it is in ON state is 14 kW, the set point temperature is 20 °C and the lower and upper dead band limits are 19.25 °C and 20.75 °C respectively. Also in the absence of noise, it is observed that the dynamics of TCL is constrained within the dead band limits $[\theta_-, \theta_+]$ [17]. The set point temperature is defined as $(\theta_+ + \theta_-)/2$ and the dead band width is $\Delta = (\theta_+ - \theta_-)$. The parameter vector $\psi = [P, C, R, \theta_{amb}]$ are as defined in previous chapter. Random temperature fluctuations (noise), is modeled by adding pseudorandom numbers having normal distribution in (1).

In steady state, when a air-conditioner is ON, the temperature of the room decreases from θ_+ to θ_- . Using initial condition $\theta(0) = \theta_+$, solving (1), we get:

$$\theta(t) = (\theta_{amb} - PR)(1 - e^{-t/RC}) + \theta_+(e^{-t/RC}) \quad (2)$$

where P is the power consumed by TCL in the ON state. And when the air-conditioner is OFF, the temperature of the room increases from θ_- to θ_+ . Using the initial condition $\theta(0) = \theta_-$, solving (1), we get:

$$\theta(t) = \theta_{amb}(1 - e^{-t/RC}) + \theta_-(e^{-t/RC}) \quad (3)$$

The time taken for the TCL to cool the room from temperature of θ_+ to θ_- can be calculated from (2). Thus $\theta(T_c) = \theta_-$, we get:

$$T_c = RC \ln\left(\frac{PR + \theta_+ - \theta_{amb}}{PR + \theta_- - \theta_{amb}}\right) \quad (4)$$

Similarly, heating time T_h when the temperature of the room rises from θ_- to θ_+ can be calculated by substituting $\theta(T_c) = \theta_+$ in (3) and arranging the terms we get:

$$T_h = RC \ln \left(\frac{\theta_{amb} - \theta_-}{\theta_{amb} - \theta_+} \right) \quad (5)$$

In general, for any intermediate temperature θ_n , (4) and (5) can be expressed as follows:

$$t_c(\theta_n) = RC \ln \left(\frac{PR + \theta_+ - \theta_{amb}}{PR + \theta_n - \theta_{amb}} \right) \quad (6)$$

$$t_h(\theta_n) = RC \ln \left(\frac{\theta_{amb} - \theta_-}{\theta_{amb} - \theta_n} \right) \quad (7)$$

Let N be the total number of TCLs. The number of loads in ON and OFF state at a particular instant be denoted by N_c and N_h respectively. The time period 'T' of a TCL cycle is given by:

$$T = T_c + T_h \quad (8)$$

The duty cycle of TCL when an air-conditioner is on is defined as:

$$D = \frac{T_c}{T} \quad (9)$$

For homogeneous population of TCLs in steady state, the number of TCLs in ON and OFF states are proportional to their respective cooling and heating times. Thus, when there is no noise we can say that:

$$N_c = DN \quad (10)$$

$$N_h = (1-D)N \quad (11)$$

$$N = N_c + N_h \quad (12)$$

Selecting $R = 2 \text{ }^{\circ}\text{C/kW}$, $C = 1.8 \text{ kWh/}^{\circ}\text{C}$, $P=14 \text{ kW}$ and using (4), (5) and (8), we get cooling time to be 20 minutes, heating time as 27 minutes and the TCL time period is 47 minutes. To model the load heterogeneity, the values of R and C for all the loads are calculated by adding pseudorandom values drawn from the standard uniform distribution on the open interval (0,1) to the aforementioned values [41]. Traditional method of direct load control to reduce the power consumption was to interrupt service to a group of TCLs for few minutes. It was observed that the aggregated power consumed by the TCLs did not return to its steady state value when the service was restored. Instead, huge oscillations of magnitude comparable to steady state value were observed. During the time when the TCLs were signaled to remain OFF, many TCLs crossed the upper dead band limit θ_+ . This caused a large number of TCLs to instantly turn ON when the service was restored. Such control of aggregated power consumption lead to unwanted oscillations that lasted for several hours. This phenomenon is called *cold load pickup* [19], [42]. We term such control methods that lead to unwanted oscillations as *unsafe*. Another such unsafe method is control of TCL by applying a set point change.

In the following section we will demonstrate the set point change control by simulating a large ensemble of around 10,000 air-conditioners. The simulations were performed in MATLAB [41]. Both homogeneous and heterogeneous population of TCLs will be simulated and will be compared on the basis of small and large set point shift applied. Thus, we will simulate the following four cases:

1. Small set point shift applied to homogeneous population of TCLs.
2. Large set point shift applied to homogeneous population of TCLs.
3. Small set point shift applied to heterogeneous population of TCLs.

4. Large set point shift applied to heterogeneous population of TCLs.

2.2: Simulation results for upward shift in set point temperature

For understanding how the TCLs switch from ON and OFF states let's us consider three homogeneous TCLs as shown in Figure 2.

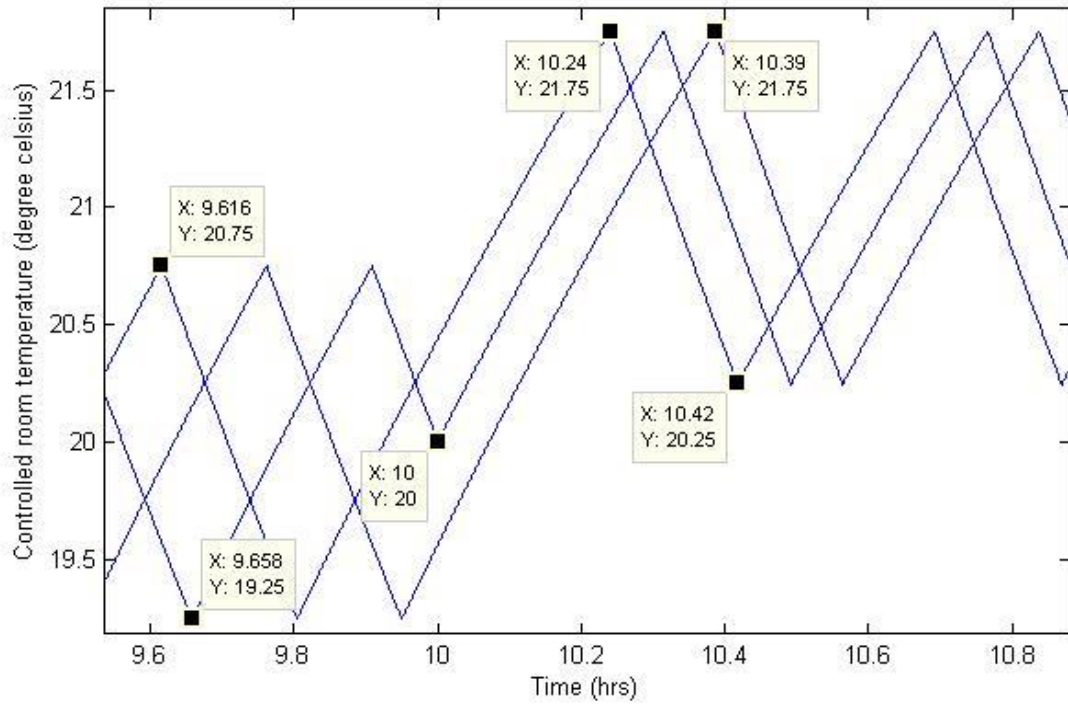


Figure 2: Effect of the imposed upward shift in temperature set point on dynamics of temperature of three TCLs

Before the shift is applied, the dead band limits are $[\theta_-, \theta_+] = [19.25^\circ\text{C}, 20.75^\circ\text{C}]$. The initial set point temperature of 20°C is shifted to 21°C at time $t = 10$ hours. The new dead band limits after the shift is applied are $[\theta_-, \theta_+] = [20.25^\circ\text{C}, 21.75^\circ\text{C}]$ as seen from the Figure 2. The dead band width is kept constant at 1.5°C . It is observed that after the control signal is applied the two TCLs that were initially in the OFF state continue to remain in the OFF state till they

reach the new upper dead band of 21.75°C after which their dynamics are constrained within new temperature dead band limits. The third TCL instantly switches ON as its temperature at $t=10$ hours is less than the new lower dead band limit. We can thus conclude that, after the control signal is applied

1. The TCLs in the OFF state continue to remain in OFF state and then operates according to new dead band limit after it reaches θ_{n+} .
2. The TCL in the ON state having temperature greater than θ_{n-} , will remain ON till it reaches θ_{n-} and will then operate within $[\theta_{n-}, \theta_{n+}]$.
3. The TCL in the ON state having temperature θ such that $\theta_{-} < \theta < \theta_{n-}$ will instantly switch OFF and operate with new dead band limits.

We will now simulate the homogeneous and heterogeneous population of TCLs and study the effect of small and large set point shift on aggregated power consumption. The total simulation time will be 20 hours and set point shift will be applied at time $t=10$ hours.

2.2.1: Small set point shift applied to homogeneous population of TCLs

Consider a homogeneous population of 10,000 TCLs with identical R, C, P parameters. The set point shift of 0.5°C .

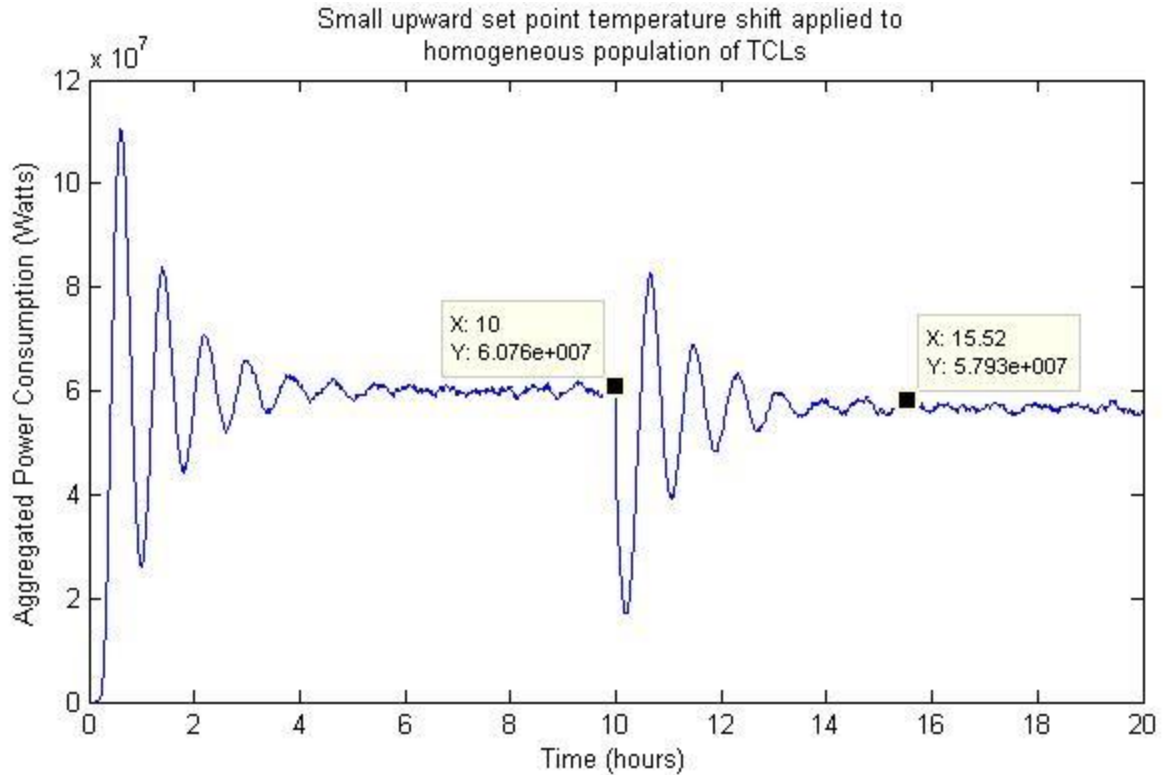


Figure 3: Aggregated response of power consumption of homogeneous population of 10,000 TCLs to an upward shift by 0.5°C in temperature set point

From Figure 3 it is observed that there is a sudden drop in power consumed at the time when the set point shift is applied. This can be understood from the fact that some TCLs that are in the ON state and have temperatures between the two lower dead band limits instantly switch OFF. Thus, upward set point shift is applied to decrease the aggregated power consumed. After this immediate drop in power, pronounced oscillations are observed that persist for several cycles. The system then reaches the steady state power consumption in around 5.5 hours. The average power consumed for the entire simulation time is 57.35 MW.

2.2.2: Large set point shift applied to homogeneous population of TCLs

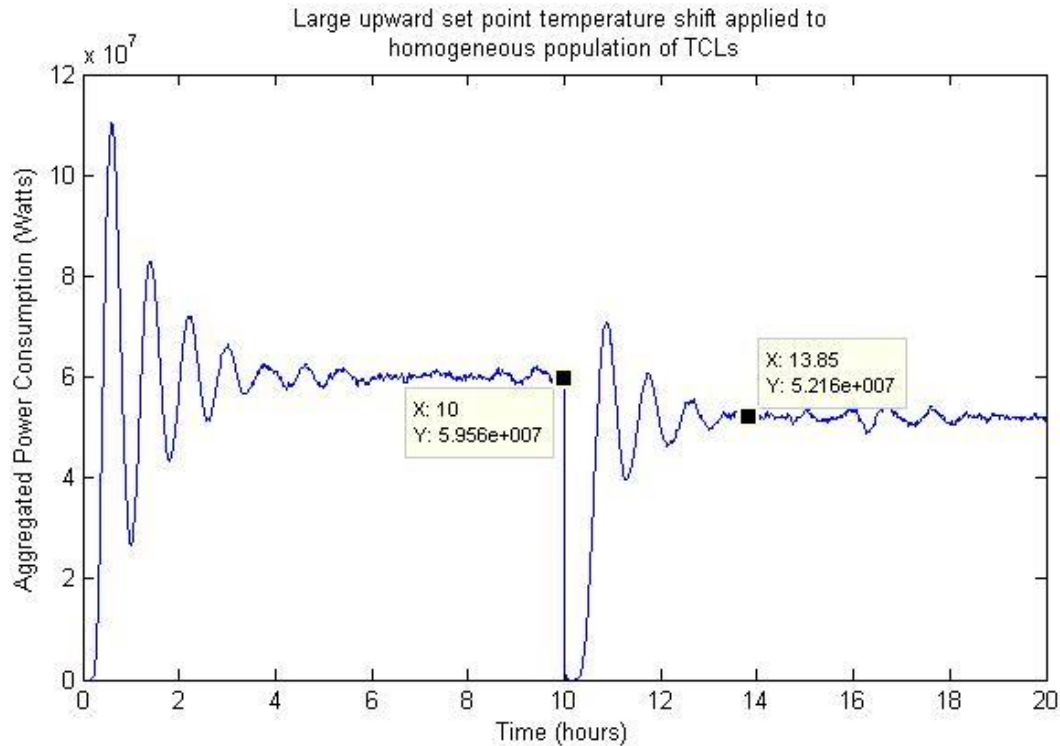


Figure 4: Aggregated response of power consumption of homogeneous population of 10,000 TCLs to an upward shift by 1.5°C in temperature set point

In Figure 4, set point shift of 1.5°C is applied to homogeneous population of TCLs. Due to large shift it is found that all TCLs have their temperatures between the new and the old lower dead band limits which causes them to instantly turn OFF. Thus, power consumed by the ensemble is found to be 0 MW for a duration of around 15 minutes. After the oscillations have been damped out, the new equilibrium power consumption is found to be lower than that of the initial steady state power consumption. The average power consumed is found to be 54.14 MW.

2.2.3: Small set point shift applied to heterogeneous population of TCLs

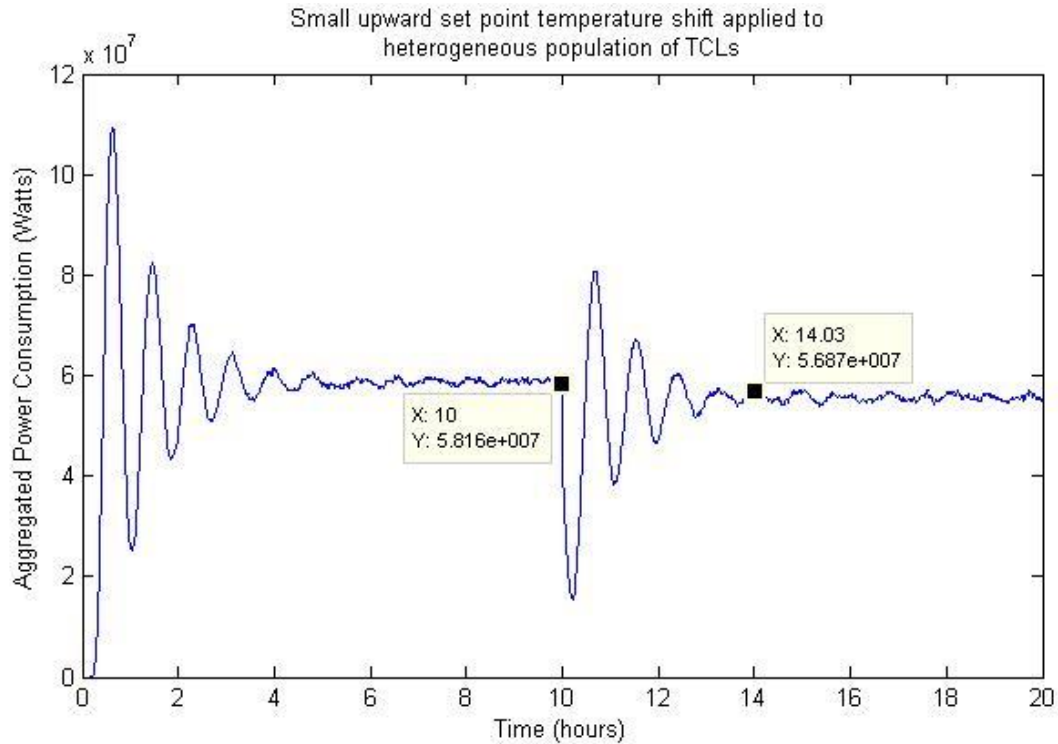


Figure 5: Aggregated response of power consumption of heterogeneous population of 10,000 TCLs to an upward shift by 0.5°C in temperature set point

Due to heterogeneity the oscillations are found to damp out faster than that seen in case of homogeneous population. A set point shift of 0.5°C is applied and the average power consumed is found to be 55.97 MW.

2.2.4: Large set point shift applied to heterogeneous population of TCLs

A set point shift of 1.5°C is applied and as observed the ensemble power consumed drops to zero after the shift is applied. The average power consumed is calculated to be 52.69 MW.

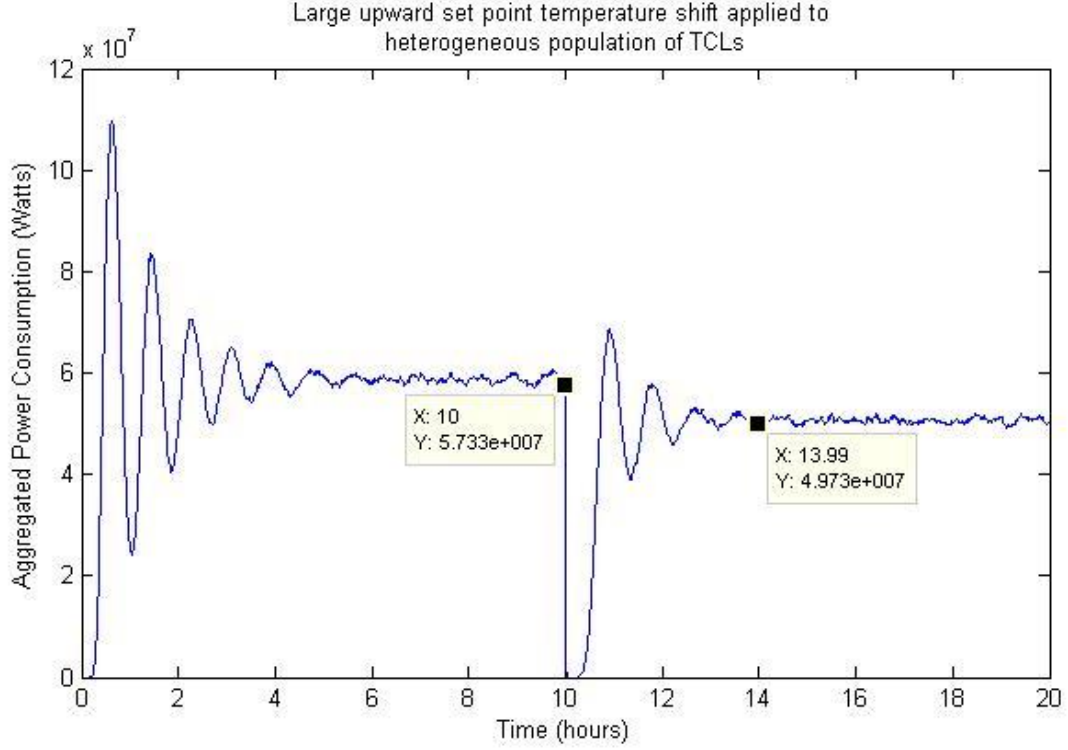


Figure 6: Aggregated response of power consumption of heterogeneous population of 10,000 TCLs to an upward shift by 1.5°C in temperature set point

2.3: Simulation results for downward shift in set point temperature

The downward shift is applied to increase the aggregated power consumption. The dead band width is kept constant at 1.5°C . $[\theta_{-}, \theta_{+}]$ are the old dead band limits and $[\theta_{n-}, \theta_{n+}]$ are the new dead band limits. The control method can be explained as follows:

1. The TCLs in the ON state continue to remain in ON state and then operates according to new dead band limit after it reaches θ_{n-} .
2. The TCLs in the OFF state having temperature lower than θ_{n+} , will remain OFF till it reaches θ_{n+} and will then operate within $[\theta_{n-}, \theta_{n+}]$.

3. The TCLs in the OFF state having temperature θ such that $\theta_{n+} < \theta < \theta_+$ will instantly switch ON and operate with new dead band limits.

We will now simulate four cases for homogeneous and heterogeneous population of TCLs and study the effect of downward set point temperature shift on aggregated power consumption.

2.3.1: Small set point shift applied to homogeneous population of TCLs

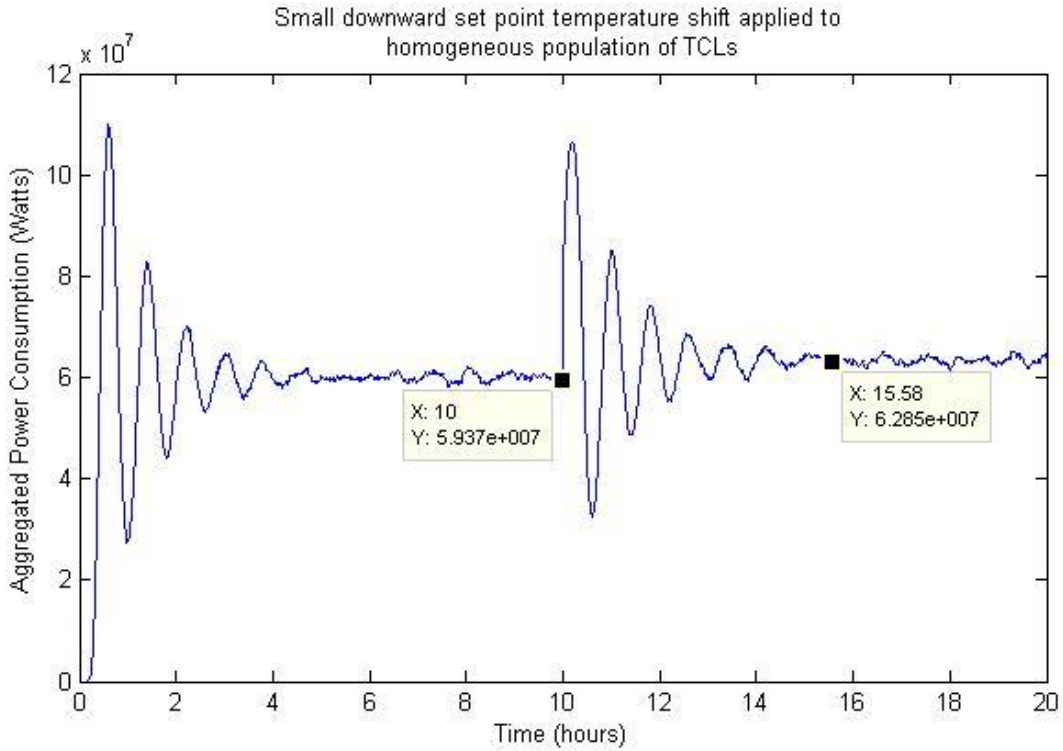


Figure 7: Aggregated response of power consumption of homogeneous population of 10,000 TCLs to a downward shift by 0.5°C in temperature set point

A set point temperature shift of 0.5°C is applied at time $t = 10$ hours. The average power consumed is 61.43 MW. There is an increase in power because TCLs in OFF state having temperatures between new and old upper band limits instantly switch ON. It is observed that the ensemble power consumption reaches steady state value in 5.5 hours after the control signal is applied. Oscillations are observed due to synchronization of individual phases of TCLs caused by

simultaneous switching of large number of TCLs from OFF to ON state.

2.3.2: Large set point shift applied to homogeneous population of TCLs

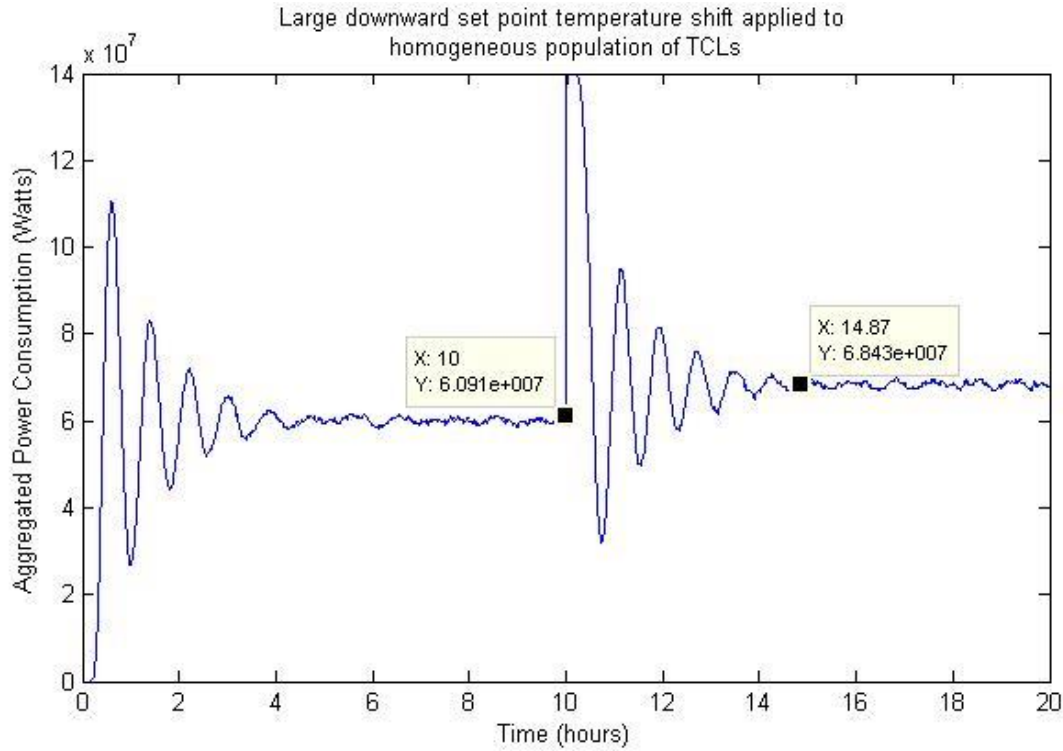


Figure 8: Aggregated response of power consumption of homogeneous population of 10,000 TCLs to a downward shift by 1.5°C in temperature set point

A set point temperature shift of 1.5°C is applied at time $t = 10$ hours. Due to large shift, all the TCLs turn on and the ensemble consumes maximum power for 15 minutes as shown in Figure 8. The average power consumed is found to be 64.76 MW.

2.3.3: Small set point shift applied to heterogeneous population of TCLs

Figure 9 shows a set point shift of 0.5°C is applied to the ensemble. The oscillations die out faster than that observed in homogeneous population of TCLs. The average power consumed is 59.97 MW.

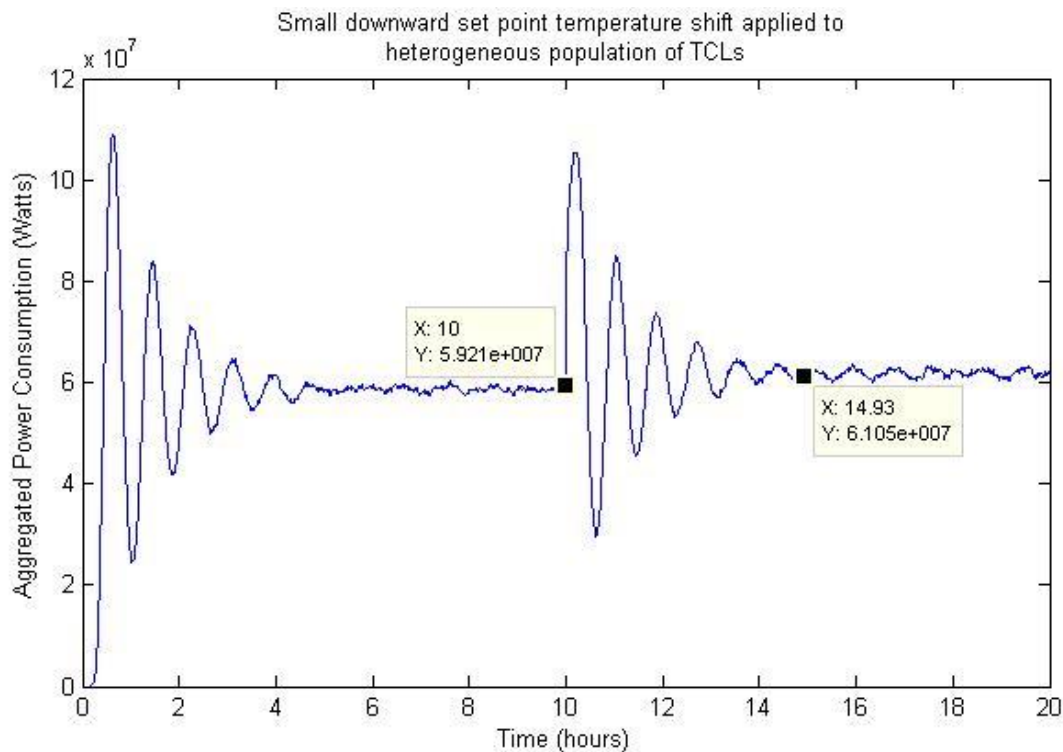


Figure 9: Aggregated response of power consumption of heterogeneous population of 10,000 TCLs to a downward shift by 0.5°C in temperature set point

2.3.4: Large set point shift applied to heterogeneous population of TCLs

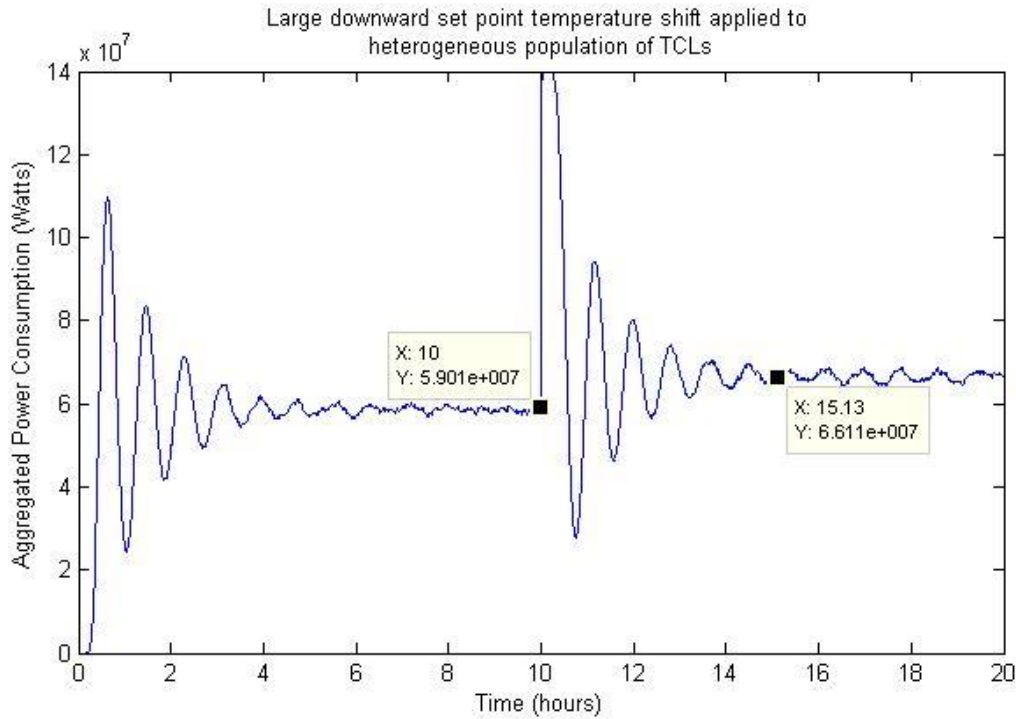


Figure 10: Aggregated response of power consumption of heterogeneous population of 10,000 TCLs to a downward shift by 1.5°C in temperature set point

A set point shift of 1.5°C is applied and the power consumed by the ensemble reaches its maximum value when the shift is applied. The average power consumed by the ensemble is 63.20 MW.

We observe from Figure 3 to Figure 10 that both homogeneous and heterogeneous population of loads respond in a similar manner to the applied control signal. A larger dead band shift can lead to sudden increase or decrease in power. This requires generators to ramp up the generation quickly which is not possible and can lead to cascading failure. As long as the set point shift applied is small enough, there is no noticeable change in the average power consumed. In real world, it is impossible to have homogeneous population of loads. Hence, it is

more practical if we study the aggregated power response of heterogeneous population of loads. From this point we will analyze the behavior of heterogeneous ensemble of loads.

2.4: Limitations of set point shift control

1. Frequent switching of TCLs can increase fatigue and lead to wear and tear of air-conditioners.
2. Large set point change can lead to consumer dissatisfaction making it difficult to convince them to participate in demand side management programs.
3. Large oscillations are observed for several hours due to synchronization to individual TCL states and the recovery of aggregated power to steady state is sluggish.

In the next chapter we study in detail the *safe* method to control TCLs avoiding synchronizing of TCL phases. Using this *safe protocol* we ensure that a sudden rise or drop in power does not lead to pronounced oscillations and steady state is reached in time equal to that of TCL's time period.

Chapter 3: Generation of Power Pulses using Safe Protocols

We retain the simplicity of the open loop control methodology discussed in the previous chapter, but eliminate the problem of unwanted synchronization of TCLs by using timers installed in the temperature controllers [19]. Using these timers, we are able to generate a power pulse and then slowly bring all TCLs back to their initial set points while avoiding unwanted oscillations.

We refer to these methods as *timer-based safe protocols* where 'Safe' refers to the lack of oscillations. Here we will discuss three strategies, which we will name, respectively, SP-T1, SP-T2 and SP-T3, where SP stands for the “safe protocol” and T is for “timer”.

3.1: SP-T1 Protocol for upward shift in set point temperature

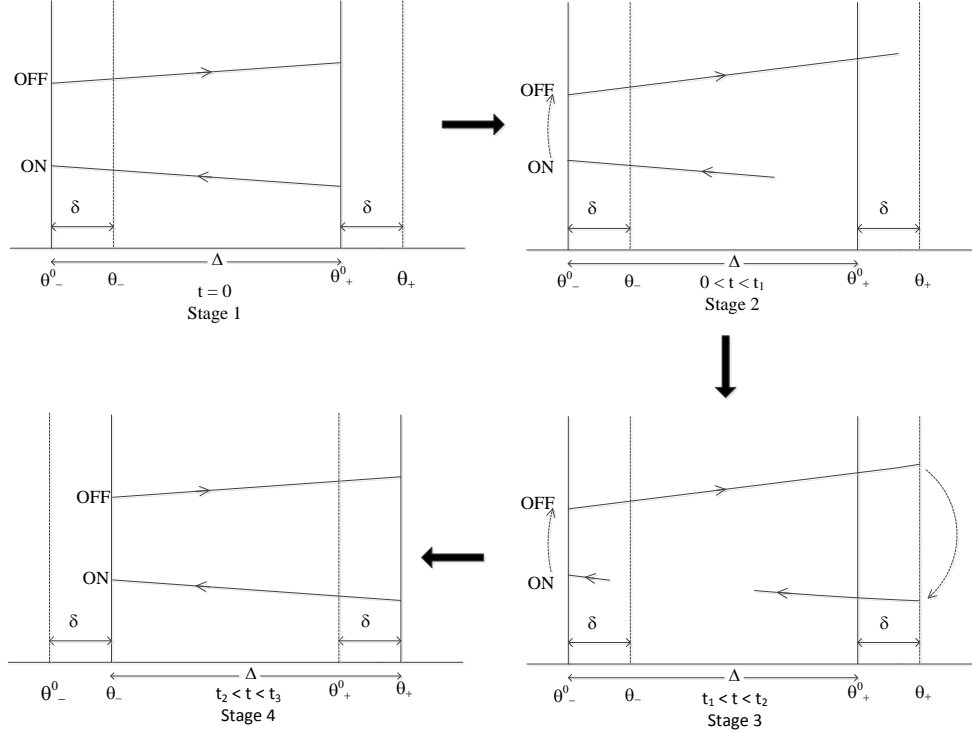


Figure 11: Flow diagram of SP-T1 for upward shift in temperature set point

As shown in Figure 11, the air-conditioners in Stage 1 operate according to their original dead band limits $[\theta_-^0, \theta_+^0]$. In Stage 2, when an upward set point shift of δ is applied the dead band limits are also shifted rightwards by the same amount. Thus, $\theta_+ = (\theta_+^0 + \delta)$ and $\theta_- = (\theta_-^0 + \delta)$. At this instant, the new transition points at which switching to ON and OFF states will take place are θ_+ and θ_-^0 respectively. From Stage 3 it can be seen that TCLs in OFF state will switch ON only after they reach θ_+ . Whereas, TCLs in ON state will remain ON until they reach θ_-^0 at which they will turn OFF. The TCL will then operate with the new dead band limits of $[\theta_-, \theta_+]$ after it switches state at one of the transition points as shown in Stage 4. Figure 12 shows simulation of heterogeneous population of 10,000 TCLs. The signal is applied at time $t = 9.5$ hours. It is observed that system reaches steady state value within TCLs time period without giving rise to unwanted oscillations.

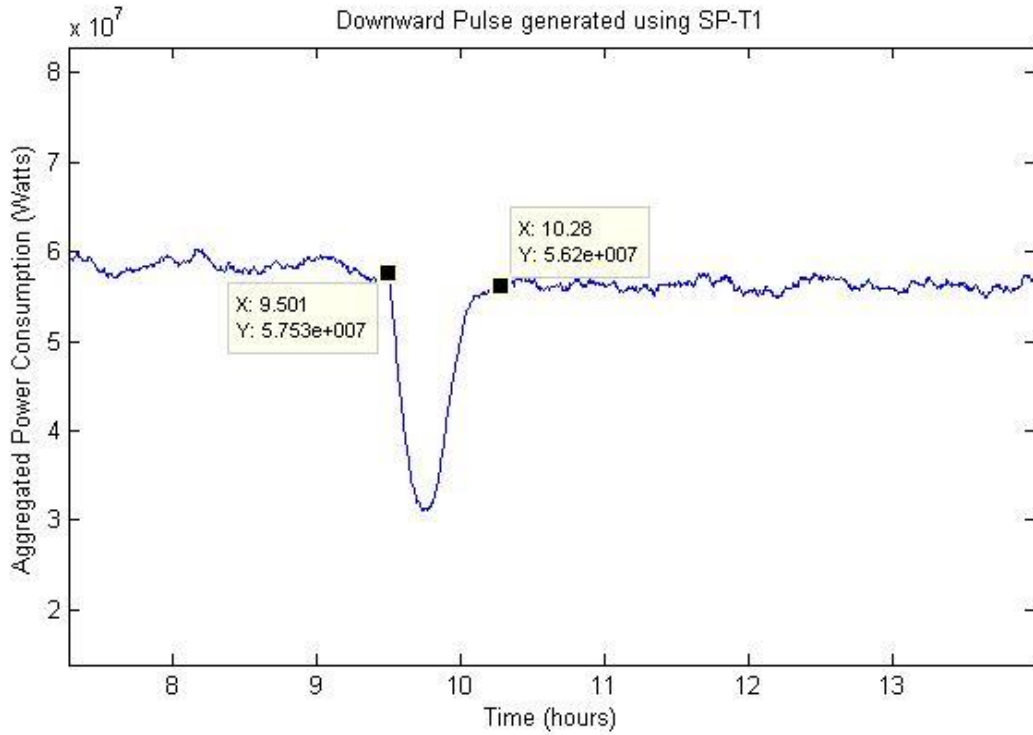


Figure 12: Aggregated power consumption of 10,000 TCLs for an upward shift by 0.5°C in temperature set point

3.2: SP-T1 Protocol for downward shift in set point temperature

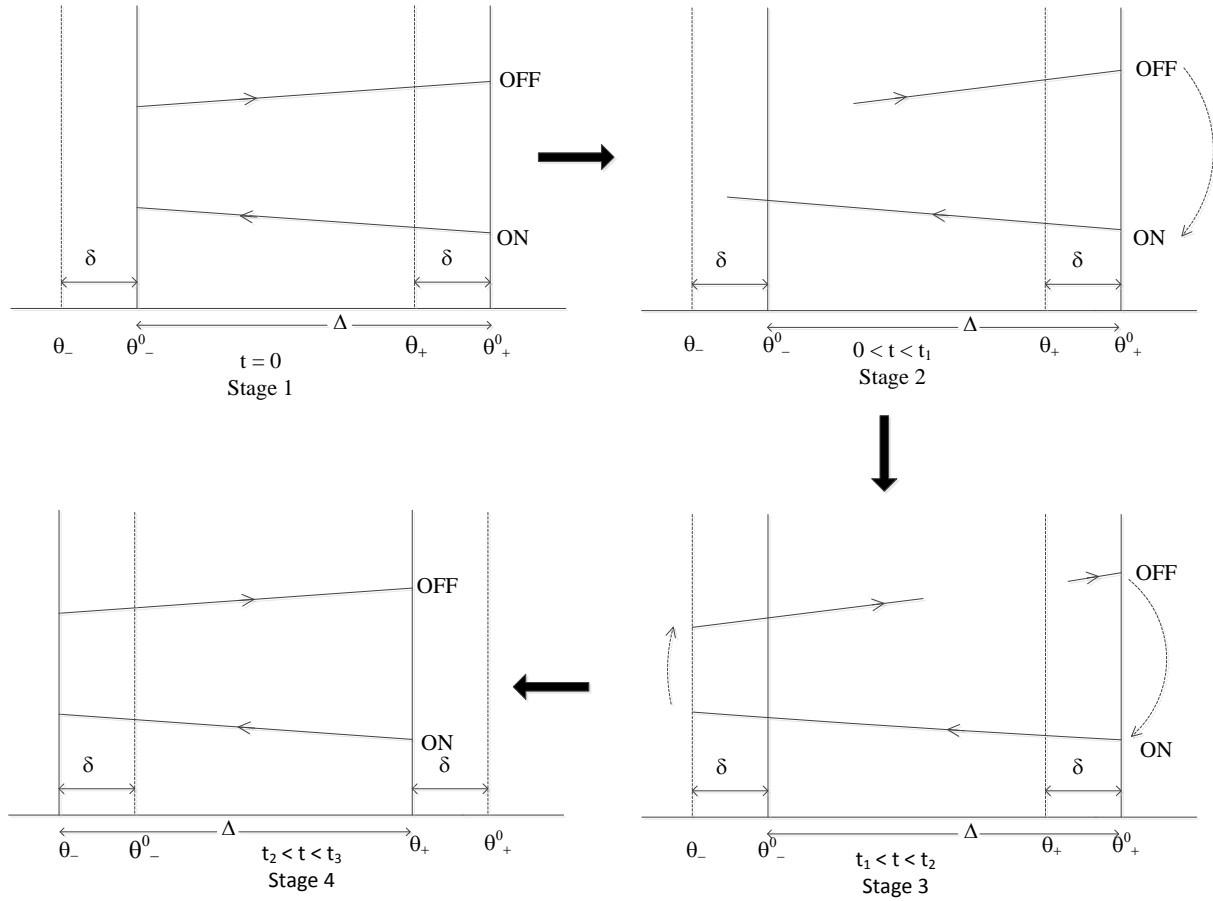


Figure 13: Flow diagram of SP-T1 for downward shift in temperature set point

In Figure 13, the set point is shifted in downward direction by and amount δ . Thus, the dead band moves leftwards and the new dead band limits are $\theta_+ = (\theta_+^0 - \delta)$ and $\theta_- = (\theta_-^0 - \delta)$. In Stage 1 all air conditioners operate within original hysteresis band with limits $[\theta_-^0, \theta_+^0]$. On application of control signal in Stage 2 the transition points at which switching to OFF and ON will take place are θ_- and θ_+^0 . Stage 3 shows that TCLs in the ON state will switch OFF after it reaches θ_- and TCLs in OFF state will switch ON after it hits θ_+^0 . TCLs will then continue to

operate with new dead band limits after it reaches one of the transition points. Figure 14 shows the simulation of heterogeneous population of 10,000 TCLs to generate upward pulse using SP-T1.

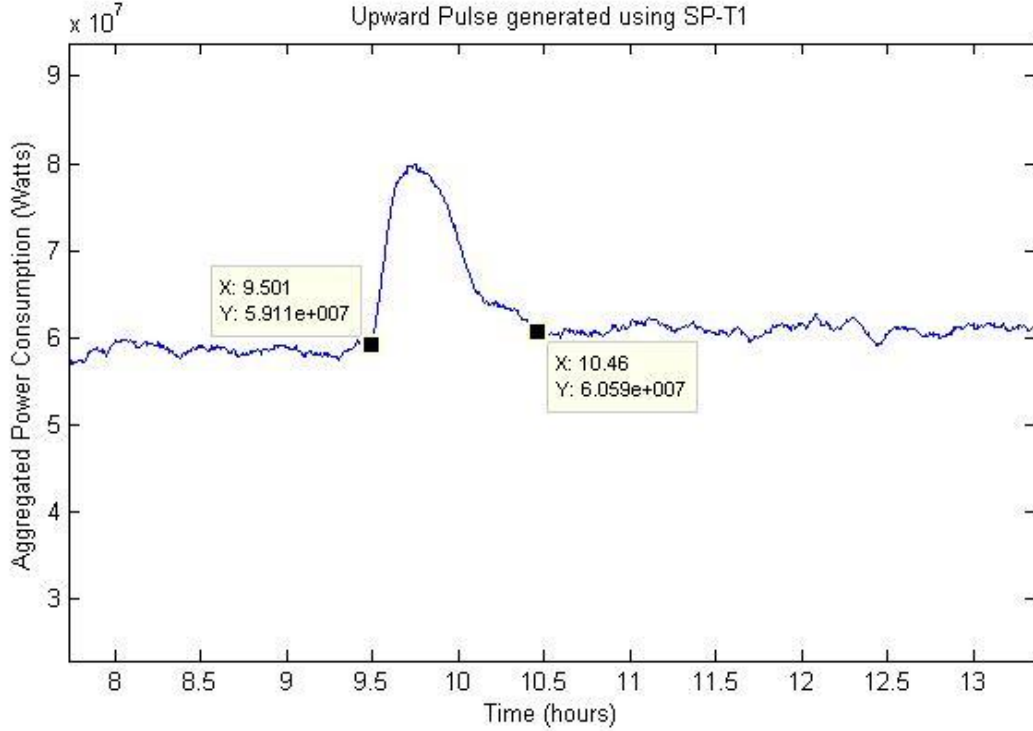


Figure 14: Aggregated power consumption of 10,000 TCLs for a downward shift by 0.5 °C in temperature set point

Let T_0 and T_n be time period of TCL before and after the control signal is applied respectively. In order to implement safe protocol we need $T_0 = T_n$ [8]. T_0 and T_n can be calculated using (4), (5) and (8). In the case of dead band shift of 0.1 °C to 1.0 °C, the variation in new time period is about 1% to 2% with respect to the original time period. This is only true if:

$$\delta \ll \theta_{\text{amb}} - \frac{(\theta_+ + \theta_-)}{2} \quad (13)$$

For $R = 2$ °C/kW, $C = 1.8$ kWh/°C, $P = 14$ kW, $\theta_{\text{amb}} = 32$ °C, $\delta = 0.5$ °C and original dead band limits of [19.25 °C, 20.75 °C], we get $T_0 = 0.7873$ hours and $T_n = 0.7967$ hours. It is

observed that T_n is just 1.19% greater than T_0 . Such small variation will not lead to unwanted oscillations. If (13) is not true and θ_{amb} is close to the set point temperature, TCLs will remain ON for less amount of time and aggregated power generation will be small enough making it impractical for commercial applications. However, if θ_{amb} is too large, TCLs will remain ON for most of the time, in which case direct interruption would prove to be more beneficial for controlling TCLs [8]. Thus, a proper choice of all parameters that shape the dynamics of TCLs is required to yield insightful results on implementation of safe protocol.

Safe protocol avoids instant switching of TCL states that is observed in *unsafe* control method. The TCLs switch states only after reaching the transition points after which they are instructed to operate with the new dead band limits. Thus, for a finite size of heterogeneous population of TCLs, a small set point shift satisfying (13) will ensure that the new time period is approximately same as that of the old time period and aggregated power consumption will reach its steady state value without leading to unwanted oscillations.

3.3: Merits and Shortcomings of Safe Protocol (SP-T1)

Merits: 1) the control can be applied on an arbitrary range until it leads to customer dissatisfaction, 2) No need for any smart meters as utility does not need information about any TCL, 3) the problem of two way communication is eliminated and there is no risk to customer privacy, 4) frequent switching of TCLs is not required, and 5) can offset slow and large power fluctuations.

Shortcomings: 1) It is 'slow'. On application of control signal, power does not change abruptly, 2) not useful to offset fast and abrupt fluctuations.

3.4: SP-T2 to delay the power consumption by TCLs

SP-T2 is a simple strategy that delays the power consumption of TCLs by a relatively large span of time (e.g. 1 hour). To achieve this, one does not have to switch TCLs to OFF for this duration of time. Figure 15 shows the flow diagram to explain the operation of SP-T2.

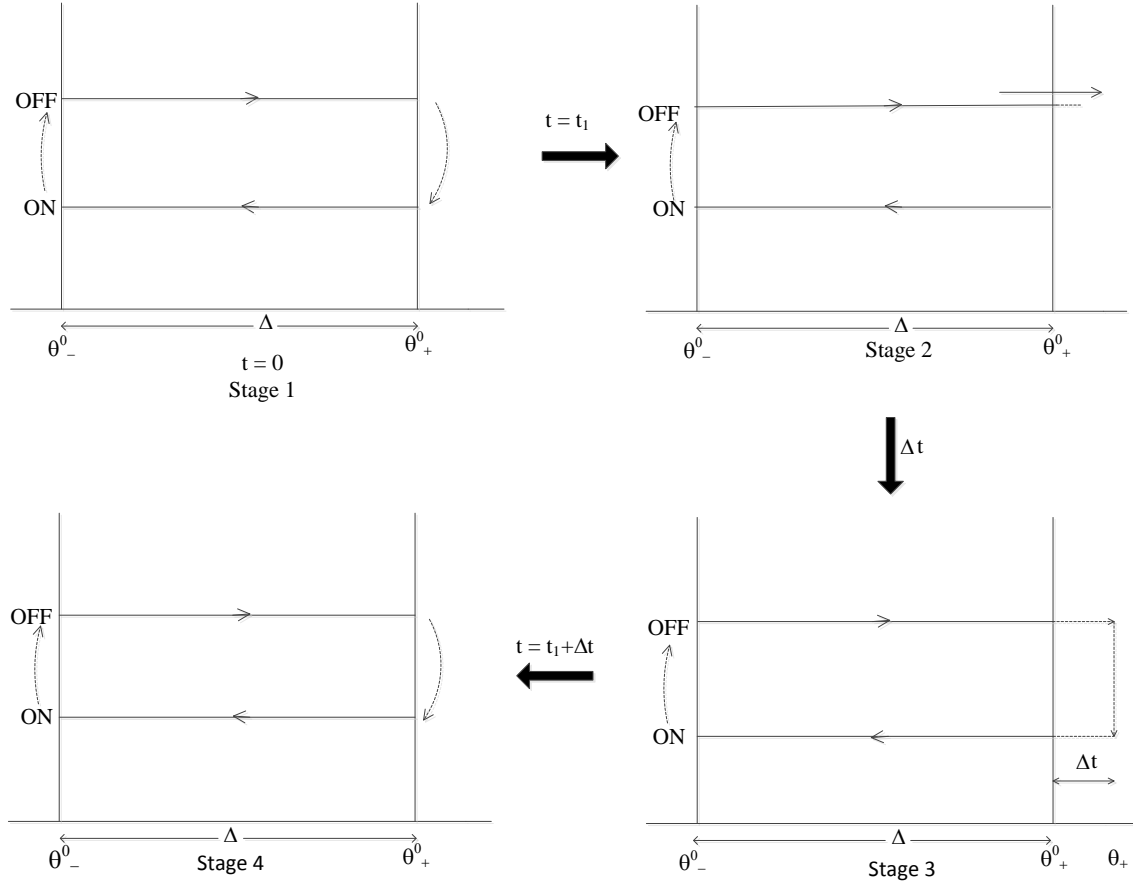


Figure 15: Flow diagram of SP-T2 commanding TCLs to stay in OFF mode for extra ‘M’ minutes

Stage 1: All TCLs operate according to their original dead band limits as indicated.

Stage 2: On application of signal at time $t = t_1$, we see that TCLs that are OFF and near the upper dead band limit, cross this limit. The signal is applied for duration say ‘M’ minutes (Δt).

Stage 3: The OFF TCLs cross the upper dead band limit for time Δt and then turn ON and continue to operate according to the original dead band limits. The TCLs that are ON when the signal is applied, turn OFF on reaching θ_-^0 and remain OFF for time Δt after reaching θ_+^0 . At this instant this OFF TCLs turn ON and continue operating according to original dead band limits.

Stage 4: In this stage as all TCLs have their dead band limits set at $[\theta_-^0, \theta_+^0]$, Stage 4 operation is same as that of Stage 1. Figure 16 illustrates the behavior with 3 TCLs for $M = 10$ minutes and SP-T1 is initiated at $t = 10$ hours.

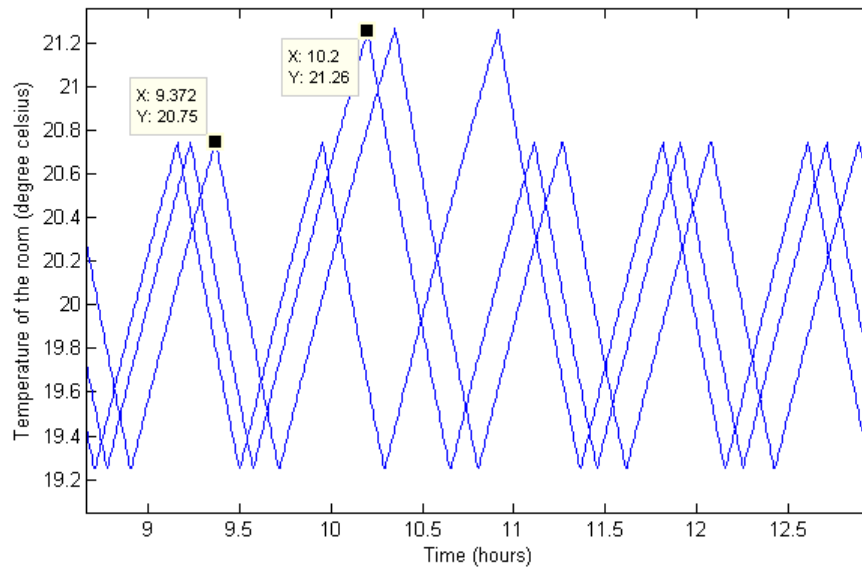


Figure 16: Operation of TCLs under SP-T2 commanding them to stay in the OFF mode for extra $M = 10$ minutes starting at $t = 10$ hours

The simulation results for 10,000 heterogeneous population of loads are shown below.

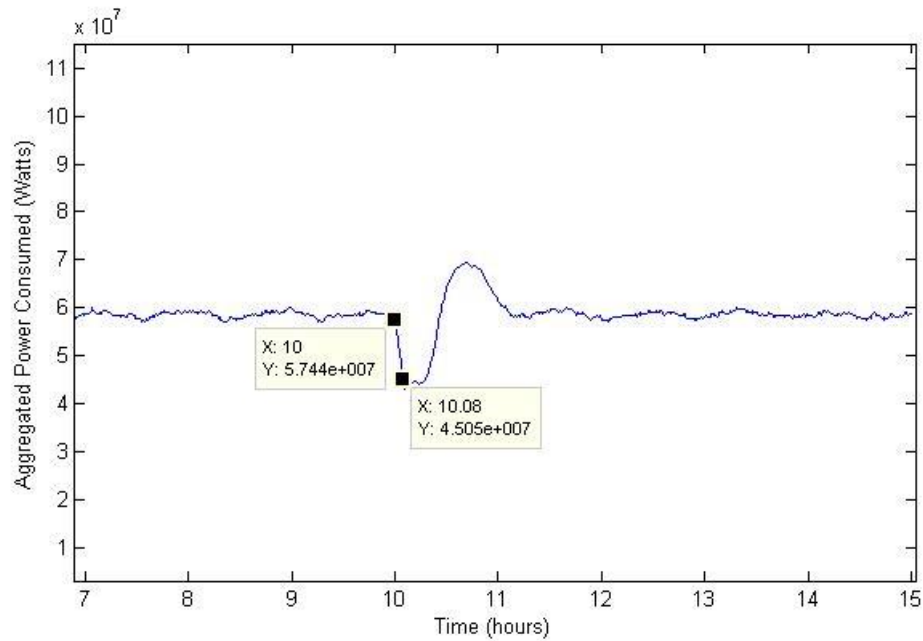


Figure 17: Aggregated Power of a 10,000 TCL ensemble responding to SP-T2 staying OFF for $M = 5$ minutes starting at $t = 10$ hours

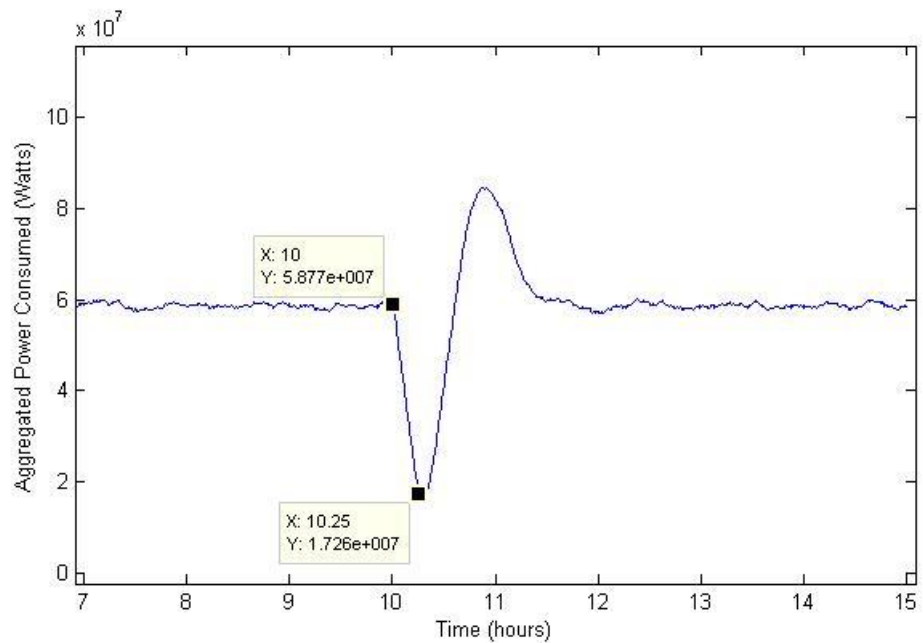


Figure 18: Aggregated Power of a 10,000 TCL ensemble responding to SP-T2 staying OFF for $M = 15$ minutes starting at $t = 10$ hours

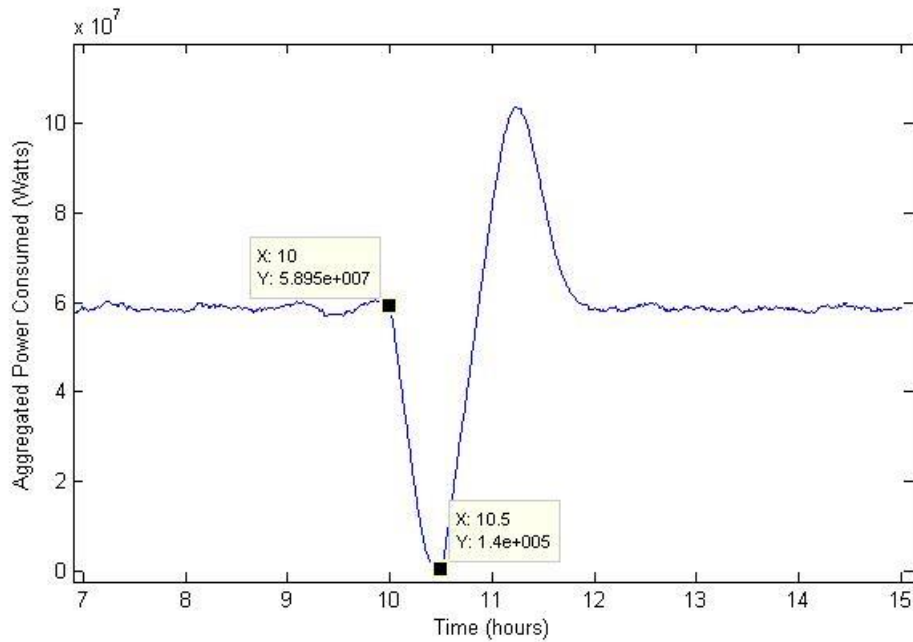


Figure 19: Aggregated Power of a 10,000 TCL ensemble responding to SP-T2 staying OFF for $M = 30$ minutes starting at $t = 10$ hours

Figures 17, 18, and 19 show the aggregated power for a heterogeneous population of 10,000 loads when SP-T2 is applied for $M = 5$, 15 and 30 minutes, respectively. The power consumed decreases linearly during the first M minutes as the TCLs remain in the OFF state. If $M > 30$ minutes, all the loads finally appear in the OFF state and the aggregated power consumed drops to a low value of 0.14 MW (see Figure 19). After achieving this minimum, the TCLs power consumption increases almost linearly due to continuous return of TCLs to their original operation state. Eventually, the distribution of TCLs returns to the uncorrelated initial distribution, without producing any substantial power oscillations.

Figure 20 shows the flow diagram to generate pulse of the opposite shape as compared to the previous case.

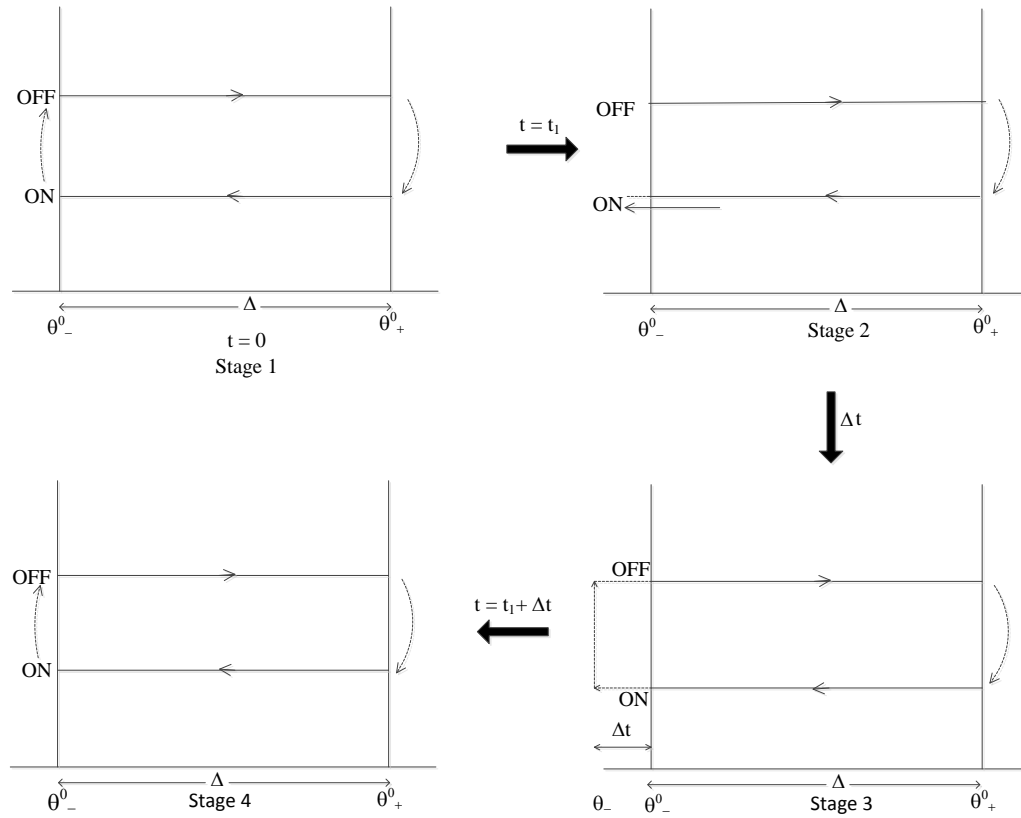


Figure 20: Flow diagram of SP-T2 commanding TCLs to stay in ON mode for extra 'M' minutes

If the goal is initially to absorb extra energy from the grid and then release it after a delay of ~30 minutes, TCLs should work as usual until they reach the point at which they would normally switch from ON to OFF. Instead, they continue in the ON state for M minutes before returning to the initially set parameters. Figure 21 illustrates this behavior for 3 TCLs with M = 10 minutes and the signal applied at time $t = 10$ hours.

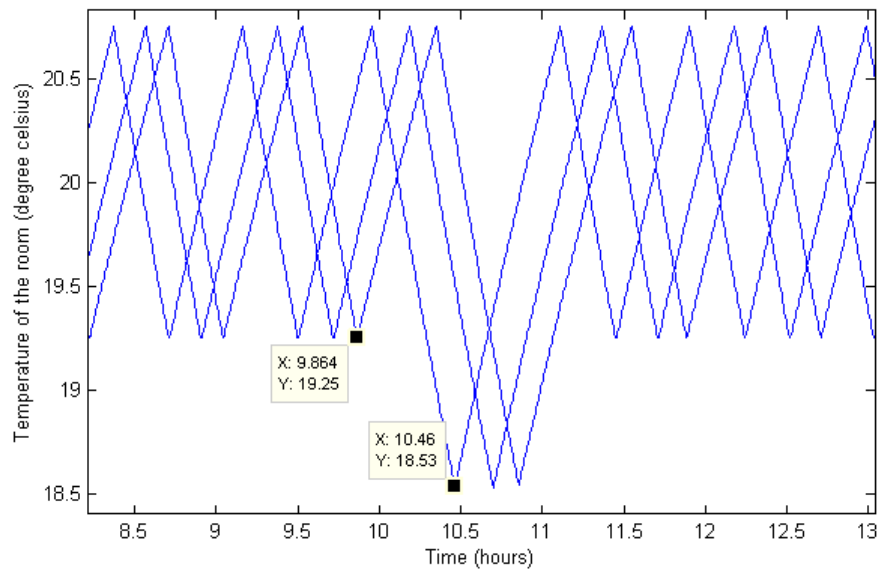


Figure 21: Operation of TCLs under SP-T2 commanding them to stay in the ON mode for extra $M = 10$ minutes starting at $t = 10$ hours

The simulation results for 10,000 heterogeneous population of loads are shown below.

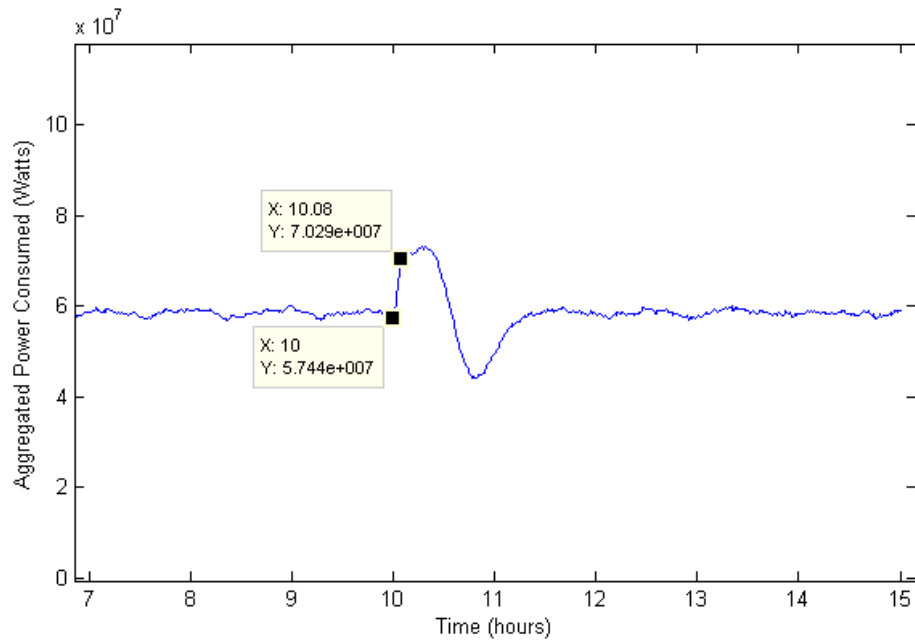


Figure 22: Aggregated Power of a 10,000 TCL ensemble responding to SP-T2 staying ON for $M = 5$ minutes starting at $t = 10$ hours

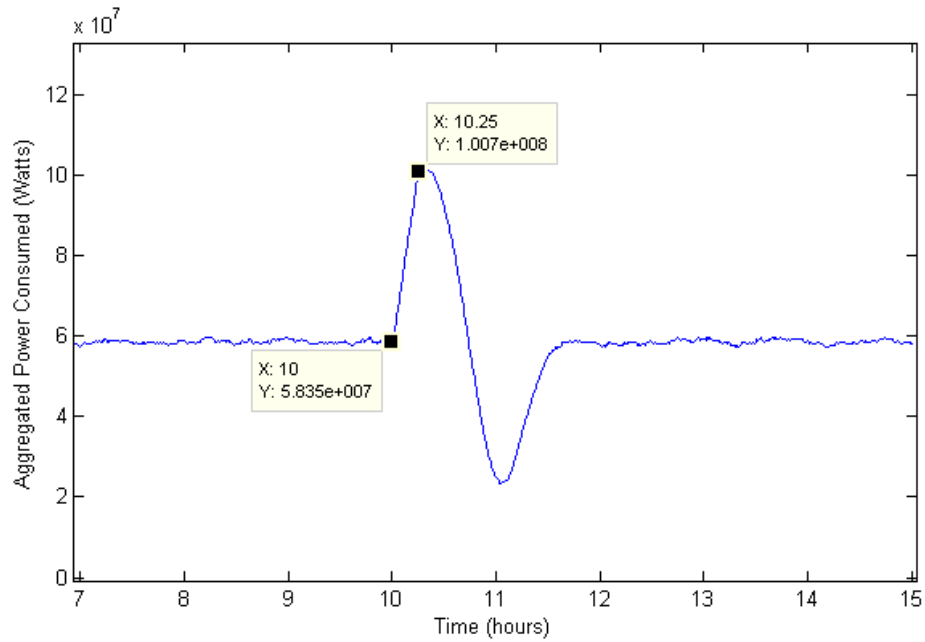


Figure 23: Aggregated Power of a 10,000 TCL ensemble responding to SP-T2 staying ON for $M = 15$ minutes starting at $t = 10$ hours

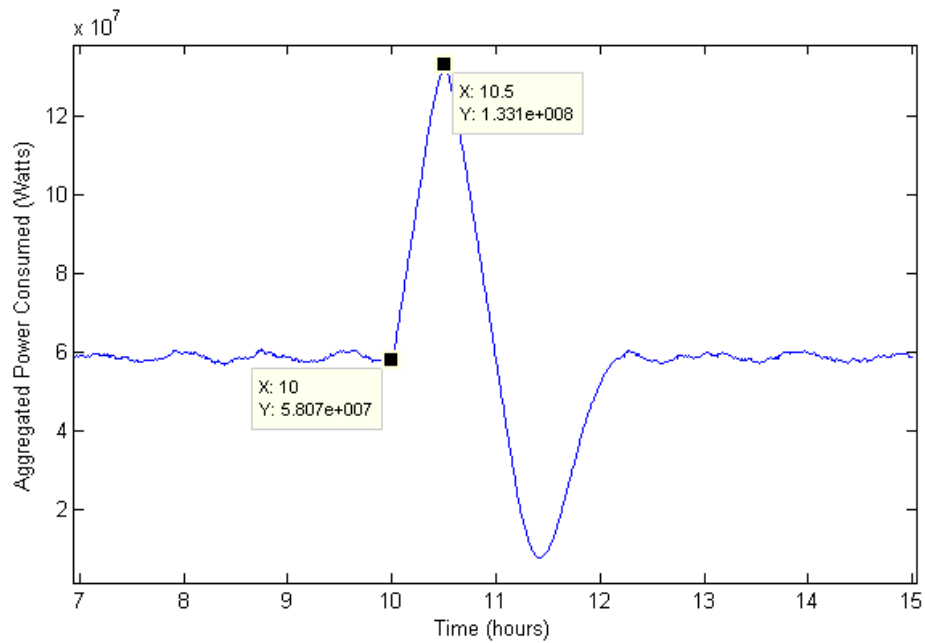


Figure 24: Aggregated Power of a 10,000 TCL ensemble responding to SP-T2 staying ON for $M = 30$ minutes starting at $t = 10$ hours

Figures 22, 23, and 24 show the aggregated power for a heterogeneous population of 10,000 loads when SP-T2 is applied for $M = 5$, 15 and 30 minutes, respectively. The power

consumed increases linearly during the first M minutes as the TCLs remain in the ON state. If $M > 30$ minutes, all the loads finally appear in the ON state and the aggregated power consumed is close to the peak value of 140 MW (see Figure 24). After achieving this maximum, the TCLs power consumption decreases almost linearly due to continuous return of TCLs to their original operation state. Eventually, the distribution of TCLs returns to the uncorrelated initial distribution, without producing any substantial power oscillations.

Here we note that the ensemble of TCLs behaves much more like batteries than standard power generators. Like batteries, for the TCLs to return to their original state, the energy that was initially absorbed (generated) by TCLs must be returned to (absorbed from) the grid. Inspection of above simulation figures shows that the shape and duration of these pulses are determined by the natural evolution of the TCL ensemble. SP-T2 can only determine when the power transient occurs and the magnitude and duration of the transient by using different times M . In this regard, SP-T2 is more restrictive than a battery.

In spite of these limitations compared to generators or batteries, SP-T2 has advantages relative to the less sophisticated methods of TCL control. Comparing to *Unsafe* control method, where TCL set points are simply shifted up or down, the additional timing input in SP-T2 contain the response to a well-defined time frame and eliminates the extended oscillations and the risk associated with these oscillations. The power pulses provided by SP-T2 are potentially useful for peak shaving or spinning reserve applications. However, the timescale of the response may better fit following power supply fluctuations, e.g. when power is provided by intermittent renewable sources.

Given the limitations of SP-T1 and SP-T2, it is necessary to develop another protocol which is 'fast' in responding to the control command and does not give rise to parasitic

oscillations. The SP-T3 protocol accomplishes the objective of generating power pulses of varying magnitudes of the order of few minutes. Thus, SP-T3 can be used to offset fast time scale power pulses which are observed more frequently and can help balance generation and demand.

3.5 SP-T3 Protocol to generate a downward pulse

In SP-T3, TCLs are signaled to turn ON or turn OFF when the control signal is applied depending on the kind of pulse that needs to be generated. In order to generate a downward (abrupt drop in power) pulse, all the TCLs are commanded to turn OFF for few minutes. All that is required is to imbed few basic instructions and some memory so that TCLs can store their original dead band limits. The following flow diagram explains how a downward pulse is generated.

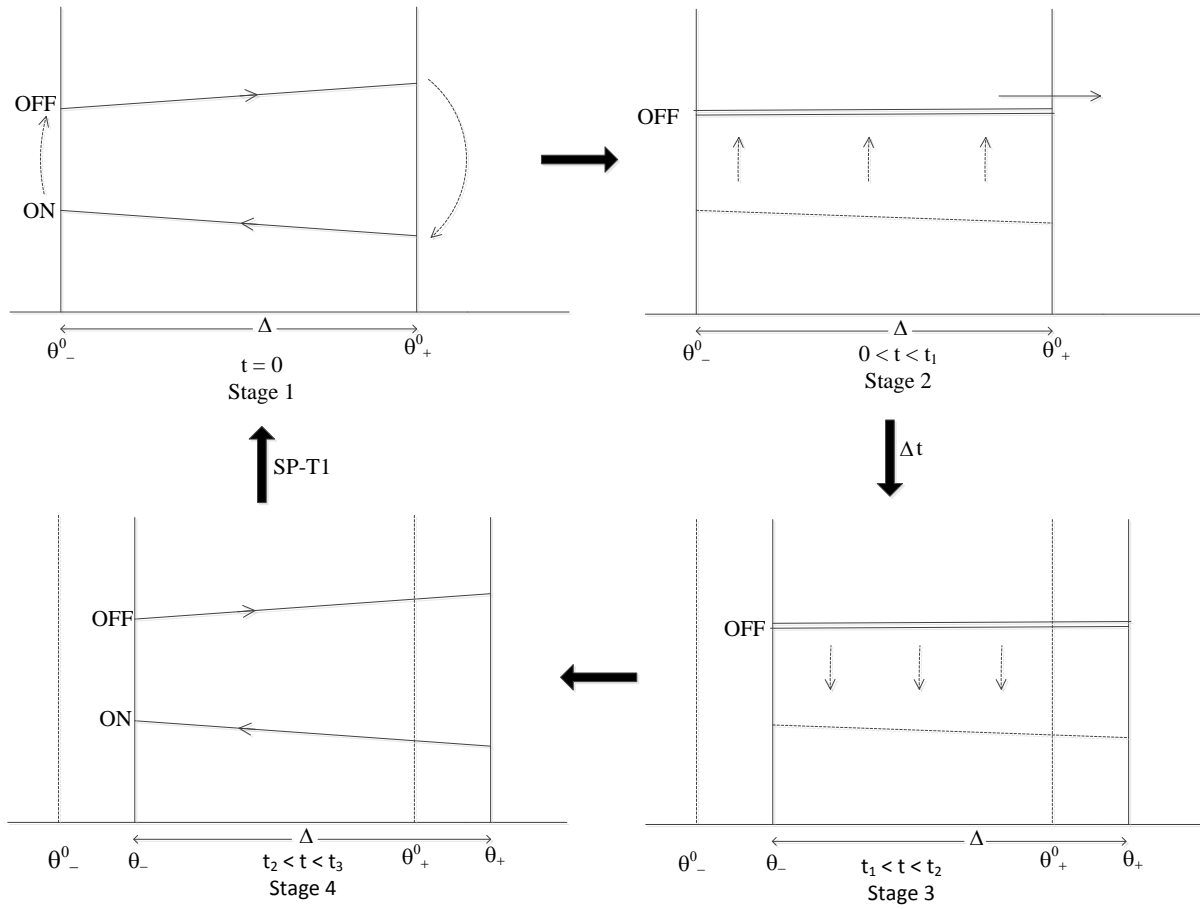


Figure 25: Flow diagram of SP-T3 to generate a downward pulse

Stage 1: All TCLs operate according to their original dead band limits as indicated.

Stage 2: On receiving the control signal, the TCLs in the ON state are instructed to turn OFF for some time Δt (2 to 3 minutes). At this instant, the TCLs store the upper and lower dead band limits. All TCLs continue to remain OFF for time Δt .

Stage 3: After time Δt , the TCLs that were turned OFF in Stage 2 are instructed to turn ON. There will be a sudden drop in aggregated power consumed and a shift in dead band position by the end of Stage 3 for time Δt as shown in Figure 25. However, this shift is not known and the amount of shift depends on the time for which the signal is applied. The set point needs to be shifted back to the original value to ensure that the interference is not permanent.

Stage 4: The set point is brought back to its original position by implementing SP-T1. The transition points are θ_+ and θ_- . The TCLs that are commanded to turn ON in Stage 3 are then made to operate according to the old dead band limits $[\theta_-^0, \theta_+^0]$. However, the TCLs in OFF state continue to remain OFF for time Δt after they reach θ_+^0 and then they are instructed to operate according to the original dead band limits. This stage is necessarily slow unlike Stage 2 to ensure that there are no sharp pulses in the opposite direction.

In order to better understand the flow diagram, an operation of five heterogeneous TCLs is shown below. At time $t = 10$ hours, signal is applied and all air-conditioners that are ON are commanded to switch OFF. Figure 26 shows that one air-conditioner is ON when the signal is applied. This TCL remains OFF till time $t = 10.04$ hours (for around 2 minutes) and then turns ON and starts operating according to the original dead band limits. Whereas, four TCLs that are OFF at time $t = 10$ hours continue to remain OFF for 2 minutes after it has reached the original upper dead band limit of 20.75°C after which these TCLs turn ON and operate within original hysteresis band.

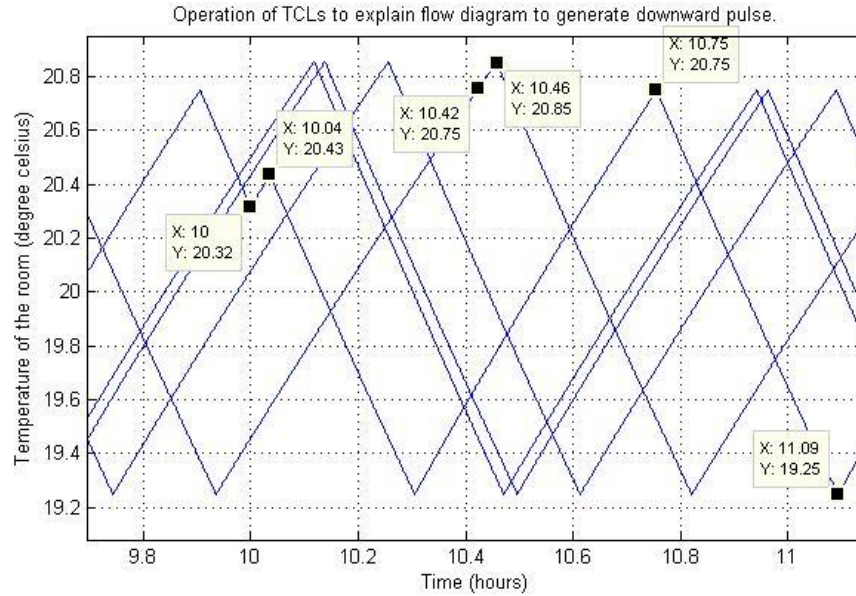


Figure 26: Temperature dynamics of five different TCLs under application of SP-T3 that generates a downward pulse

It is observed that set point shift of 0.1°C occurs for the duration of the applied signal after which the set point is brought back to its original value. Thus, if the signal is applied for few minutes it will not cause the set point to change by a large amount.

3.5.1: Simulation results

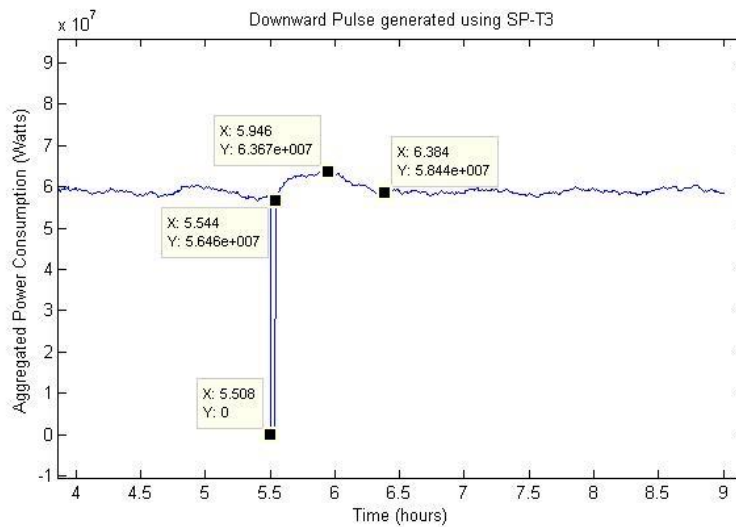


Figure 27: Downward pulse of 2 minutes duration generated by TCL population using SP-T3 safe protocol

Figure 27 shows the simulation of ensemble of 10,000 heterogeneous population of loads. The power drops to zero when the signal is applied at time $t = 5.508$ hours. The signal is applied for 2 minutes after which the aggregated power consumption increases and reaches the steady state value in time equal to that of TCLs time period. Parasitic oscillations are not observed and the peak amplitude when the system tries to reach the equilibrium is found to be a small fraction of the pulse generated. Similarly we can generate different shapes of downward pulses of varying magnitude and width as shown in the following figures.

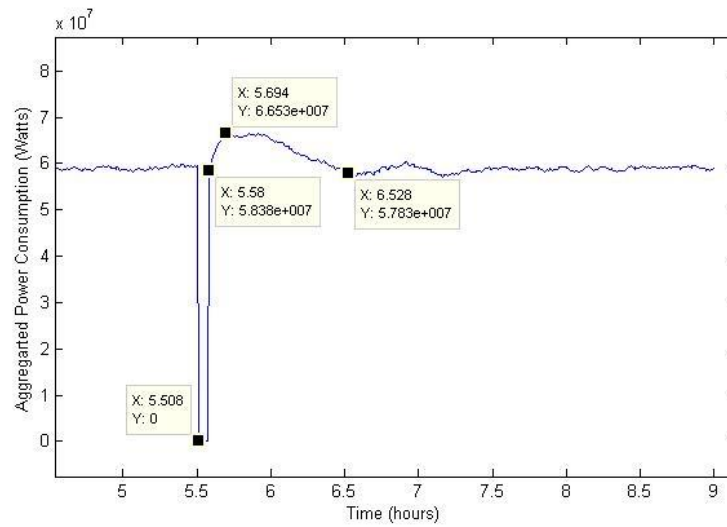


Figure 28: Downward pulse of 4 minutes duration generated by TCL population using SP-T3 safe protocol

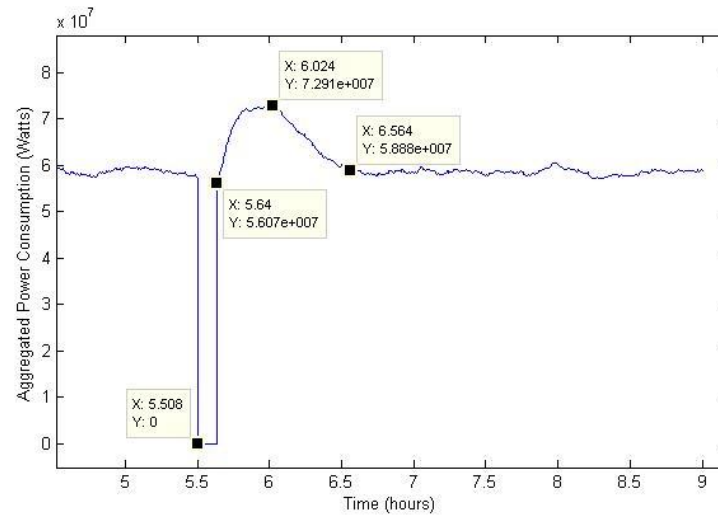


Figure 29: Downward pulse of 8 minutes duration generated by TCL population using SP-T3 safe protocol

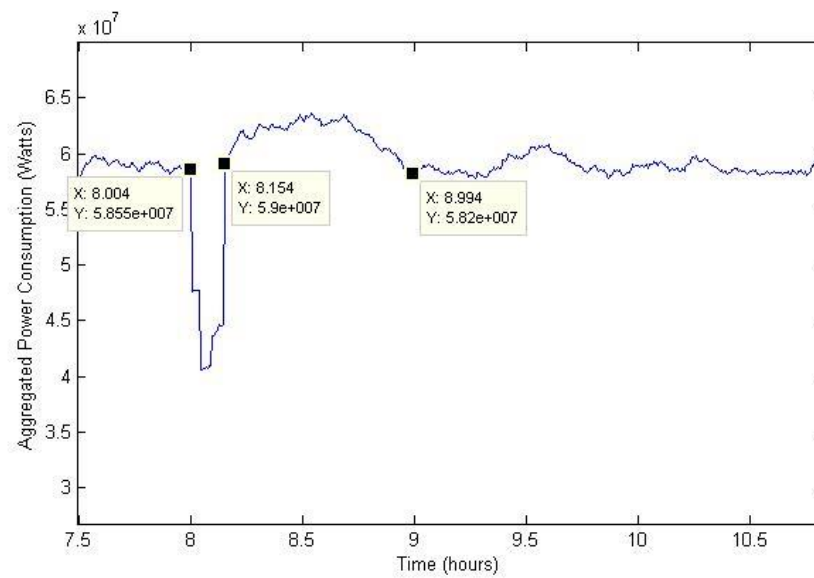


Figure 30: Downward pulse of arbitrary shape generated by TCL population using SP-T3 safe protocol

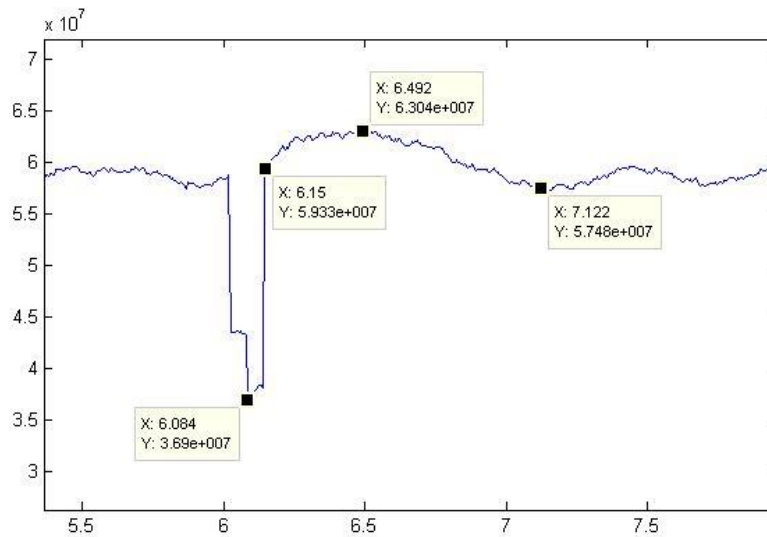


Figure 31: Downward pulse of arbitrary shape generated by TCL population using SP-T3 safe protocol

The control signal is given for 2, 4 and 8 minutes in Figure 27, 28 and 29 respectively. It is observed that longer the width, more is the peak value of power consumed when the system tries to reach equilibrium after the signal is removed. Figure 30 shows 3 arbitrary pulse of 11 MW, 18 MW, and 15 MW generated one after the other. Whereas, Figure 31 shows 2 pulses of magnitudes 15 MW and 21 MW. In all the cases, it is observed that the power consumed reaches its steady state value in time equal to that of TCLs time period.

3.6: SP-T3 Protocol to generate an upward pulse

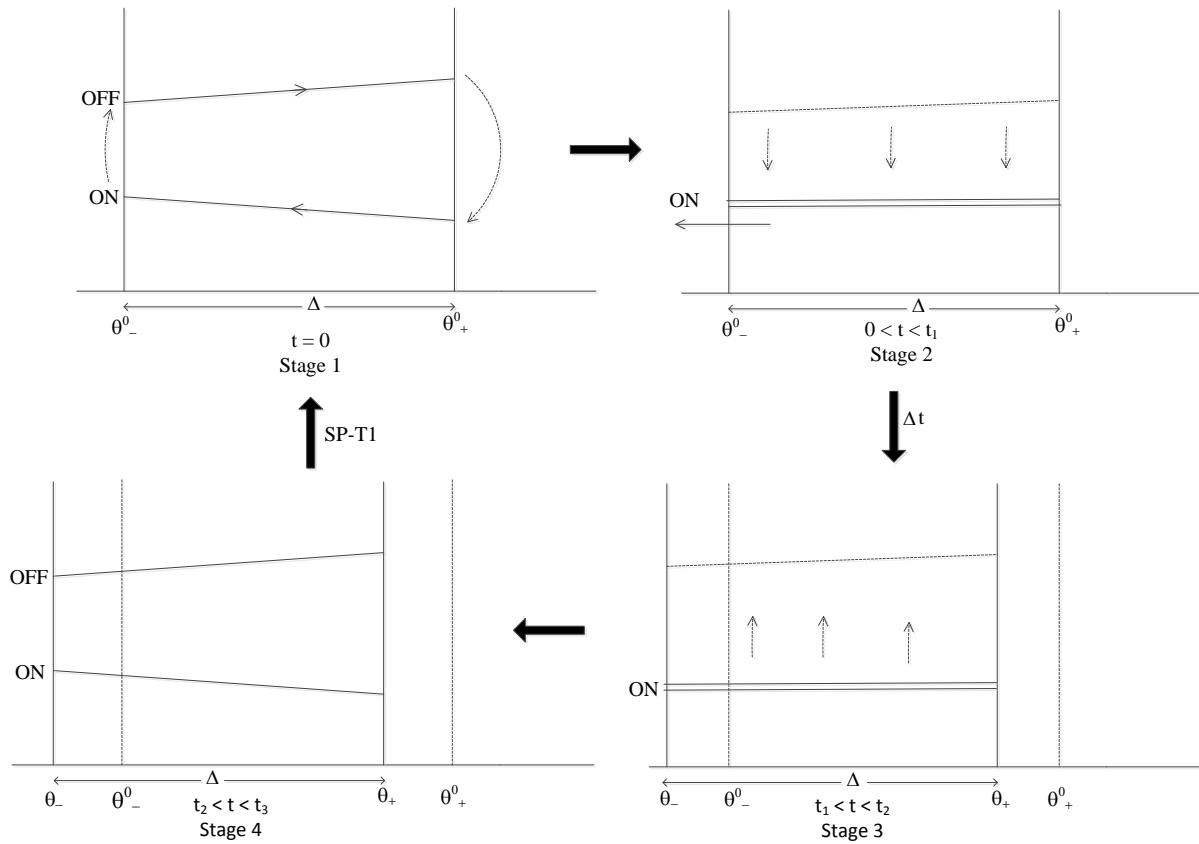


Figure 32: Flow diagram of SP-T3 to generate an upward pulse

Stage 1: All TCLs operate according to their original dead band limits as indicated.

Stage 2: On receiving the control signal, the TCLs in OFF state are instructed to turn ON. At this instant, the TCLs store the upper and lower dead band limits. All TCLs continue to remain ON for time Δt .

Stage 3: During time Δt maximum power will be consumed by the ensemble as all the TCLs are ON. However, in this case the dead band is shifted towards left as shown in Figure 32 and the amount of shift is not known. At the end of time Δt , the TCLs that were commanded to turn ON in Stage 2 are instructed to turn OFF.

Stage 4: The set point is brought back to its original position by implementing SP-T1. The TCLs that turned OFF at the end of Stage 3 operate according to their original dead band limits $[\theta_-^0, \theta_+^0]$. Whereas, the TCLs that were ON remain ON for time Δt after they reach θ_-^0 and then turn OFF and start operating with the original dead band limits. At the end of Stage 4, all TCLs operate as shown in Stage 1 and the set point is brought back to its original value.

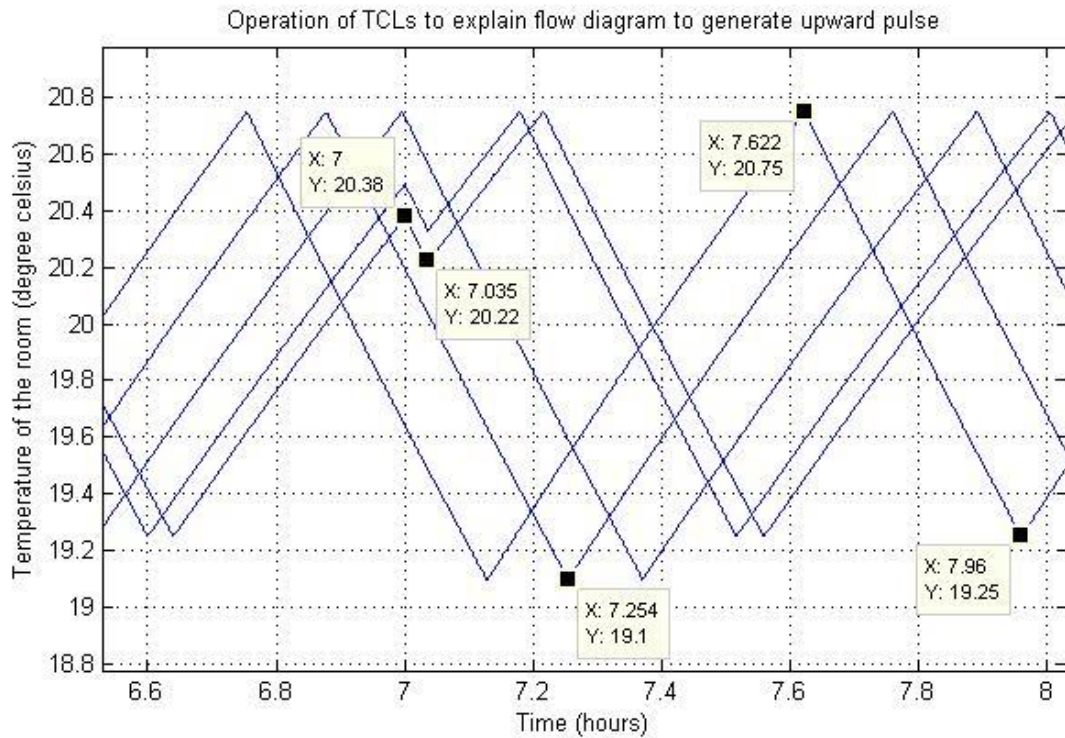


Figure 33: Temperature dynamics of five different TCLs under application of SP-T3 that generates an upward pulse

Figure 33 shows operation of five heterogeneous TCLs to explain the flow diagram. The signal is applied at time $t = 7$ hours. It is observed that two TCLs that were OFF, turn ON for 2 minutes and then switch OFF and start operating according to original dead band limits of $[19.25^\circ\text{C}, 20.75^\circ\text{C}]$. Whereas at the time of application of signal the other three TCLs that were ON, remain ON for 2 minutes after they reach 19.25°C and then turn OFF and operate with original dead band limits. It is observed that in during the time of application of signal, the dead band is shifted by 0.15°C and is then restored to its initial position.

3.6.1: Simulation results

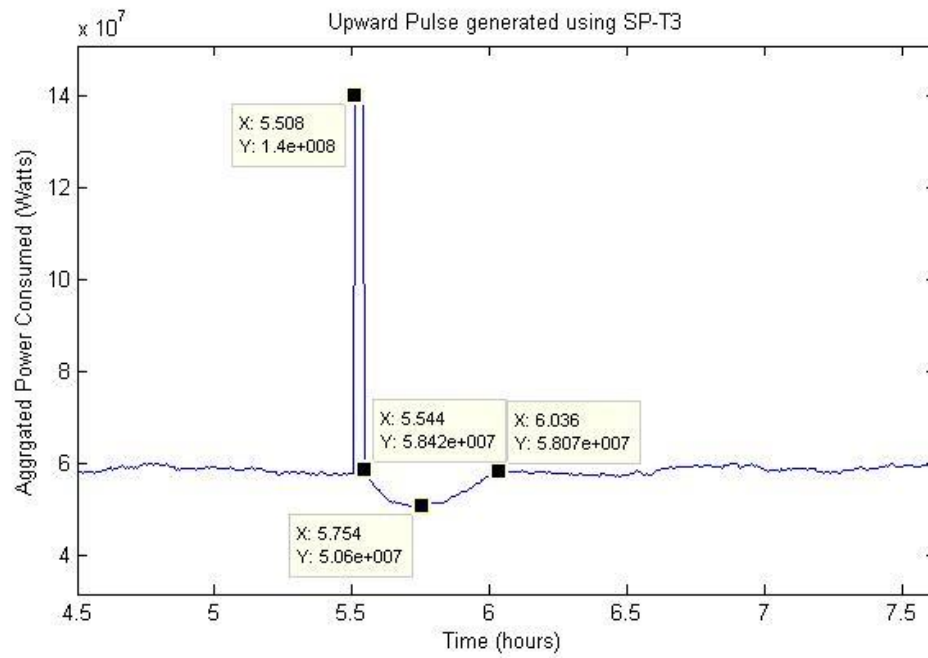


Figure 34: Upward pulse of 2 minutes duration generated by TCL population using SP-T3 safe protocol

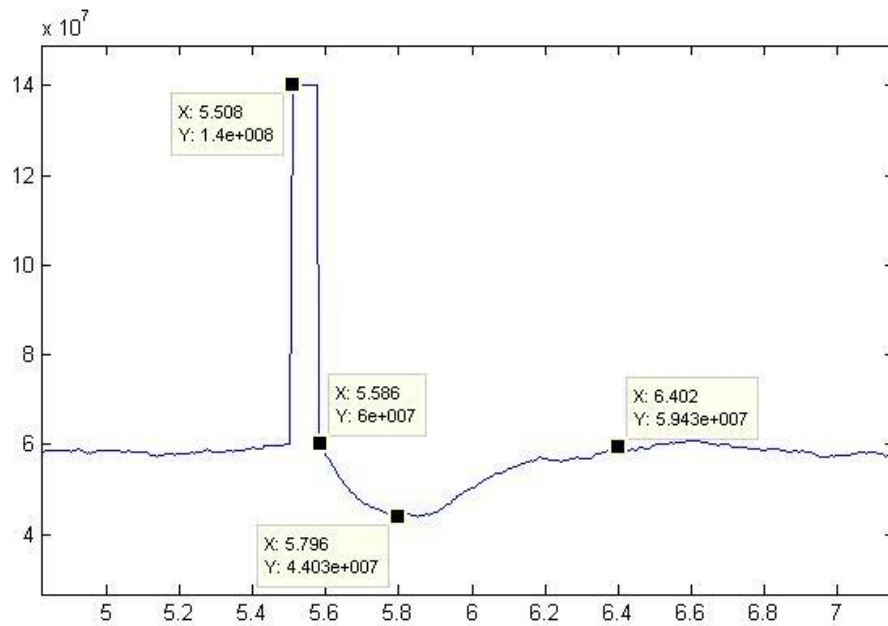


Figure 35: Upward pulse of 4 minutes duration generated by TCL population using SP-T3 safe protocol

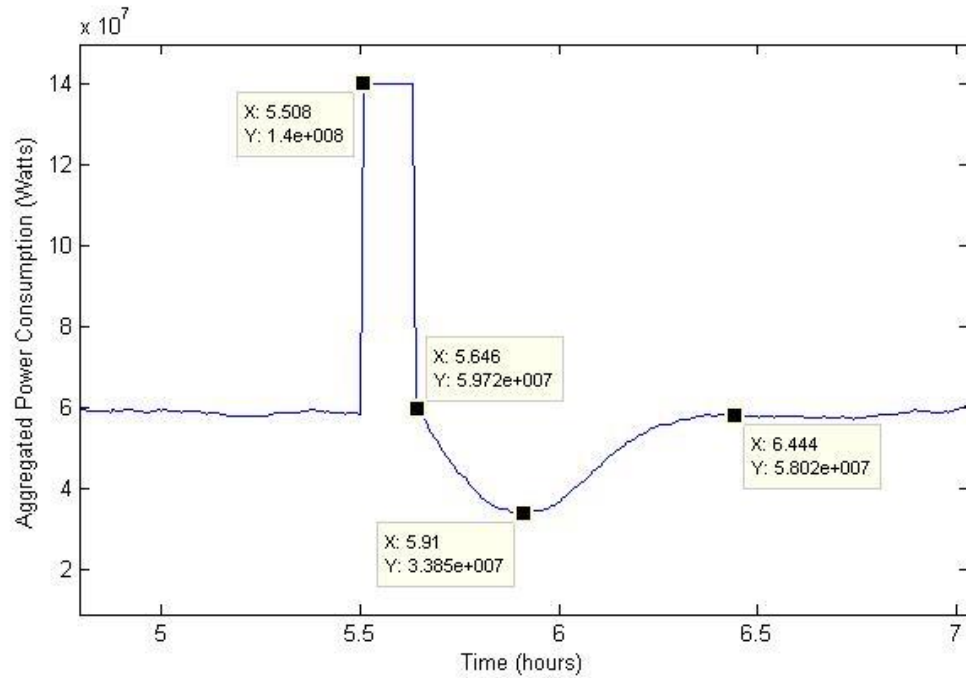


Figure 36: Upward pulse of 8 minutes duration generated by TCL population using SP-T3 safe protocol

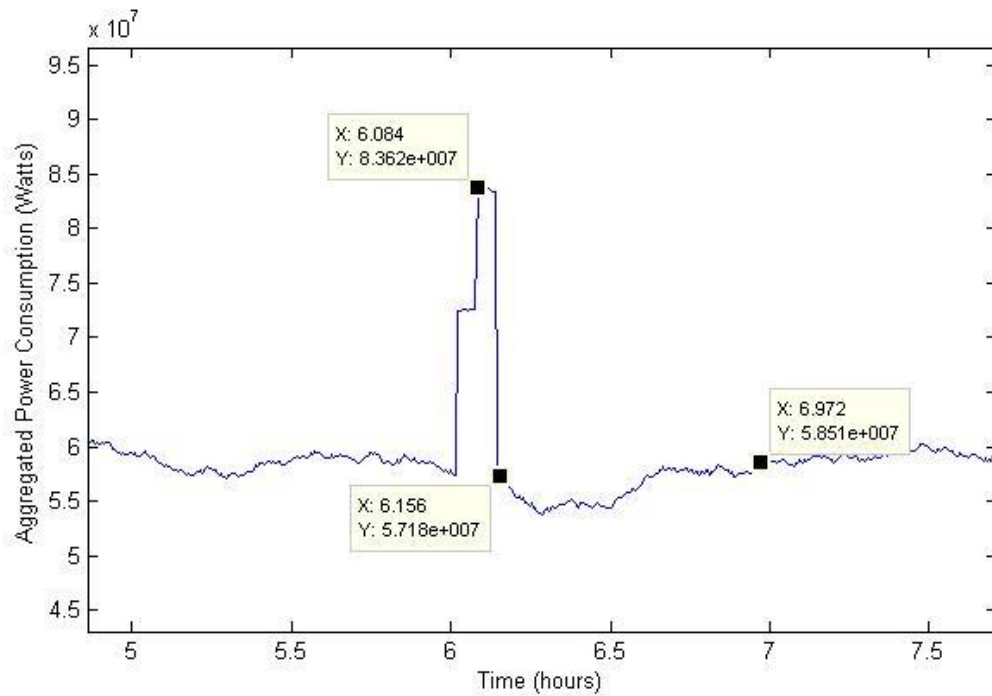


Figure 37: Upward pulse of arbitrary shape generated by TCL population using SP-T3 safe protocol

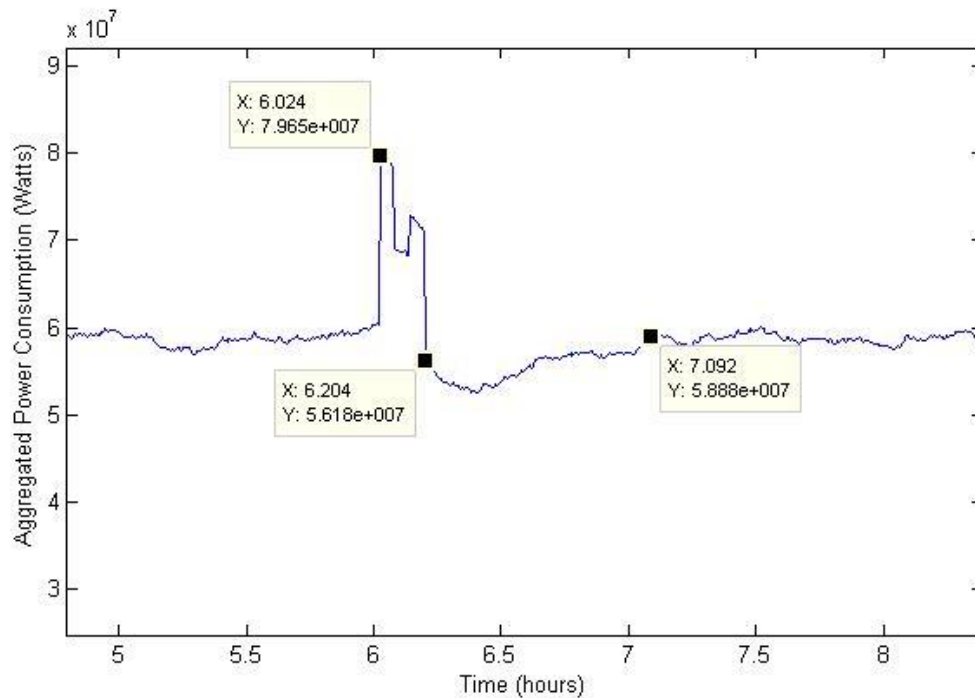


Figure 38: Upward pulse of arbitrary shape generated by TCL population using SP-T3 safe protocol

A heterogeneous population of 10,000 TCLs is simulated. The control signal is given for 2, 4 and 8 minutes in Figure 34, 35 and 36 respectively. As each TCL consumes 14 kW when ON, the aggregated power consumption rises to the maximum value of $14 \text{ kW} \times 10,000 = 140 \text{ MW}$ for the duration of applied signal. More the width of the pulse more is the peak power consumed in the opposite direction. However, in each case it is observed that the aggregated power consumed reaches its steady state value in time equal to that of TCLs time period without giving rise to any parasitic oscillations. Figure 37 shows two pulses of magnitudes 15 MW and 25 MW for the duration of 3.6 minutes each. And three pulses of magnitudes 20 MW, 10 MW and 15 MW are shown in Figure 38 where width of each pulse is 3.6 minutes. In a similar manner both upward and downward pulse can be generated and an arbitrary demand profile can be created.

3.7: Merits and Shortcomings of Safe Protocol (SP-T3)

Merits: 1) Fast time scale pulses of different magnitude and duration can be generated without giving rise to unwanted oscillations that occur due to synchronization of individual phases of TCLs, 2) interference with the operation of TCLs is only for few minutes and then the set point is brought back to its original value, 3) signal applied for a short duration will not lead to customer dissatisfaction and there is no risk to customer privacy, 4) it just requires a one way communication channel to instruct the TCLs to turn ON or turn OFF eliminating the need of installing smart meters.

Shortcomings: 1) finite size of TCLs limit the total power consumed and the maximum magnitude of pulse that can be generated, 2) frequent switching of TCLs can increase the fatigue.

Chapter 4: Offsetting fast time scale fluctuations

In the previous chapter we studied different protocols to generate a power pulse. In this chapter, we will look at how SP-T3 can help offset fast time scale fluctuations on the order of 2 to 3 minutes. Considering a huge ensemble of heterogeneous population of loads, a group of TCLs are switched ON or OFF depending on the type of pulse to be generated. Having the knowledge of the net-demand profile from the utility, we apply control to different group of TCLs thus avoiding frequent switching to the same set of TCLs. The magnitude of the pulse to be generated is directly proportional to the size of the ensemble. This can be explained as follows:

$$P_- = \alpha_- * N \quad (13)$$

$$P_+ = \alpha_+ * N \quad (14)$$

where N is the size of the ensemble, P_- and P_+ are magnitude and α_- and α_+ are the constants of proportionality for downward and upward pulses respectively. Thus, α_- and α_+ can be calculated from (13) and (14). Let us divide the ensemble into different groups such that:

$$N = \sum_{i=1}^n N_i \quad (15)$$

Fluctuations may occur in either direction and increase during peak hours. It is required that TCLs respond immediately to offset these fluctuations. If the fluctuation is in the upward direction, we will generate the pulse in the downward direction to maintain a flat demand profile. Knowing the magnitude of the fluctuation that occurs at time t_1 and the constant of proportionality, the number of TCLs (say N_1) to which the turn OFF signal should be applied is:

$$N_1 = \frac{P_{up}}{\alpha_-} \quad (16)$$

where P_{up} is the fluctuation in the upward direction. Now suppose at time t_2 the fluctuation occurs in downward direction. In order to offset it we will generate the pulse in the upward direction. Then, the number of TCLs (say N_2) that are commanded to remain ON for a short duration is:

$$N_2 = \frac{P_{dn}}{\alpha_+} \quad (17)$$

where P_{dn} is the fluctuation in the downward direction. In this way control can be applied to different groups of TCLs till the sum of TCLs of all the groups equal N , after which the process can be repeated.

4.1: Simulation Results

Following are the simulation results that demonstrate the effectiveness of SP-T3 in offsetting fast time scale fluctuations without leading to synchronization of individual states of TCLs.

4.1.1: Heterogeneous Population of 10,000 TCLs

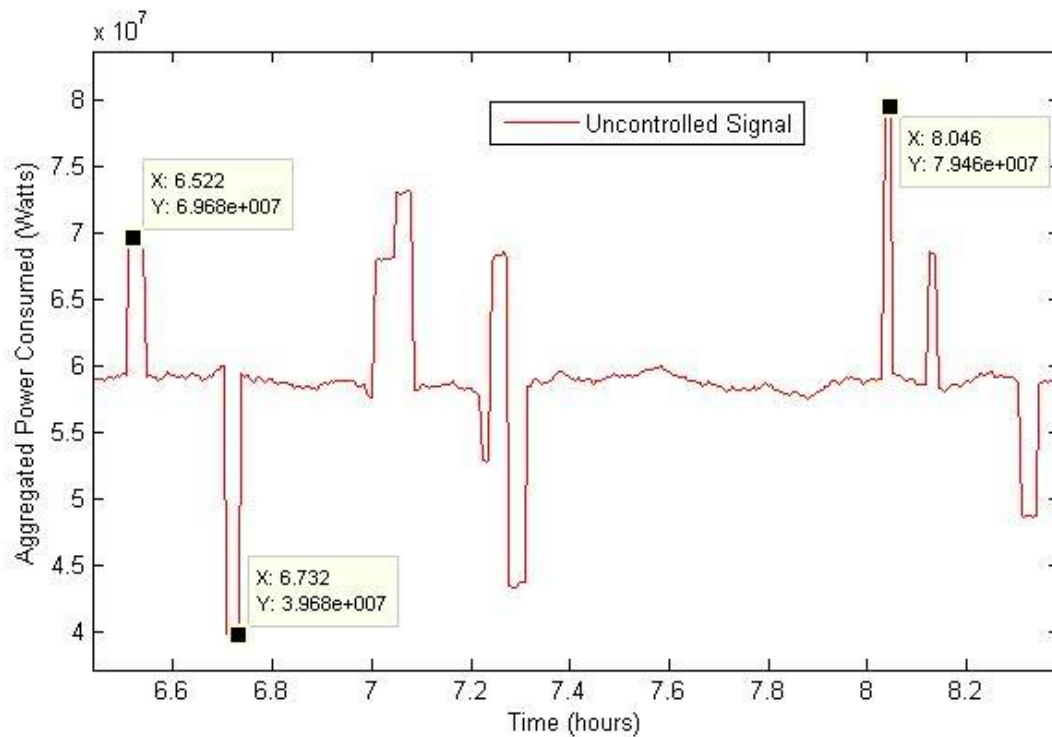


Figure 39: Aggregated Power Consumption of 10,000 TCLs plus the arbitrary external fluctuations that operator desires to eliminate

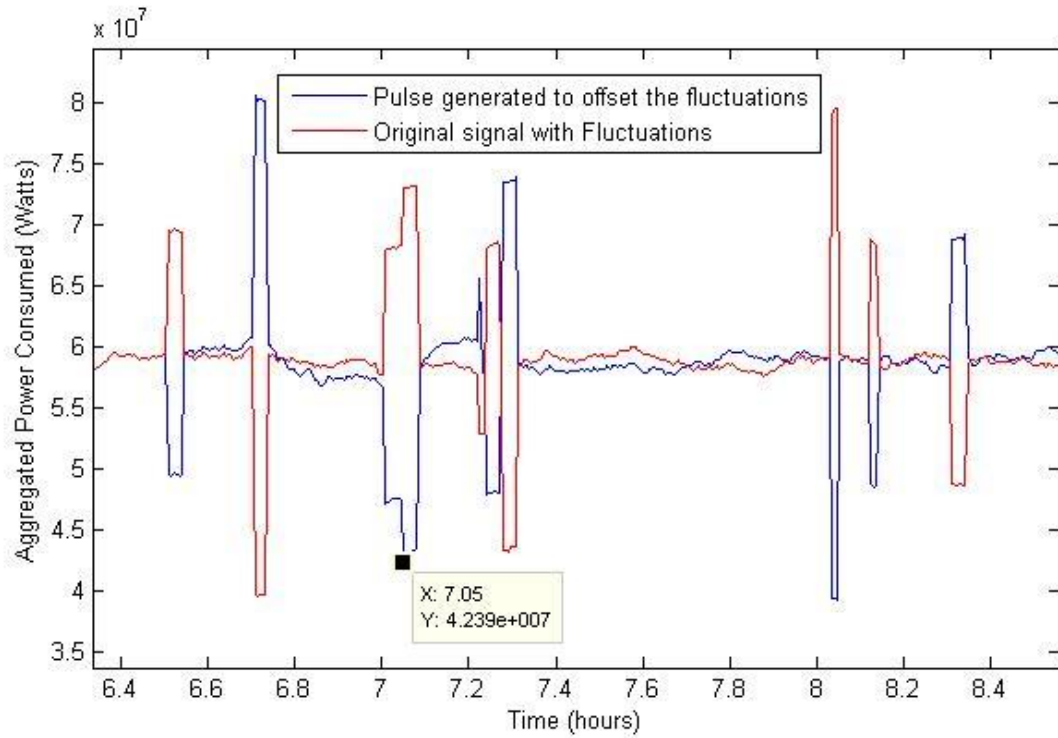


Figure 40: Offsetting fast time scale fluctuations. Blue curve is the power output of the TCL ensemble that receives control signal to reduce fluctuations (red)

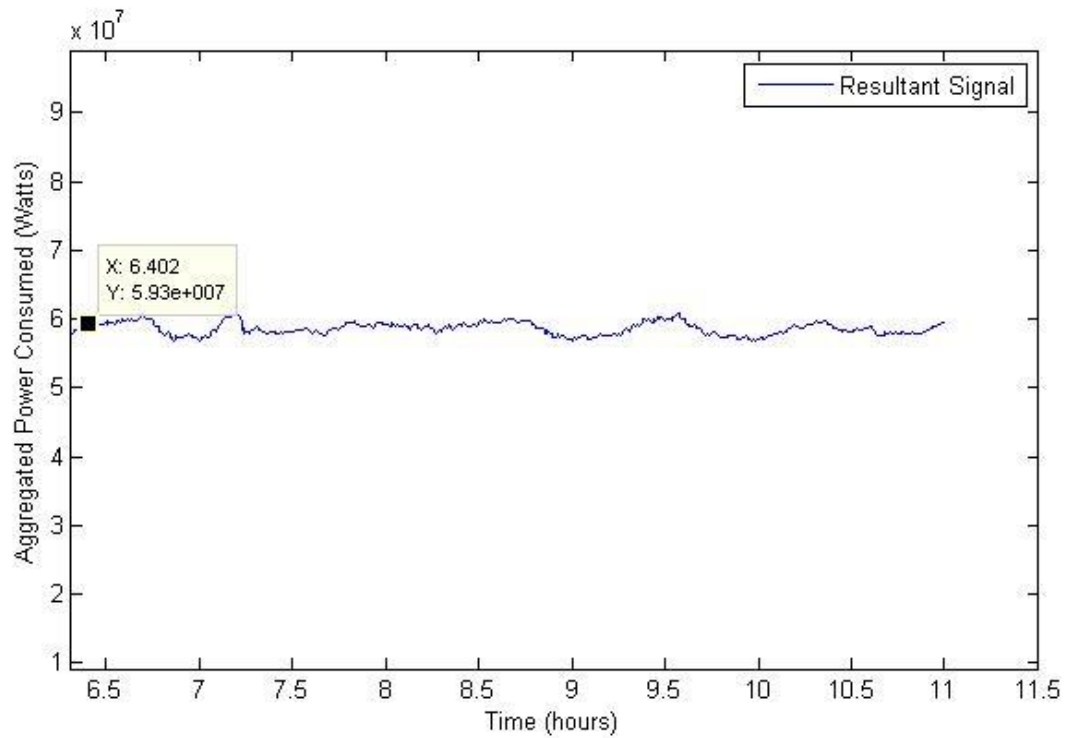


Figure 41: Resultant Signal

Figure 39 shows the arbitrary demand profile. This is a simple case where pulses are generated either in upward or downward direction. We observe that there are fluctuations of the order of 5 MW to 20 MW. The average power consumption is 59.1484 MW. When there is sudden rise in power consumed for a small duration, a sufficient number of TCLs should be signaled to turn OFF so that we obtain a flat demand profile. Similarly if there is a drop in power consumed, the required number of TCLs should be turned ON. The blue signal in Figure 40 shows the pulses that are equal in magnitude and duration but are in the opposite direction to that of the fluctuation. The resultant signal is shown in Figure 41 and the average power consumption on application of control is 58.7542 MW.

4.1.2: Heterogeneous Population of 15,000 TCLs

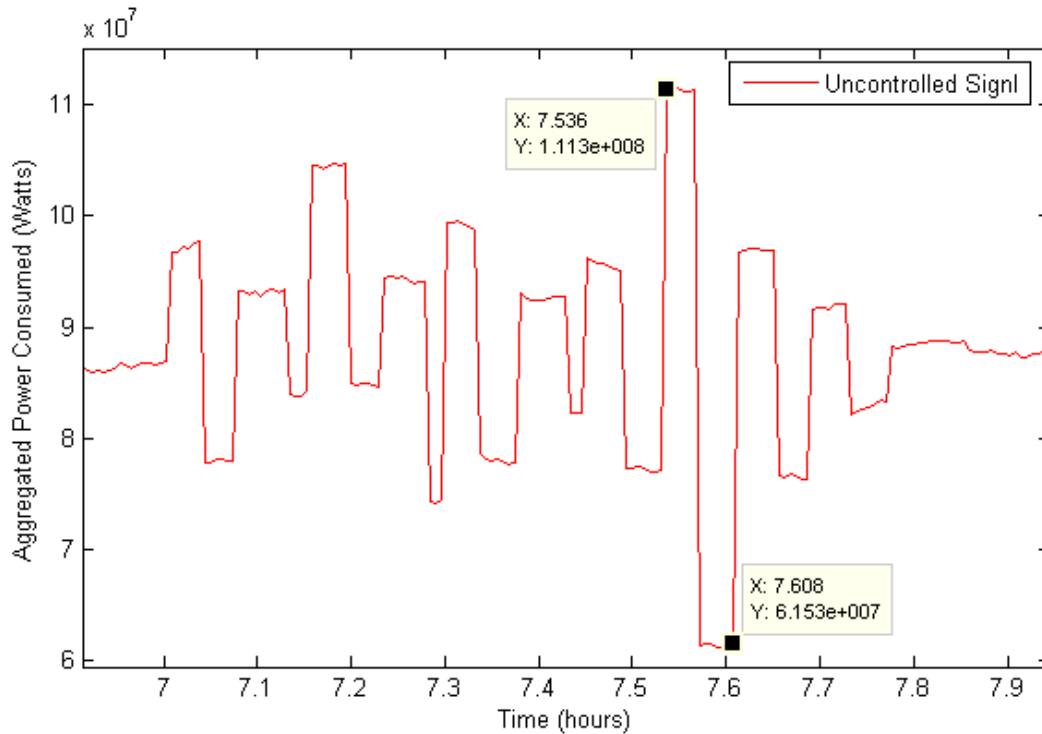


Figure 42: Aggregate Power Consumed by 15,000 TCLs plus the step-like external fluctuations that operator desires to eliminate

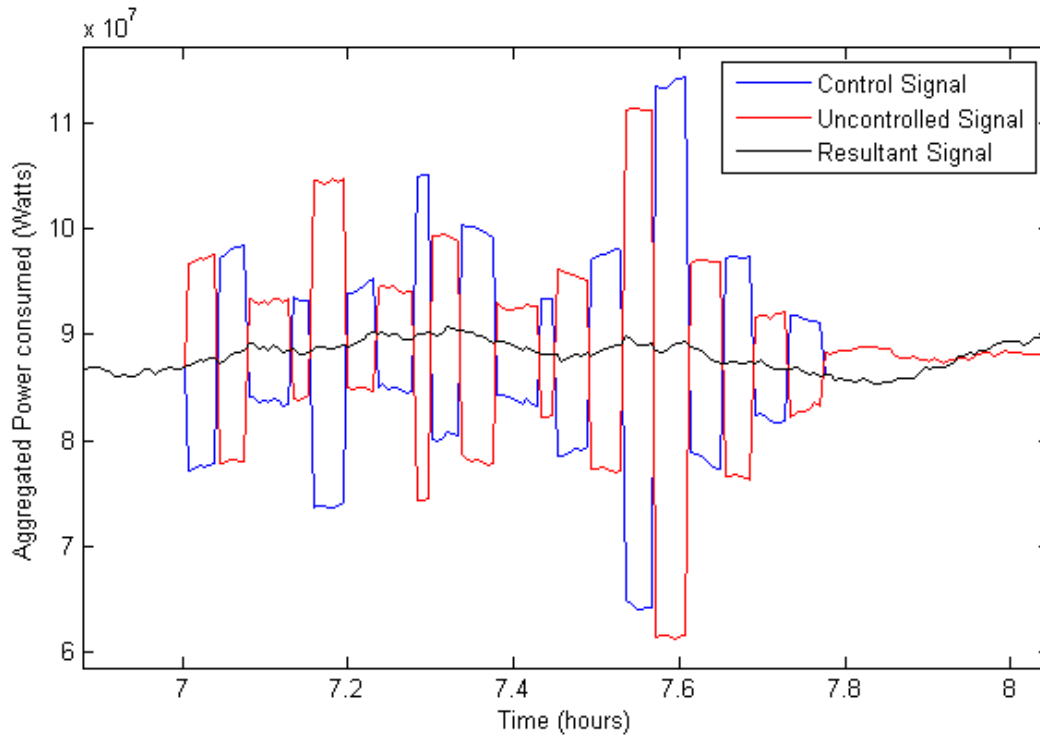


Figure 43: Offsetting fast time scale fluctuations. Blue curve is the power output of the TCL ensemble that receives control signal to reduce fluctuations (red). Black curve is the total power consumption, which illustrates the smoothing effect of control

Figure 42 shows a series of fluctuations occurring continuously one after another. As the size of the ensemble is bigger, the magnitude of fluctuations is also large. A pulse with a maximum magnitude of 25 MW is shown to be generated. For better comparison, Figure 43 shows the control, the uncontrolled and the resultant signal. These set of results demonstrate that TCLs are able to respond quickly to offset fast time scale fluctuations that occur continuously due to variation in demand. The average power consumed with the uncontrolled signal is calculated to be 88.5274 MW. Thus, we observe that on applying the control to generate the pulse in opposite direction we are able to get a flat demand profile. The average power consumed of the resultant signal is 88.5137 MW. The control is applied from time $t = 7$ hours to time $t = 7.8$ hours.

4.1.3: Heterogeneous Population of 25,000 TCLs

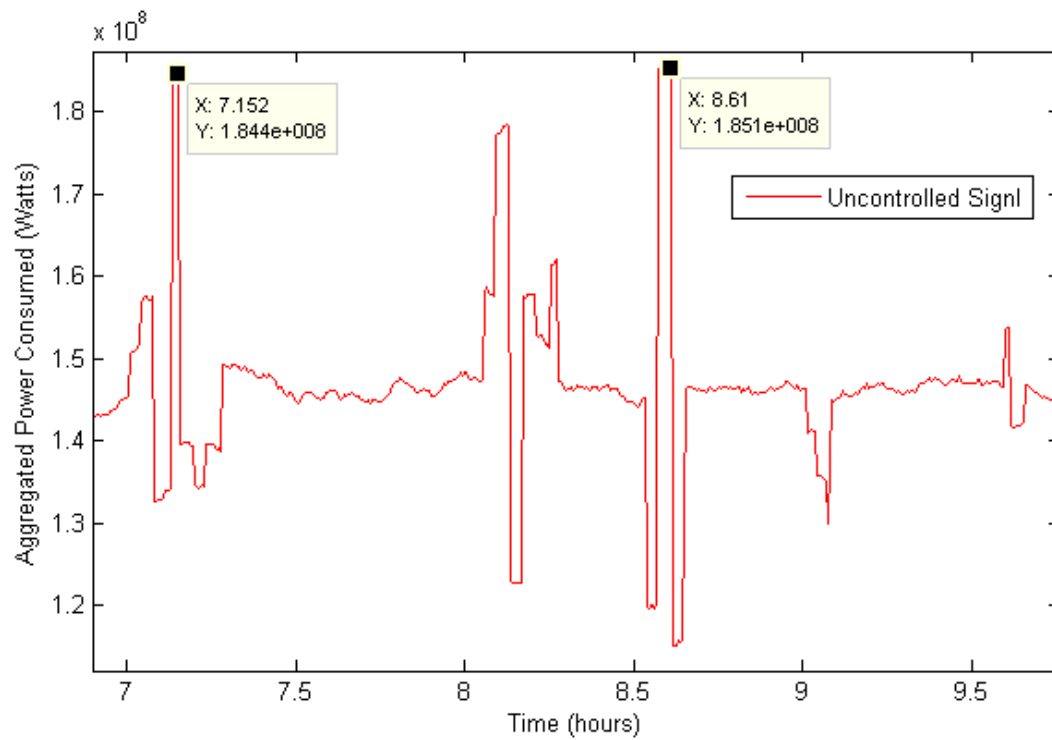


Figure 44: Aggregate Power Consumed by 25,000 TCLs plus the arbitrary external fluctuations that operator desires to eliminate

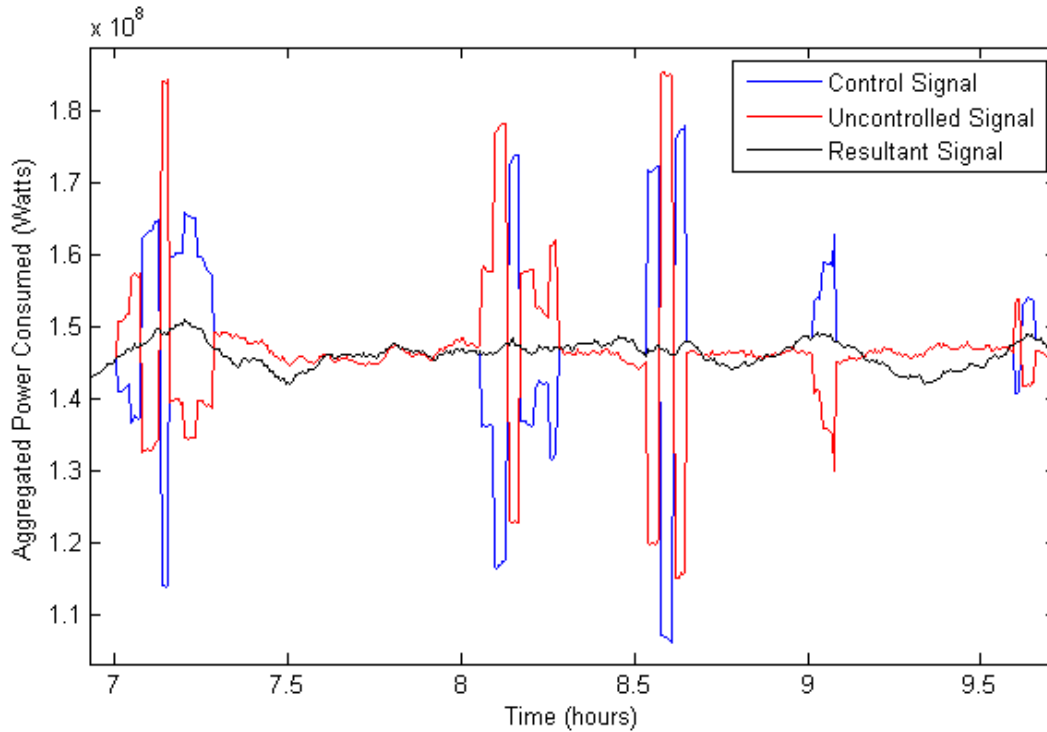


Figure 45: Offsetting fast time scale fluctuations. Blue curve is the power output of the TCL ensemble that receives control signal to reduce fluctuations (red). Black curve is the total power consumption, which illustrates the smoothing effect of control

Figure 44 shows a more general case of fluctuations with random shapes. With an increase in size of the ensemble, pulses of magnitude 35 MW to 40 MW can be generated to offset the fluctuations. The versatility of SP-T3 lies in the fact that pulses of arbitrary shapes can be generated for short duration without leading to any parasitic oscillations. The average power consumption of the uncontrolled signal is 144.6641 MW and that of the resultant signal is 146.3518 MW.

Chapter 5: Understanding the role of heterogeneity

In previous chapters we investigated the aggregated power response of heterogeneous population of loads. The ambient temperature, set point and the dead band width were kept constant and the response to the control signal was studied assuming that aggregated power consumption is initially fully equilibrated [12], [17], [19]. In reality, ambient temperature continuously changes during the day. If the degree of randomness is not sufficiently strong, the assumption that the ensemble is near equilibrium may not apply. In order to justify the additive noise, in this chapter we will investigate the aggregated power consumed in the absence of noise with more complex models. We will vary the ambient temperature, set point and dead band width and study the effect of heterogeneity in helping the aggregated power reach a steady state.

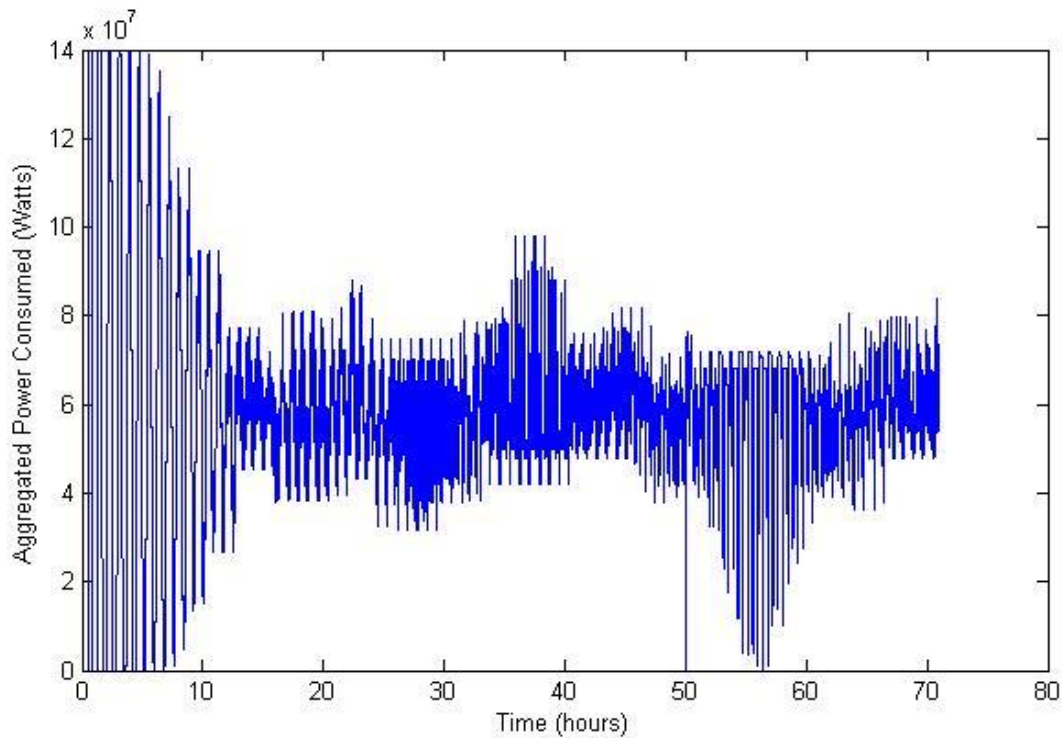


Figure 46: Aggregated power consumed by 10,000 heterogeneous population of TCLs keeping the ambient temperature, set point and the dead band width constant

Figure 46 shows the aggregated power consumed by 10,000 heterogeneous population of TCLs keeping the ambient temperature, set point and the dead band width constant. The heterogeneity of the above loads lies in a fact that the thermal resistance and the thermal capacitance of all TCLs are different. We observe that, in the absence of noise, the system does not reach a steady state value and oscillations are seen to persist for the entire time. The control signal is applied at time $t = 50$ hours signaling all TCLs to turn OFF for 2 minutes. After the time duration of the control signal, parasitic oscillations occur due to synchronization of individual states of TCLs. Thus, in this case it is very difficult to test the effectiveness of the safe protocol. In the next part we will vary the ambient temperature and look at different cases to understand the role of heterogeneity.

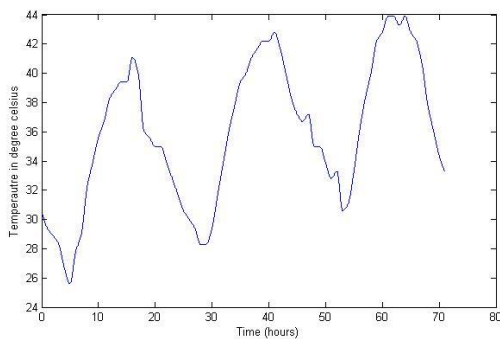


Figure 47: Ambient temperature in Arizona

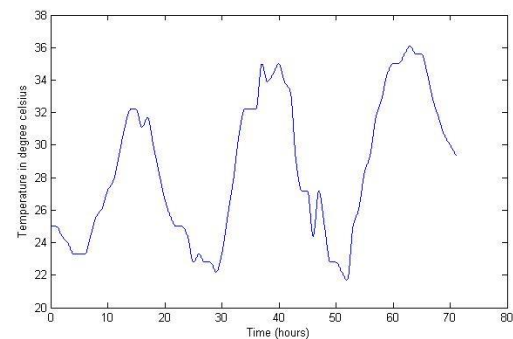


Figure 48: Ambient temperature in Madison

Figure 47 and Figure 48 shows the ambient temperature variation in Arizona and Madison respectively during summer 2012 [43]. We will consider the following three cases to test the heterogeneity for both cities:

1. Varying ambient temperature keeping dead band limits and dead band widths constant.
2. Varying the ambient temperature and dead band limits keeping the dead band widths constant.
3. Varying ambient temperature, dead band limits and dead band widths.

In the first section we will look at the above three cases for ambient temperature variation in Arizona and in the next section we will present results for Madison.

5.1 Arizona

We consider a heterogeneous population of 10,000 loads. The control signal is applied at time $t = 50$ hours in all the cases signaling all the TCLs to turn OFF for 2 minutes.

5.1.1: Varying ambient temperature keeping dead band limits and dead band widths constant

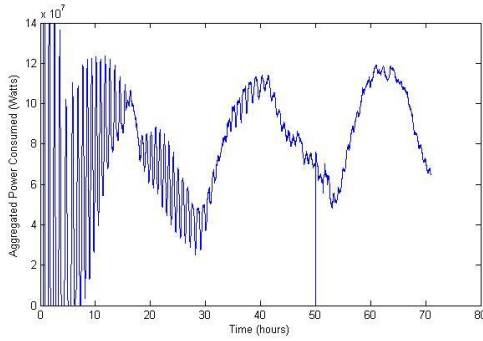


Figure 49: Aggregated power consumed with varying ambient temperature in absence of noise

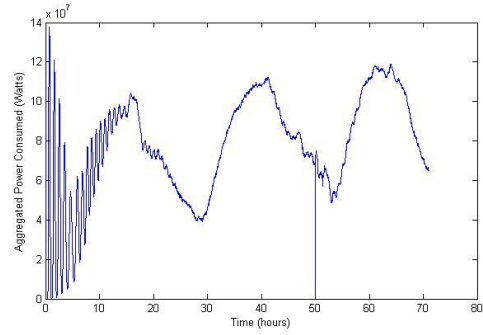


Figure 50: Aggregated power consumed with varying ambient temperature with negligible amount of noise

Figure 49 shows the variation in aggregated power consumed in absence of noise. Whereas, negligible amount of noise is added in Figure 50 by generating pseudorandom numbers having normal distribution. The variation in aggregated power is observed to vary in a similar way as that of an ambient temperature. We have seen earlier in the case where ambient temperature was kept constant, the aggregated power was also found to remain constant. We see that as the degree of heterogeneity is increased, oscillations damp out after some time unlike the case in Figure 46. Also the safe protocol SP-T3 works as desired and does not lead to synchronization of individual states of TCLs after the control signal is removed. However,

oscillations damp out quickly in the second figure due to presence of noise as expected. The aggregated power consumed is found to be 77.6054 MW and 77.6123 MW respectively.

5.1.2: Varying the ambient temperature and dead band limits keeping the dead band widths constant

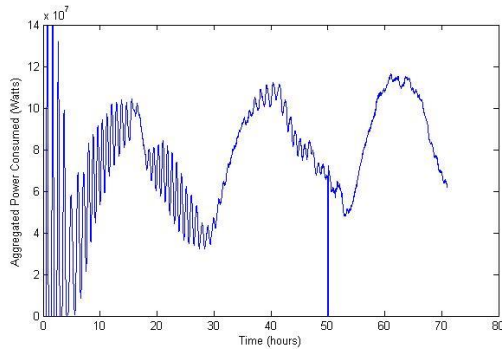


Figure 51: Aggregated power consumed with varying ambient temperature and dead band limits in absence of noise

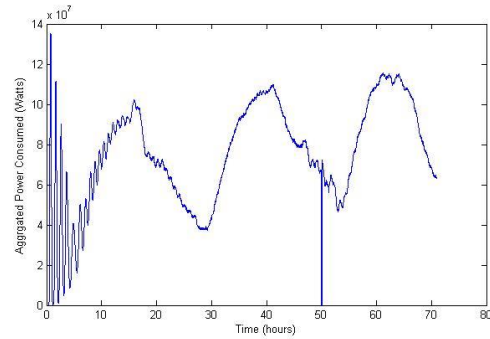


Figure 52: Aggregated power consumed with varying ambient temperature and dead band limits with negligible amount of noise

In the above figures we see that the amplitude of initial oscillations are smaller than in the previous case as the degree of heterogeneity is increased and SP-T3 works as expected. The mean and standard deviations of the dead band limits, set point and the average power consumed is shown in the table below for both the cases.

Table 1: Mean and standard deviation of different parameters when downward pulse is created and only the dead band widths are kept constant

	Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Average Power (MW)
	Mean	Standard Deviation (SD)	Mean	Standard Deviation (SD)	Mean	Standard Deviation (SD)	
No Noise	21.2479	0.2901	19.7479	0.2901	20.4979	0.2901	75.1843
Noise	21.2519	0.2899	19.7519	0.2899	20.5019	0.2899	75.1758

5.1.3: Varying ambient temperature, dead band limits and dead band widths

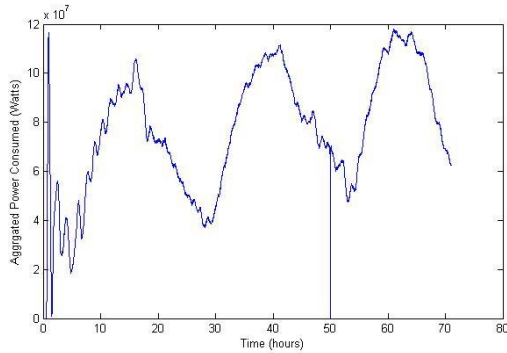


Figure 53: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths in absence of noise

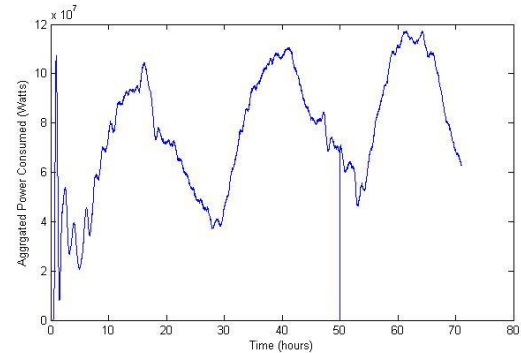


Figure 54: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths with negligible amount of noise

In the above figures the oscillations damp out earlier as compared to all previous cases. The amplitude of oscillations is also less. This is because the population is heterogeneous in all respects. Also there is very close resemblance between Figure 53 and Figure 54. Calculations are tabulated below.

Table 2: Mean and standard deviation of different parameters when downward pulse is created and the ensemble is heterogeneous in all respects

	Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Dead band width (DW) $^{\circ}\text{C}$		Average Power (MW)
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
No Noise	21.2470	0.2885	19.2435	0.4062	20.2453	0.3218	2.0035	0.2867	76.3679
Noise	21.2485	0.2884	19.2489	0.4057	20.2487	0.3210	1.995	0.2885	76.3695

Similarly, we can signal all TCLs to turn ON for 2 minutes at time $t = 50$ hours and generate an upward pulse as shown and results are tabulated:

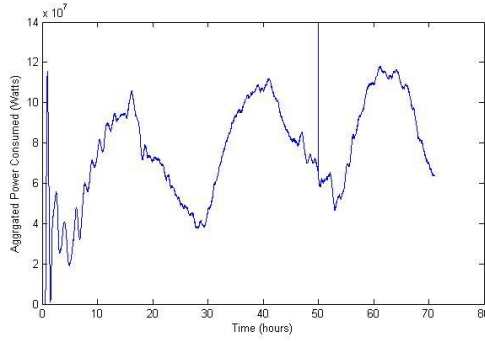


Figure 55: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths in absence of noise when an upward pulse is created

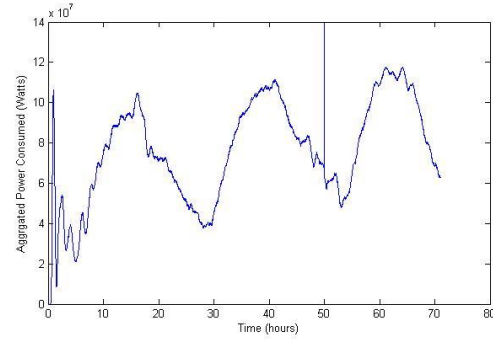


Figure 56: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths with negligible amount of noise when an upward pulse is created

Table 3: Mean and standard deviation of different parameters when upward pulse is created and the ensemble is heterogeneous in all respects

	Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Dead band width (DW) $^{\circ}\text{C}$		Average Power (MW)
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
No Noise	21.2534	0.2863	19.2517	0.4047	20.2562	0.3196	2.0017	0.2891	76.3368
Noise	21.2591	0.2878	19.2605	0.4106	20.2598	0.3237	1.9986	0.2895	76.2997

In this case, for better comparison we plot the controlled and uncontrolled signal together to ensure proper working of SP-T3.

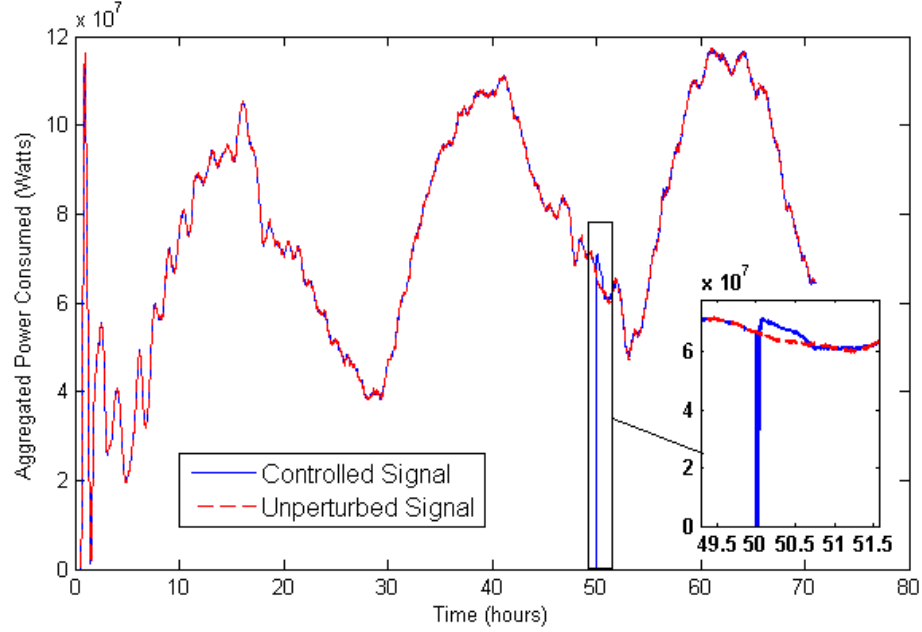


Figure 57: Aggregated power response of controlled (blue) and unperturbed (red) TCL ensemble when a downward pulse is created

Figure 57 shows our results for the aggregated power consumed by an ensemble of 10,000 TCLs. The blue signal represents the controlled signal and the red signal is the signal at no control. In the blue trace, all TCLs subject to a 2 minute SP-T3 at time $t = 50$ hours to generate downward pulse and return to the initial set point. We find that, after the duration of the applied signal, synchronization of individual states of TCLs does not take place and extra oscillations are not observed. It shows, in particular, that the broad heterogeneity of the ensemble, alone, is sufficient to make power consumption of TCLs relatively smooth while clearly following the trend of the outdoor temperature dynamics.

SP-T3 works as desired, i.e. we did not observe any additional side effects on top of the natural power demand evolution and fluctuations of the ensemble. We observe that both signals trace the same path ensuring proper working of the safe protocol as described in section IV. The mean, standard deviation (SD) of distribution of different TCL parameters are tabulated in Table 4.

Table 4: Mean and standard deviation of different parameters when a downward pulse is created

Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Dead band width (DW) $^{\circ}\text{C}$	
Mean	SD	Mean	SD	Mean	SD	Mean	SD
21.2463	0.2895	19.2435	0.4076	20.2449	0.3230	2.0027	0.2873

Similarly Figure 58 demonstrates generation of upward pulse and results are tabulated in Table 5.

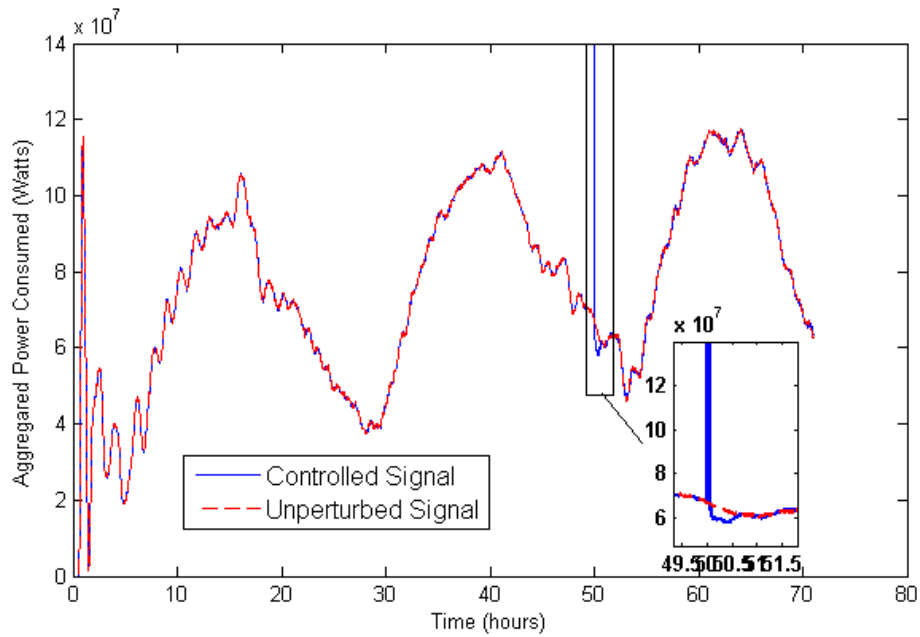


Figure 58: Aggregated power response of controlled (blue) and unperturbed (red) TCL ensemble when an upward pulse is created

Table 5: Mean and standard deviation of different parameters when an upward pulse is created

Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Dead band width (DW) $^{\circ}\text{C}$	
Mean	SD	Mean	SD	Mean	SD	Mean	SD
21.2521	0.2891	19.2552	0.4052	20.2537	0.3207	1.9969	0.2899

5.2 Madison

We consider a heterogeneous population of 10,000 loads. The control signal is applied at time $t = 50$ hours in all the cases signaling all the TCLs to turn OFF for 2 minutes.

5.2.1: Varying ambient temperature keeping dead band limits and dead band widths constant

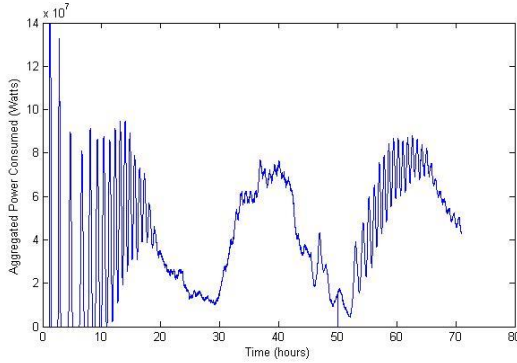


Figure 59: Aggregated power consumed with varying ambient temperature in absence of noise

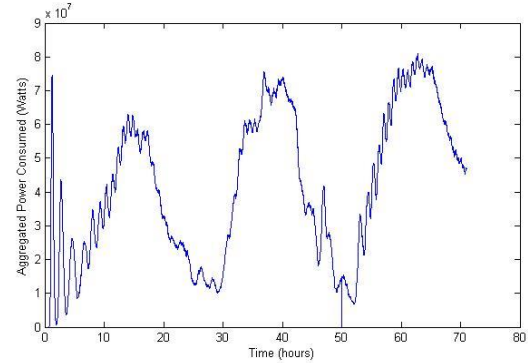


Figure 60: Aggregated power consumed with varying ambient temperature with negligible amount of noise

Figure 59 shows the variation in aggregated power consumed in absence of noise. Whereas, negligible amount of noise is added in Figure 60 by generating pseudorandom numbers having normal distribution. The variation in aggregated power is observed to vary in a similar way as that of an ambient temperature. From Figure 48 we observe that at time $t = 52$ hours, the ambient temperature is 21.7°C which is close to the upper dead band limit of 21.75°C . Due to this air-conditioners remain OFF and there is drop in aggregated power consumed. This also leads to temporary synchronization of individual states of TCLs. However, the safe protocol works as desired and there are no parasitic oscillations after the control signal is removed. The aggregated power consumed in both the cases is 41.5467 MW and 41.5559 MW respectively.

5.2.2: Varying the ambient temperature and dead band limits keeping the dead band widths constant

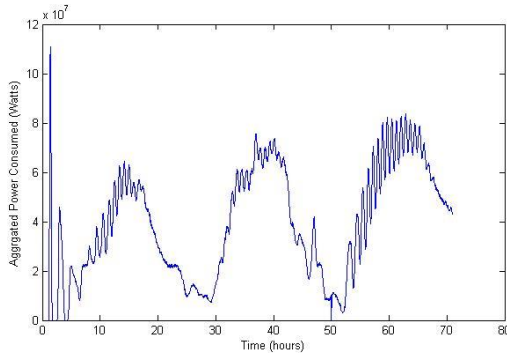


Figure 61: Aggregated power consumed with varying ambient temperature and dead band limits in absence of noise

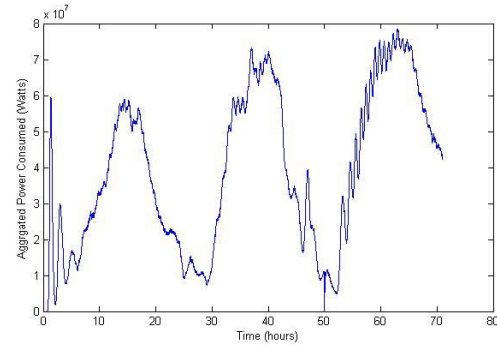


Figure 62: Aggregated power consumed with varying ambient temperature and dead band limits with negligible amount of noise

In the above figures we see that the amplitude of initial oscillations are smaller than in the previous case as the degree of heterogeneity is increased and SP-T3 works as expected. The mean and standard deviations of the dead band limits, set point and the average power consumed for both cases are shown in Table 6. Oscillations are still observed after time $t = 52$ hours but have lesser amplitude as compared to the previous case.

Table 6: Mean and standard deviation of different parameters when downward pulse is created and only the dead band widths are kept constant

	Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Average Power (MW)
	Mean	Standard Deviation (SD)	Mean	Standard Deviation (SD)	Mean	Standard Deviation (SD)	
No Noise	21.2461	0.2893	19.7461	0.2893	20.4961	0.2893	39.1171
Noise	21.2462	0.2895	19.7462	0.2895	20.4962	0.2895	39.1252

5.2.3: Varying ambient temperature, dead band limits and dead band widths

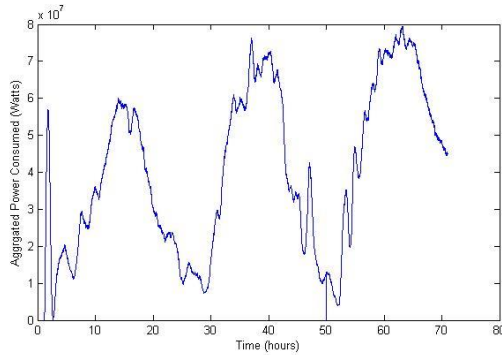


Figure 63: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths in absence of noise

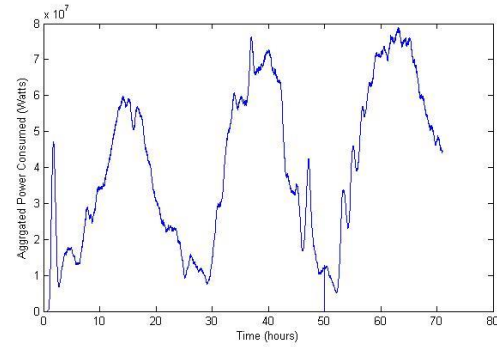


Figure 64: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths with negligible amount of noise

In the above figures the oscillations damp out earlier as compared to all previous cases. The amplitude of oscillations is also less. This is because the population is heterogeneous in all respects. Also there is very close resemblance between Figure 63 and Figure 64. Due to degree of heterogeneity, the synchronization of individual TCL states does not lead to pronounced oscillations. Calculations are tabulated below.

Table 7: Mean and standard deviation of different parameters when downward pulse is created and the ensemble is heterogeneous in all respects

	Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Dead band width (DW) $^{\circ}\text{C}$		Average Power (MW)
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
No Noise	21.2463	0.2895	19.2435	0.4076	20.2449	0.3230	2.0027	0.2873	40.1529
Noise	21.2521	0.2891	19.2552	0.4052	20.2537	0.3207	1.9969	0.2899	40.1363

Similarly, we can signal all TCLs to turn ON for 2 minutes at time $t = 50$ hours and generate an upward pulse as shown and results are tabulated:

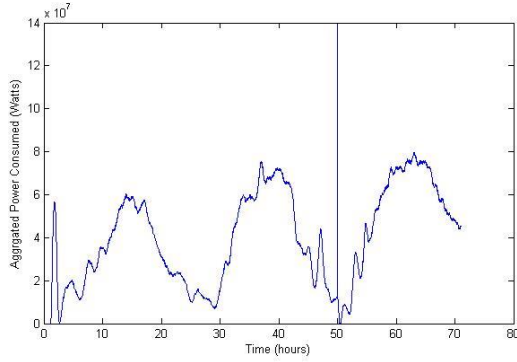


Figure 65: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths in absence of noise when an upward pulse is created

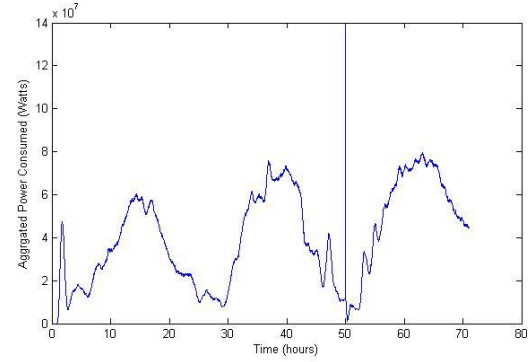


Figure 66: Aggregated power consumed with varying ambient temperature, dead band limits and dead band widths with negligible amount of noise when an upward pulse is created

Table 8: Mean and standard deviation of different parameters when upward pulse is created and the ensemble is heterogeneous in all respects

	Upper dead band limit (UDL) $^{\circ}\text{C}$		Lower dead band limit (LDL) $^{\circ}\text{C}$		Set point (SP) $^{\circ}\text{C}$		Dead band width (DW) $^{\circ}\text{C}$		Average Power (MW)
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	
No Noise	21.2488	0.2871	19.2489	0.4049	20.2489	0.3207	1.9998	0.2853	40.1288
Noise	21.2523	0.2902	19.2558	0.4117	20.2541	0.3256	1.9965	0.2891	40.1146

Based on these studies, we conclude that additive noise model is an acceptable way to study the aggregated power response. With increase in the degree of heterogeneity, the model becomes more complex. Also the additive noise model is a simpler model that incorporates the variations observed in the complex models.

Conclusion

Power generators are constrained by their physical ramp rates, however, electric loads can adjust their aggregated power consumption quickly (at time scales of seconds). Thermostatically controlled loads thus have considerable potential to provide ancillary services for demand side management.

In this work, we showed that adding timers to the endpoint temperature controller can be used to generate upward or downward pulses of large magnitude and small duration making it suitable to offset fast time scale fluctuations with knowledge of only several basic aggregate parameters that describe the state of the ensemble. Pulses of varying shapes, magnitudes and duration can be generated with no synchronization of individual states of TCLs and associated power oscillations at the end of the protocol. We also demonstrated that even during considerable variation of the outdoor temperature, safe protocols produce the desired response without any visible unwanted effects.

The TCL control protocols described in this thesis are minimally invasive and less expensive to implement. For example, they only require one-way communication and do not require the collection of data for each individual TCL. Also, the set point can be guaranteed to change within a comfortable level when the control signal is applied with the set points returning to their original value after the needed power pulse is generated. Such a minimally invasive strategy will avoid customer dissatisfaction.

Large power pulses require large ensembles; however, the protocols presented here become more accurate for larger ensembles showing the advantageous scaling properties of these methods. This is both an advantage and a restriction for their technological implementation. For

example, we expect that strategies based on the safe protocols should become commercially interesting when the number of TCLs in a community under control exceeds several thousands.

Our results suggest that it can be economically attractive for utility companies to develop demand side management programs in which few basic upgrades, such as timers and a small amount of memory, are imbedded in TCLs to instruct them to turn ON or OFF according to safe protocol strategies. Such demand side control strategies will help to reduce cost and maintain grid reliability.

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