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A phase model approach for thermostatically controlled load demand response

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HIGHLIGHTS

- A novel phase model for thermostatically controlled load (TCL) dynamics.
- A phase response-based open-loop control for tracking an area control error (ACE).
- Heterogeneous TCLs can provide demand response (DR) at different time scales.
- The proposed control architecture reduces equipment cost and provides privacy.

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ABSTRACT

A significant portion of electricity consumed worldwide is used to power thermostatically controlled loads (TCLs) such as air conditioners, refrigerators, and water heaters. Because the short-term timing of operation of such systems is inconsequential as long as their long-run average power consumption is maintained, they are increasingly used in demand response (DR) programs to balance supply and demand on the power grid. Here, we present an *ab initio* phase model for general TCLs, and use the concept to develop a continuous oscillator model of a TCL and compute its phase response to changes in temperature and applied power. This yields a simple control system model that can be used to evaluate control policies for modulating the power consumption of aggregated loads with parameter heterogeneity and stochastic drift. We demonstrate this concept by comparing simulations of ensembles of heterogeneous loads using the continuous state model and an established hybrid state model. The developed phase model approach is a novel means of evaluating DR provision using TCLs, and is instrumental in estimating the capacity of ancillary services or DR on different time scales. We further propose a novel phase response based open-loop control policy that effectively modulates the aggregate power of a heterogeneous TCL population while maintaining load diversity and minimizing power overshoots. This is demonstrated by low-error tracking of a regulation signal by filtering it into frequency bands and using TCL sub-ensembles with duty cycles in corresponding ranges. Control policies that can maintain a uniform distribution of power consumption by aggregated heterogeneous loads will enable distribution system management (DSM) approaches that maintain stability as well as power quality, and further allow more integration of renewable energy sources.

1. Introduction

Significant efforts have been made in recent years to reduce the greenhouse gas emissions caused by fossil-fueled power plants throughout the world. In the United States, many states have been adopting or increasing their renewable energy generation portfolio standards [1]. The increasing penetration of such renewable energy sources (RESs) affects power quality on electric distribution systems and complicates load balancing in power systems [2]. These issues compel the development of new approaches to regulate the inherently fluctuating and uncontrollable power outputs of RESs [3,4].

Demand response (DR) programs enable electricity users to adjust their consumption in response to energy prices or incentive payments [5,6], and thus provide significant capability to balance supply and demand on the power grid. Indeed, demand-side management technology has been under development since the late 1970s and early 1980s [7], with consideration of diverse objectives that include peak shaving, valley filling, and strategic energy conservation [8]. With the

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advent of smart grid technologies and the integration of RESs in distribution systems around the world, system operators will now have to rely on DR and ancillary services (AS) to balance supply and demand of energy more than ever before. It is therefore imperative to develop technologies that can exploit the resources available for DR to the fullest extent.

A comprehensive review on the current challenges and barriers to a full deployment of demand response programs is given in [9]. One important observation made in the review is that, despite receiving information about their energy consumptions, the majority of the participants in a DR study continued with their everyday routines and habits. This kind of consumer behavior will diminish the potential of DR. In order to maximize DR capabilities, it may be better to remove human decisions from the loop. This could be achieved by using a transactive control paradigm, which is a popular direct load control approach in which customers have agreed to allow the power company to control some of their flexible loads [6]. This control approach reacts faster to market price fluctuations and enables TCLs to participate in the real-time retail electricity market [5].

The integration of RESs into the power grid reduces the inertia of the system, which poses a challenge for automatic generation control (AGC), which is used to control frequency by balancing supply and demand. Several studies have examined ways to utilize electric vehicles (EVs) and battery energy storage systems (BESSs) to provide frequency regulation reserves [10,11]. For instance, [12] developed a techno-economic evaluation framework to quantify the challenges and assess benefits to primary frequency control by using EV batteries. Although BESSs can provide primary frequency control, the cost of deployment in large capacities remains prohibitively high [13]. Hence, the focus has been turned to TCL loads such as refrigerators [14,15], heating ventilation and cooling (HVAC), and electric water heaters (EWH) that have been shown to be suitable for providing ancillary services to the grid [16,17].

In this paper, we consider the direct control of TCLs through thermostat set-point changes for DR provision. Although we consider AC systems, the modeling and control approach presented herein is applicable to any general TCL. In the recent past, various modeling and control methods for TCLs were developed, and experiments were conducted to demonstrate the ability of TCLs to provide ancillary services. Field experiments conducted using domestic refrigerators in [15,14] aimed at quantifying the flexibility of household TCLs, and the computational resource constraints for the control of large TCL populations. The frequency controller in [14] switches the TCLs OFF one by one based on the ability of each refrigerator to stay OFF longer. In [15], the same authors introduced a delay in their control scheme to improve the performance of the controller, which reduced the power overshoot. They noted that withdrawing a large number of loads abruptly produced instability and caused the loads to synchronize their duty cycles. In [13], such synchronization of TLCs is avoided by randomizing the parameters in the control scheme. This approach consisted of dividing the compressor cycle into four different states based on the compartment temperature. Their control architecture was based on the utility sending a regulation signal to Cooperative Home Energy Management (CoHEM) systems located at distribution transformers, with each CoHEM then sending different control signals to home energy management systems that control the refrigerators. The investigation in [18] combined three different control protocols to improve the accuracy in tracking an AGC signal. The controller switched between a temperature priority based control, a sliding mode control, and a two-stage regulation control. A two-level scheduling method intended to facilitate the scheduling of flexible TCLs in the intra-day electricity market was proposed in [16]. However, the performance of this method deteriorates with parameter heterogeneity, and worsens as forecast uncertainty increases. Control approaches based on model predictive control techniques have also been considered. In [19], a multi-objective model predictive control strategy for residential heating with heat pumps was proposed. This approach takes into account the users' energy cost, the environmental impact, and expansion of electricity generation capacity. In addition, it considers detailed models for heat pump and thermal energy storage, and accounts for the feedback effect of individual controllers on electricity generation. This level of detail will make scaling the approach to a large TCL population problematic.

One very important question that was posed in [20], and that still needs to be accurately answered, is *how large is the potential of DR and on which time scale can DR be the most effective?* This is not a particularly easy question to answer. In this paper we propose a novel procedure for evaluating the maximum capacity and the appropriate time scale for DR provision by a collection of TCLs. Based on phase reduction theory [21], this approach can evaluate the capacity of a TCL population in different bandwidths. In [22], a theoretical upper bound on the capacity of TCLs to provide ancillary services as a function of frequency was proposed. The capacity-bandwidth constraints was derived based on standard linear dynamical system models. The proposed bound indicates that for a given TCL population with a fixed time constant, the capacity for AS provision is inversely proportional to the frequency of the regulation signal to track. Our method supplements this observation by further showing that the capacity does not monotonically decreases with frequency. Indeed, while the capacity monotonically decreases for a regulation signal with frequency below the mean natural frequency of a given TCL population, it then increases and decreases again in some frequency bandwidths higher than the TCLs' mean frequency. This is particularly significant because this theory can be used to analyze different TCL populations and classify them based on their capacities to provide AS in different bandwidths (time scales).

Unwanted synchronization of TCL duty cycles by the control policy is most likely the main factor that limits the time scale and capacity of ancillary services that a given population can provide. This phenomenon has motivated the research and development of control policies such as the safe control protocols [23,24], which aim to minimize unwanted power oscillations in response to pulse-like changes of the set-point temperature. One protocol allows the TCL to stay in its current state until the temperature hits one of the transition points, then starts following a new pair of deadband limits [23], and the other adds a delay of M-minutes before changing the status of the TCL [24]. Other control strategies with similar goals consist of turning ON/OFF some TCLs in the OFF/ON stack based on their priority measure [25,26]. The priority measure is defined as the distance from the switching boundary and hence, if the TCLs' aggregate power needs to be reduced, the TCLs in the ON stack closer to the switching boundary will be turned OFF first. Conversely, if the aggregate power needs to be increased to follow an increase in the generated power, the TCLs in the OFF stack closer to the switching boundary will be turned ON first.

In an effort to further the understanding of the oscillatory behavior of the aggregate power consumption, the damping of oscillations in aggregate power was characterized as a function of parameter heterogeneity by exploiting the similarities that exist between a population of mass-springs systems and an ensemble of TCLs [27]. Concurrently, the dependence of the mixing rate of the population on the model parameters was characterized in [28].

To summarize, the work in this paper provides an novel approach for evaluating DR capacity and time scale using a novel phase model representation of TCLs. The evaluation is conducted by computing the entrainment regions also known as Arnold tongues [21]. To obtain the phase model, we started by first extending the common hybrid-state model of TCL dynamics to a neuroscience-inspired representation in the form of a continuous two-dimensional system, then applying a widely-used phase reduction computation [29]. The phase model is a one-dimensional system with scalar state, and its simplicity has made it one of the most popular models for studying oscillatory systems, including power grids [30] and neural oscillators [31], with particular advantages for control design in the presence of parameter uncertainty [32]. The second novel contribution of this work is the proposed phase response