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Effective power management modeling of aggregated heating, ventilation, and air conditioning loads with lazy state switching

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A B S T R A C T

This study aimed to improve the grid power quality by demand response control algorithm; by controlling the aggregate population of heating, ventilation, and air conditioning (HVAC) loads with lazy state switching mode to mitigate fluctuations of overall power consumption. It is known that the power quality is crucial to the efficiency of industrial activities. However, monitoring of power quality is not a trivial task. Increasing use of intermittent renewable power brings new problems to the reliability of the grid. New control technologies are required to maintain instantaneous balance between power generation and consumption. Like distributed generation, distributed storage, demand response is one important kind of Distributed Energy Resources (DER) in smart grid. In order to regulate power consumption of the aggregated population of loads, the units' thermostat set-point is adjusted according to the amount broadcast from the control center. In addition, the power fluctuations and high frequency of loads on/off state switching are always the cost of many control algorithms. This study provides a new concept of lazy state switching combined with the state-space model. When there are needs to change set-point, the aggregated HVAC units will change their thermostat set-point gradually. Some of the HVAC units keep their working state until the switch conditions are satisfied. Accurate estimation of the dynamics of large number of loads is really valuable for the power grid to integrate renewable sources and to provide load-shifting and other valuable services. The proposed mode is validated through realistic simulations of thousands of HVAC units using GridLAB-D. Simulation results indicate that the proposed mode can effectively reduce the fluctuations when adjusting the aggregated HVACs thermostat set-point with less on/off switching operations, without sacrificing end-use performance.

1. Introduction

AMI (Advanced Metering Infrastructure) and programmable communicating thermostat (PCT) can realize two-way communication between users and utilities (Yang, 2017; Callaway, 2009; Yao and Lu, 2009), demand Response (DR) is becoming one of the research focus in smart grid enabling technologies (Faruqui and Sergici, 2010; Sun et al., 2016; Zhang et al., 2012). With the ability to adjust the real-time power consumption of user's at minute level, DR can provide peak shaving, load shifting and other ancillary services to enhance the system stability and reliability. With DR, the power consumption can be adjusted to follow the power generation. Dynamic pricing (Borenstein et al., 2002; Faruqui and Sergici, 2010) and direct load control are universally applicable demand response programs. However, dynamic pricing, such as real-time pricing (RTP), time of use (TOU) pricing, and critical peak pricing (CPP) (Borenstein et al., 2002), are kinds of indirect control strategy, which require customers to be price sensitive, and they are not suitable for real time DR systems.

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Direct load control (DLC) is another kind of important DR control method (Zhang et al., 2012, 2012; Zhu et al., 2015; Perfumo et al., 2012; Ruiz et al., 2009). With user's permission, the operating programs or system operators can control users' power consumption directly. Using DLC, the system can achieve full load response, and can realize faster and more predictable response system control, this enables the system to provide peak shaving, load shifting, frequency regulating, load following and other valuable ancillary services (Sun et al., 2013; Soudjani and Abate, 2015). Recent researches often focus on the optimal load control schedules of large number of domestic devices. The heating, ventilation, and air conditioning (HVAC) load is one of the most flexible elastic load (Wei et al., 2015; Yoon et al., 2014; Kusiak et al., 2011), which is suitable to be aggregated together to smooth the energy demand variations in the time scale of minute-level (Zheng and Cai, 2014). The literature (Lu, 2012; Katipamula and Lu, 2006) made an evaluation of the HVAC load potential for providing load balancing service.

With the rapid development of renewable energy sources (Ye et al., 2016), DR technology is becoming increasingly crucial (Liu and Shi, 2016). In recent years, people have developed a variety of renewable energy technologies, including photovoltaic (PV), wind power, fuel cells, etc. (Zhu et al., 2015). Due to the inherent intermittency and volatility of renewable energy, the output power varies greatly from time to time. As means to achieve better intelligent consumption, DR plays an important role in maintain instantaneous balance between power supply and demand. More and more renewable energy will be connected to the grid (Wei et al., 2014), which have become the driven force for demand response technology to catch up with the need of future smart grid. Hence, it is urgent to develop and improve DR related technologies.

Higher power quality requirement is another aspect of the future smart grid. It is known that the reliability and efficiency of the grid heavily rely on the power quality (Ceaki et al., 2017; Ali et al., 2016). With the rapid development of technology and economy, the requirements of power quality become higher and higher. There are various reasons that could lead to power quality problems. Among them the variations of power consumption at demand side contribute much of the part. However, it is possible to reduce the bad effect of the aggregate load by smoothing the overall demand profile, in other words, reducing the overall power fluctuations, with the aim to mitigate voltage and frequency variations. Yan et al. (2017) proposed the use of combined smart load to improve power quality from the demand side. However, it is more remarkable to improve the power quality by controlling the aggregated population of loads.

The aggregate loads control methods have been studied extensively in the literature (Kalsi et al., 2012; Chang et al., 2013). Dynamic state-queuing model was first studied by Lu and Chassin (2004), in which thermostatically controlled appliances' (TCAs) thermostat set-points are adjusted according to the market price. The state queuing-model is extended by works with the first order Equivalent Thermal Parameter (ETP) model (Bashash and Fathy 2011, 2013). These early studies indicate that the power of the aggregated HVAC units can be estimated and controlled. Ignoring the effects of indoor objects and considering the relationship between indoor air temperature and power consumption to be linear, the first order ETP model can realize simple and fast control systems. However, the first order ETP will result in some calculation errors.

In order to obtain more accurate results, recent works studied the aggregated dynamics based upon the second order ETP model (Kalsi et al., 2012; Zhang et al., 2013; Zhang and Lu, 2013), considering the coupling relationship between indoor air and indoor object temperature dynamics. Kalsi et al. (2012) use linearization method to simplify the second order ETP model. Zhang et al. (2013) developed a 2D population flow diagram according to the air and object temperature, while taking the lockout effect into consideration. Zhang and Lu (2013) used the ETP model based on state space description and use linearization method to simplify the second order ETP model. Then the load balancing capability was investigated, which reveals that the number of HVAC units varies significantly with baseline settings, dead-band settings, and outdoor temperatures. All these models assume that the HVAC Unit will respond to the command immediately, and the power fluctuates seriously during the adjusting process.

The main contribution of this study is the development of lazy state switching control mode, with the aim to improve the grid power quality from the demand side. On the one hand, it can greatly reduce the power fluctuations when adjusting all the HVAC units' thermostat set-point by the command broadcast from the control center, which is of great significance to the stability of the power grid. Another benefit is that it tends to keep the HVAC's working state as long as possible, so it will reduce the frequency of HVAC unit's on/off switch cycles to avoid overusing the HVAC units. Here, this study focus on one of the possible process for brevity, i.e. heating process, when the HVAC unit works to generate heat to increase the room temperature. The cooling process can be developed similarly.

The rest of this study is organized as follows. In Section 2, a second order ETP model of an HVAC system is introduced. The lazy state switching controller is developed for the aggregated HVAC units in section 3. Then the proposed lazy state switching mode and control method are validated using GridLAB-D (GridLAB-D, 2012) in section 4, Finally, some concluding remarks and future works are given in Section 5.

2. Thermal dynamics of an HVAC unit

The temperature evolution of an HVAC unit is nonlinear, and the power consumption is affected by ambient weather conditions. It can be assumed that the weather condition remains stable in short period of time, and the HVAC is working in a steady state. Considering the thermal capacity of the building, the HVAC unit acts as energy storage, while the power toggling between two or more relatively fixed values. Our work is based on the second-order ETP model (see Fig. 1), which consists of two coupled differential equations describing the air and mass temperature dynamics, adopted from the work of Kalsi et al. (2016).

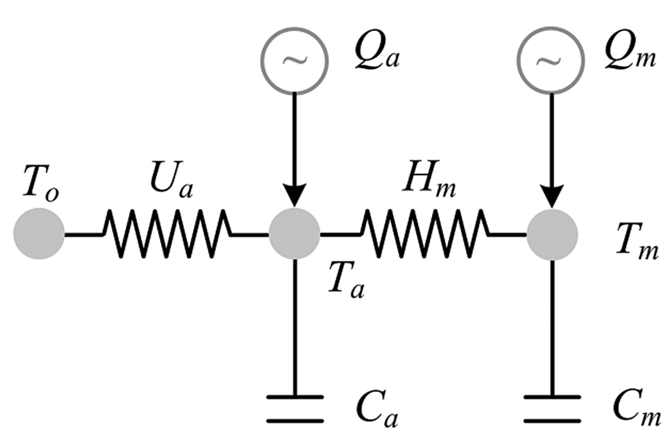

Fig. 1. The second order ETP model of an HVAC unit.