On the Use of Thermostatically Controlled Loads for Frequency Control

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***Abstract*—Demand response (DR) is an essential component of the modern power systems. DR service could be considered as a certain extend solution for integrating renewable generation with power systems to increase economic efficiency and enhance reliability. Specific loads such as residential loads could be controlled by using droop-like control methods to attain autonomous DR. One of the most significant advantages of applying droop-like control methods is that they require no communication links. This paper presents three control methods for residential thermostatically controlled loads (TCLs) for frequency control. They are simulated on two scenarios: a TCL connected to the main grid in an open loop, and a TCL connected to a stand-alone microgrid (MG).The present research identifies that the new proposed algorithms can increase quality of energy supply in MGs and, in turn, increase flexibility and reliability of power systems.**

***Index Terms*—Microgrid, demand response, frequency control, droop control, thermostatically controlled load.**

I. INTRODUCTION

Towards inertial-less power systems. Smart grid (SG) technologies and renewable energy sources (RES) bring several advantages to modern life. Affording clean energy services with almost zero carbon emissions, enhancing energy supply reliability, extending organic fuel economy and developing rural and remote regions by providing sufficient electrification [1], [2]. However, the integration of SGs with specific types of RES technologies, such as solar photovoltaic and wind energy, may increase the power system uncertainty which encounters the simultaneous power balance between supply and demand and leads to instability issues of the grid frequency [3]. Consequently, the appropriate control techniques to keep power balance in the power systems is necessary. The conventional solution to regulate the grid frequency in large power systems is the generators' spinning reserve which would raise operational expenses. Additionally, it is not environmentally friendly due to using partly-loaded fossil-fuel generators [4].

Demand response as enabler of flexibility. DR is an indispensable component to integrate renewable generation with high reliability for smoothing of the demand curve when the power network is under stress [5]. By emergency load relieving and managing of demand peaks, DR ancillary services, such as frequency and voltage control [6], can help to reduce generation and transmission investments, compensate a deficiency of generation and keep the frequency within limits, instead of adding spinning reserves services and provide additional services for the system operator. DR may be an economical applicant to sustain the frequency security thresholds and lower the surplus volume of frequency response required from conventional sources [7].

Despite the long list of benefits from DR, power systems are incorporating DR services in a very slow steps. It is much complicated in dealing with thousands or millions of small loads than few tens or hundreds of large generators. Difficulties in two-way communications among many loads and central control systems accompanying with the investment issues hinder the adoption of DR.

Primary frequency control plays a crucial role to protect power networks from failing in the first moments of a disturbance. The result should be a cost-effective, synchronized and robust planning of frequency. Increasing frequency-responsive load level results in lower thermal generation contribution in providing primary frequency control and its related cost [8]. Compared to prevailing methods for the primary control, the droop controller has advantages when implemented in islanded mode MGs. Evading communication links among paralleled converters is the key benefit of applying droop controller which provides significant flexibility and high reliability for the system [9]. For instance, a model-free based generalized droop control for a broad variety of load change setups is represented in [10]. A primary power-frequency controller which enhances the closed-loop system dynamic response without changing the frequency accuracy is presented in [11].

Potential of residential TCL for frequency control. Today, in the developed countries, more than $20\,\%$ of the loads are house appliances [8]. Usually, $36\,\%$ of the residential consumption is related to TCLs, where heaters usually consume about $15\,\%$ [12]. The TCLs significantly affect the total demand and grid frequency changes. Thus, thermal loads constitute an excellent alternative to batteries and conventional frequency control methods.

Paper contributions and organization. In the article, two different cases are analyzed. The first case consists of a single controllable TCL that provides frequency control directly to

This work was supported by Skoltech NGP Program (Skoltech-MIT joint project).

the main grid in an open-loop fashion. We refer to this case as grid-connected frequency control (GC-FC). The second case, a connected TCL to an isolated MG with a single generator provides support for frequency control in a close-loop fashion. We refer to this case as a stand-alone frequency control (SA-FC) in the MG. Simulations are tested against real data from the National Grid from United Kingdom [13].

Thus, the main aim of this paper is to propose and examine three algorithms for the use of TCL to support frequency control in power grids. The algorithms are tested in two cases of study (GC-FC and SA-FC). Section II presents a description of the TCL model and the single area generation model with a connected TCL. Section III introduces three control methods. Section IV presents the simulation results. Finally, section V is devoted to present the main conclusions.

II. System Models

In the first part of this section, we introduce a TCL thermal model. Then, we present the model for a MG with a single generator where the TCL is supporting frequency control with the generator.

A. Thermostatically Controlled Load Model

The model consists of a thermal model of the room with a heating system which includes an electrical heater and a controller. It provides a relation between the heater's consumption and the room temperature. The model parameters were set according to [14]. The thermal energy transferred from the heater to the room is considered as a power consumption of the heater and described as:

$$P_{heater} = \frac{dQ_{gain}}{dt}, \tag{1}$$

where Q_{gain} is the heat transferred from the heater to the room (in J), P_{heater} is the power consumption of the heater (in W).

The thermal energy losses of the room by conduction through the surface of the room (walls, windows, etc.) are:

$$\frac{dQ_{loss}}{dt} = \frac{1}{R_{eq}} \left(T_{room} - T_{out}\right), \tag{2}$$

where T_{out} is the outdoor temperature (in °C), R_{eq} is the equivalent thermal resistance[1] for the room (in $\mathrm{J^{-1}\,°C\,s}$).

The variation of the room's temperature can be obtained as:

$$\frac{dT_{room}}{dt} = \frac{1}{C}\left(\frac{dQ_{gain}}{dt} - \frac{dQ_{loss}}{dt}\right), \tag{3}$$

where C is the heat capacity of the room (in $\mathrm{J\,°C^{-1}}$). The heat capacity of the room can be calculated as:

$$C = \sum_n c_n m_n, \tag{4}$$

[1] R_{eq} can be calculated as $\frac{1}{R_{eq}} = \sum_n \frac{1}{R_n}$, where R_n is the thermal resistance of each surface of the room. The thermal resistance can be represented (for rectangular geometries) as $R = D/kA$, where k is the thermal conductivity of the particular material (in $\mathrm{J\,m^{-1}\,s^{-1}\,°C^{-1}}$), A is the surface area (in $\mathrm{m^2}$), and D is depth of the surface (in m) for example, the depth of the wall.

where c_n and m_n are specific heat capacity and mass of each component in the room (air, walls, floor, etc.), respectively. This is a simple model and a more detailed model should take into account thermal resistance among indoor air, walls, etc. The block diagram of the thermal model is presented in Fig. 1 which includes also the single generator model introduced below.

B. Single Area Power System Model

The model of the stand-alone MG (Fig. 1) is simulated to test the proposed control algorithms and to evaluate the influence of the TCL on the grid frequency. A simplified MG model was developed based on [15].

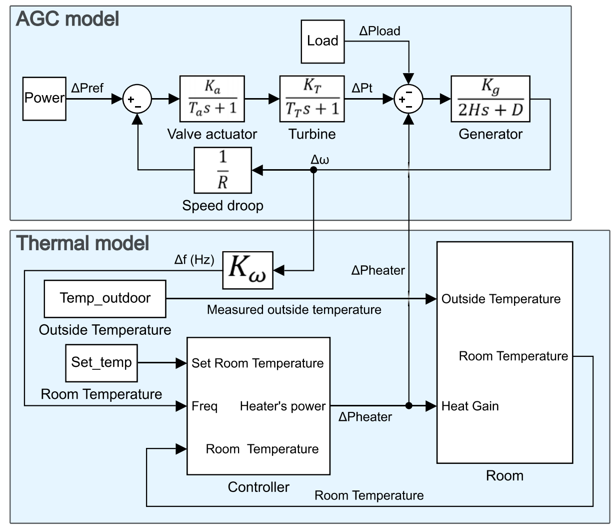


Figure 1. Block diagram of the interconnected models.

The main model includes two subsystems: the TCL model and the automated generation and control (AGC) system model which is in charge of frequency control. The AGC model includes a turbine, a generator, and the controller. The controller consists of a valve actuator and a speed droop controller as a part of the governor, which regulates the electric generator output power. Notice that, in the model, the electrical load and turbine active power are inputs for the AGC system. The AGC model is also called the primary load frequency control (LFC) loop. The main goal of the LFC loop is to match of power balance by changing the turbine output according to changes in the load demand and make the frequency deviation equal to zero. In the conventional AGC system, the output frequency is restored to its nominal value by an additional integral control loop [16]. Parameters of the AGC model are presented in Table I. In this study, the TCL provides an additional support to compensate power imbalance in the system. Any changes in unpredictable load are reflected in the grid frequency. The TCL system controls the power consumption according to frequency deviations to help to restore frequency to the reference value.

III. Frequency Control Algorithms

This section presents three different control algorithms. The first algorithm, *modified ON/OFF control*, is performing based on a hysteresis ON/OFF control including the grid

TABLE I
PARAMETERS OF THE AGC MODEL [17]

K_a (pu)	K_T (pu)	K_g (pu)	T_a (s)	T_T (s)	H (s)	D (pu)	R (pu)	P_{base} (GW)
1	1	1	0.2	0.3	6.3	1	0.05	33

frequency variable to make ON/OFF switching decisions. The second algorithm, *droop control*, is based on the conventional frequency droop control strategy. The third algorithm, *hybrid control*, provides a combination of both mentioned control algorithms.

A. Modified ON/OFF Control

In a conventional TCL control methods, the control sets the TCL (e.g. heater) ON when the temperature falls below a lower bound (e.g., 20 °C) and sets the heater OFF when the temperature reaches an upper bound (e.g., 24 °C) to keep the temperature within comfortable limits.

In the modified ON/OFF control, the grid frequency is taken into account to make the ON/OFF decision. The grid frequency is continuously measured and compared with defined frequency limits. If the frequency falls below 49.9 Hz, the heater is switched OFF, and if the frequency increases above 50.1 Hz, the heater is switched ON. At the same time, the temperature in the room should not exceed the temperature limits. If the temperature exceeds its limits, the heater is switched ON or OFF independently of the grid frequency deviations according to traditional ON/OFF algorithm. In addition, to avoid frequent changes of the heater state, a dead zone is defined. If the temperature in the room reaches the upper limit and frequency is still high, the heater will be switched OFF until the temperature reaches the lower limit of the dead zone. If the temperature reaches the lower limit and the grid frequency is still low, the heater is switched ON until the temperature reaches the upper limit of the dead zone. The pseudocode of modified ON/OFF control algorithm is presented in ALGORITHM 1.

B. Droop Control

The droop control algorithm is a linear controller that changes the power consumption according to the grid frequency deviations and keeps the frequency within defined limits. The equation of the droop characteristic of P – Δf is written as follows:

$$P_{heater} = P_{heater,ref} + m_f \Delta f \tag{5}$$

where P_{heater} is the power consumption of the heater (in W), $P_{heater,ref}$ is the heaters power consumption reference (in W), Δf is the frequency deviation relatively to reference frequency 50 Hz and m_f is the coefficient that relates the power consumption with the frequency deviations (in Hz^{-1} W). The droop characteristic is presented in Fig. 2.

Additionally, a model of the algorithm with a dead band 50 ± 0.05Hz for droop characteristic was implemented . The idea behind this method is to neglect a control of the load when the value of frequency is within a bandwidth. If the frequency is out of the dead band, the load is changed according to (5). The pseudocode of the droop control algorithm is defined in ALGORITHM 2.

Algorithm 1: Modified ON/OFF control

Data:
  Temperature limits $[T_{min}, T_{max}]$;
  Frequency Limits $[f_{min}, f_{max}]$;
  Maximum active power P_{max};
  Temperature deadband ΔT;
Get indoor temperature T
if $T_{min} \leq T \leq T_{max}$ **then**
  get grid frequency f;
  if $f \leq f_{min}$ *or* $f \geq f_{max}$ **then**
    if $f \geq f_{max}$ **then**
      if $T \leq T_{max} - \Delta T$ **then**
        set the heater input power equal to P_{max};
    else
      if $T \geq T_{min} + \Delta T$ **then**
        set the heater input power equal to zero;
else
  if $T < T_{min}$ **then**
    set the heater input power equal to P_{max};
  else
    set the heater input power equal to zero;

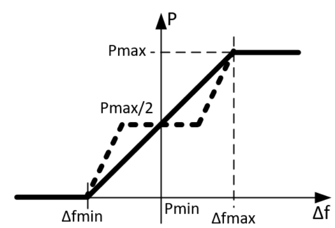


Figure 2. Droop control characteristics without dead band (solid line) and with dead band (dashed line).

Algorithm 2: Droop control

Data:
  Temperature limits $[T_{min}, T_{max}]$;
  Frequency Limits $[f_{min}, f_{max}]$;
  Maximum active power P_{max};
Get indoor temperature T
if $T_{min} \leq T \leq T_{max}$ **then**
  get grid frequency f;
  calculate active power of droop control (5);
else
  if $T < T_{min}$ **then**
    set the heater input power equal to P_{max};
  else
    set the heater input power equal to zero;

C. Hybrid Control

In this algorithm, the aforementioned control methods are combined in one control system. If the frequency exceeds the determined frequency limits, the heater switches the mode according to the modified ON/OFF algorithm. While the heater is working in its ON mode, the droop control algorithm controls the temperature and heat transferring of the electrical heater regarding frequency deviations of the grid. The pseudocode of the combined control algorithm is presented in ALGORITHM 3.

Algorithm 3: Hybrid control

Data:
  Temperature limits $[T_{min}, T_{max}]$;
  Frequency Limits $[f_{min}, f_{max}]$;
  Maximum active power P_{max};
  Temperature deadband ΔT;
Get indoor temperature T
if $T_{min} \leq T \leq T_{max}$ **then**
  get grid frequency f;
  if $f \leq f_{min}$ *or* $f \geq f_{max}$ **then**
    if $f \geq f_{max}$ **then**
      if $T \leq T_{max} - \Delta T$ **then**
        set the heater input power equal to P_{max};
    else
      if $T \geq T_{min} + \Delta T$ **then**
        set the heater input power equal to zero;
  else
    calculate active power of droop control, (5);
else
  if $T < T_{min}$ **then**
    set the heater input power equal to P_{max};
  else
    set the heater input power equal to zero;

IV. Numerical Results

The performance results of each mentioned control algorithm for both scenarios are presented in this section. The first scenario considers a TCL (electric heater) that is directly connected to the grid to provide frequency control in an open loop. This case is referred as GC-FC. The second scenario is based on a single-area system model where the TCL is connected to the isolated MG for providing frequency control in a closed loop. This case is referred as SA-FC.

A. Grid-Connected Frequency Control Model: GC-FC

This scenario was simulated to check the performance of each algorithm to provide temperature control within allowed limits according to frequency deviations in the grid. In this case, the TCL is connected to the main grid in an open loop. Historical data of frequency from UK National Grid, [13], and outdoor temperature in London, [18], is used as inputs. Fig. 3 shows the grid frequency variation during February 2^{nd} 2016. The power consumption of the TLC model is represented as an equivalent load that is equal to 10% of the total available power of heaters in the power system. The results of simulations for different control algorithms are compared with traditional heating control system's result. The simulations were performed using MATLAB and Simulink. The changes in the room temperature for the traditional and modified ON/OFF control are presented in Fig. 4a.

The TCL switching mode changes according to the frequency deviations in the grid and the indoor temperature. Results from ALGORITHM 1control simulations are presented in Fig. 4. Small fluctuations of the temperature close to the upper limit show a working mode when the TCL cannot provide

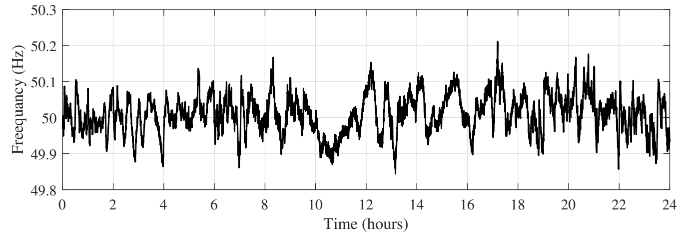
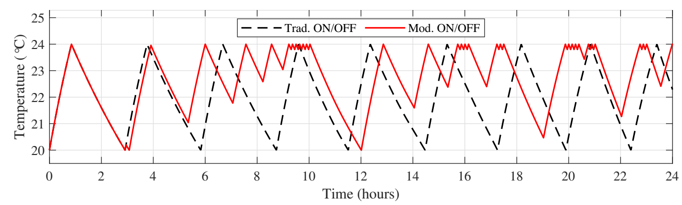
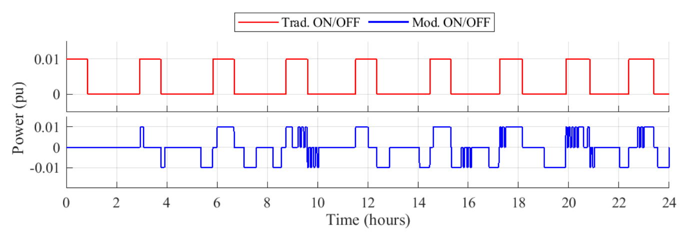


Figure 3. Grid frequency, February 2^{nd} 2016, UK national grid.

enough capacity for the load response to compensate power unbalance in the grid. In this mode, the TCL switches OFF and ON periodically to keep temperature below the upper limit and add load to reduce frequency in the grid. Fig. 4b shows a power difference between the power consumption of traditional and modified ON/OFF control (red line). The black line shows the power consumption of traditional domestic heater without frequency control. The positive value of difference presents periods when the TCL consumes more than a heater with traditional ON/OFF control and works as a load for the grid. The negative value shows periods when the consumption of the TCL is working as an virtual generator. In the virtual generating mode, the TCL consumes less power than the consumption profile of the traditional TCL control.



(a)



(b)

Figure 4. Modified ON/OFF control: (a) room temperature, (b) power consumption of thetraditional heater (black line) and difference between the power consumption of the model with traditional and the model with modified ON/OFF control (red line).

Two different approaches are considered for the droop control algorithm (ALGORITHM 2): droop control works in the whole range of frequencies, or it only works outside of the defined dead-band between 50 $\pm$ 0.05 Hz (see Fig 2). For both cases, the indoor temperature is shown in Fig. 5a. Fig 5b shows the power difference between the power consumption of traditional ON/OFF control droop control.

For the third algorithm (ALGORITHM 3), temperature and difference between the power consumption with traditional ON/OFF control and hybrid control techniques are presented in Fig. 6.

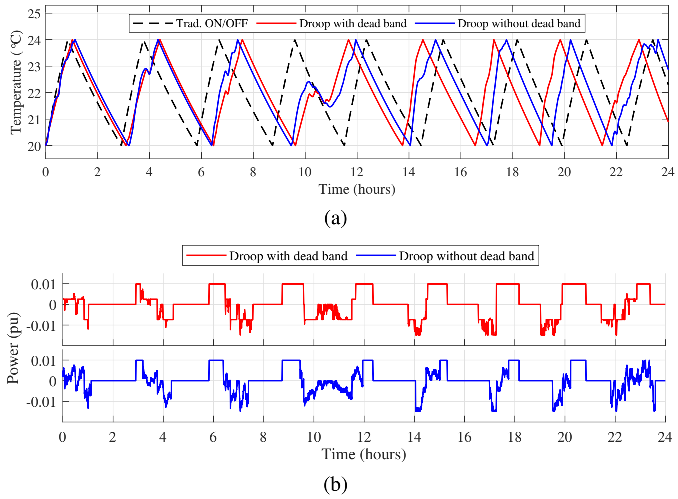


Figure 5. Droop control: (a) room temperature, (b) power difference between the power consumption of the model with traditional ON/OFF control and models with droop control techniques.

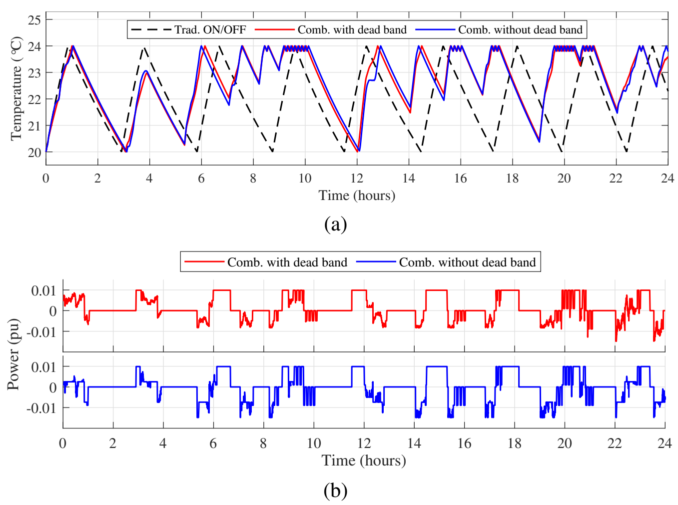


Figure 6. Hybrid control: (a) room temperature, (b) power difference between the power consumption of the model with traditional ON/OFF control and models with hybrid control techniques.

Observe that all control algorithms can provide control of temperature in the room while, at the same time, they can change the real-time power consumption of the TCLs' consumption and, therefore, providing frequency control support to the main grid.

B. *Stand-Alone Frequency Control Model:* SA-FC

In this scenario, the TCL (electric heater) assists the MG to control the frequency (Fig. 1). The total load demand is divided into stochastic and controllable loads. Following the three proposed control algorithms, the TCL power consumption is changed according to the grid frequency to keep power balance between demand and supply and regulate frequency to its reference value.

Fig. 7 shows the stochastic load demand realization used as an input signal for performing the simulations. The controllable load represents the 10% of the total space heaters' load in the microgrid. The outcome indoor temperature resulting from simulations with the modified ON/OFF control (ALGORITHM 1) and traditional ON/OFF control is compared in Fig. 8a. Fig. 8b shows the frequency histograms resulting from the simulations. They allow comparing performance among the different proposed controls. According to the histogram in Fig. 8b, the frequency deviations of the traditional control method exceed the limits 49.9 and 50.1 Hz. The grid frequency standard deviation (σ) of frequency is presented in the legend of histogram. σ for the connected TCL with modified ON/OFF control is lower than when it is not connected. However, it is worst than when the TCL is connected without offering frequency support to the grid.

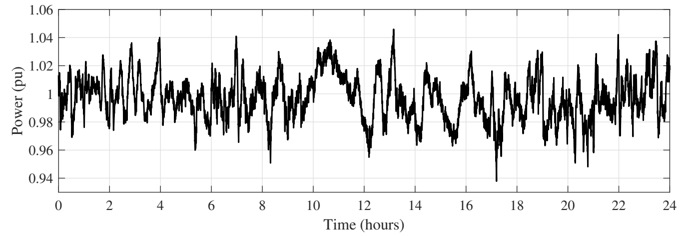


Figure 7. Unpredictable load deviations.

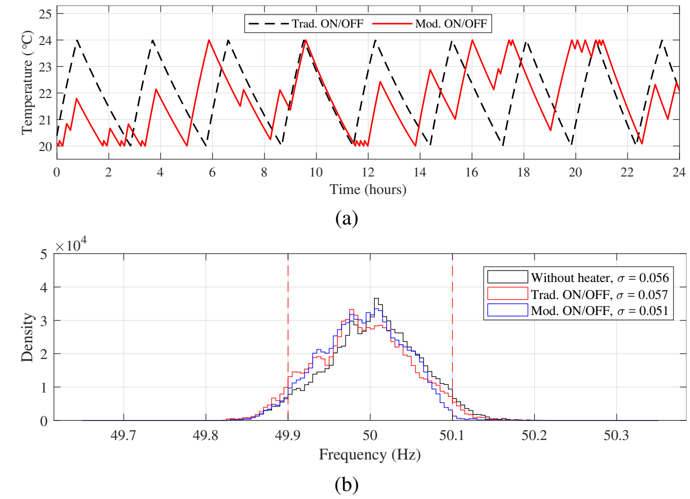


Figure 8. Modified traditional control: (a) room temperature, (b) frequency histogram.

The resulting indoor temperature and grid frequency histograms for the droop-based control method (ALGORITHM 2) are presented in Fig. 9. The comparison of histograms between the droop-based control and the traditional ON/OFF control shows that the duration when the frequency was higher than the upper limit is slightly reduced in the droop control algorithm. Below to 49.9 Hz histograms are very close even without the TCL connected. In any case, both algorithms can reduce the standard deviation, σ, although the droop-based control without dead band has the best performance.

The indoor temperature and histogram outcomes from simulations for the hybrid control method (ALGORITHM 3) are represented in Fig. 10. In contrast to the results of the droop-based control techniques, recurrence when the frequency is higher than the upper limit of 50.1 Hz is almost zero. σ for hybrid control without a dead band is greater in comparison with the droop control and the modified ON/OFF control.

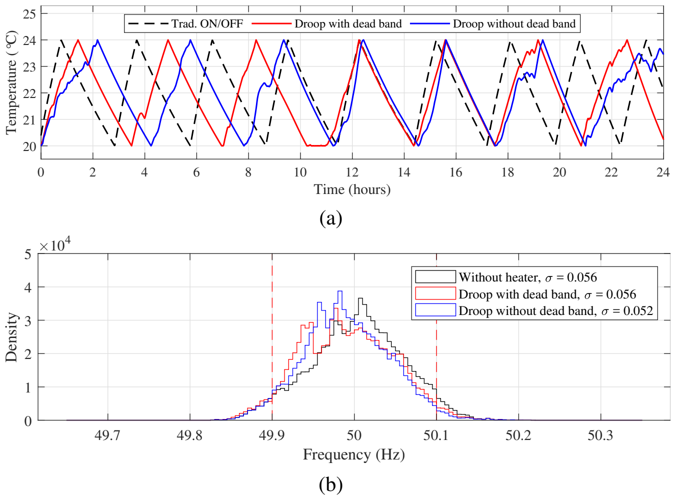


Figure 9. Droop control: (a) room temperature, (b) frequency histogram.

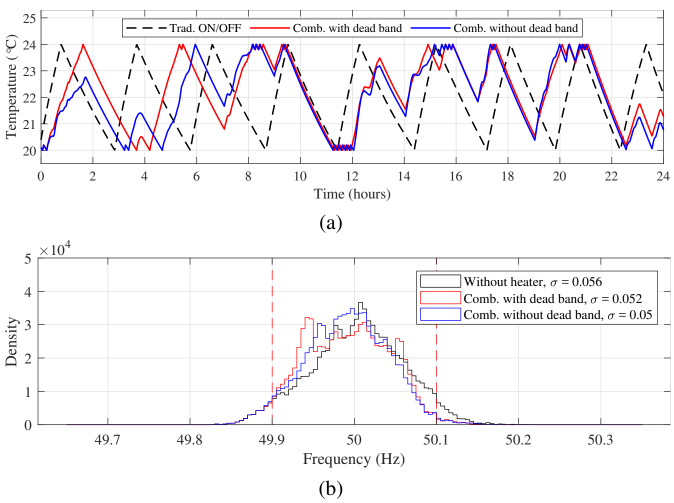


Figure 10. Hybrid control: (a) room temperature, (b) frequency histogram.

V. Discussion and Conclusions

The frequency droop-based control method of domestic loads seems to be a new effective method to manage frequency disturbances, energy management and demand response in the distribution power system. This paper explores extended droop-based control mechanisms to perform frequency regulation from demand-side. Three algorithms are proposed and tested in two scenarios: a single TCL providing frequency control to a power grid in the first scenario, and to a stand-alone microgrid in the second scenario.

The results from different control techniques using TCLs show a promising opportunity to provide frequency and indoor temperature control. The modified ON/OFF control algorithm (Algorithm 1) can compensate frequency spikes, the droop-based control algorithm (Algorithm 2) can reduce frequency deviations. The hybrid algorithm (Algorithm 3) with and without a dead band has shown the lowest deviations. However, the droop control with a dead band does not have any significant advantages. This effect of frequency compensation can be more pronounced in systems with high variability of RES and systems with low inertia as a source for improvement of flexibility and reliability in power grids. However, in big power systems, the impact of the TCL on the grid frequency will depend on the value of the overall TCL's consumption relative to the total consumption in the grid.

In summary, we have run an extensive number of simulations to test that droop control-based methods for the load management has a possibility to provide a decentralized control, which is not requiring explicit communication links. But further research is needed. Our future extension of this work will be focused on evaluating the impact of a large number of heterogeneous TCLs and improvement of provided basic droop-based algorithms considering a collective dynamic of loads in an aggregated model.

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