Power System Virtual Inertia Implemented by Thermostatically Controlled Loads

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***Abstract*—Thermostatically controlled loads (TCLs) (e.g. air conditioners) have large potentials for providing ancillary services to power systems. In this paper, an approach to implementing power system virtual inertia by TCLs is proposed, while maintaining customers' comfort levels. Considering the TCLs' own unique power consumption fluctuation and response uncertainty, a tracking control strategy based on PI controller is proposed to preserve the performance of power system virtual inertia. Some simulation results are provided to verify the effectiveness of the control scheme.**

***Index Terms*—Thermostatically controlled loads, virtual inertia, frequency regulation, power consumption tracking control, direct load control**

I. INTRODUCTION

In the last decade, renewable technologies have been developing rapidly, such as photovoltaics (PV) generation and wind power generation. However, high penetrations of renewable energy sources (RESs) will cause the power system inertia reduction, and therefore, increase the spinning reserves [1], which can significantly challenge the system frequency regulation. Therefore, additional resources and associated control that can provide power system virtual inertia are highly needed.

One significant way to solve this problem is to regulate the existing power system resources, such as grid-connected power converters. By regulating the dc-link voltages, aggregated dc-link capacitors are converted into an equivalent capacitor which serves as an energy buffer to emulate the inertia [2]. In [3], the rotating mass connected to the DFIG shaft or a super-capacitor connected to the DC-link of a back-to-back inverter of a wind power generator was used to smooth the power output and improve the frequency regulation.

Along with the development of intelligent measurement technology, the residential electrical load can be controlled accurately, such as TCLs which can respond to the control signal quickly through direct load control (DLC) strategy while the users' comfort level is not affected [4]. According to different mechanisms of TCLs participating in the DLC, the control methods can be mainly categorized into direct form [5]-[8] and indirect form [9]-[11]. The direct form means that the on/off states of the compressor in the TCLs are directly controlled to regulate the power. While in the indirect form, the parameters of TCLs, such as the temperature set-points and the switch cycles of the TCLs, are indirectly controlled to regulate the power. In DLC mode with a centralized controller, the aggregated TCLs are able to respond to the control signal rapidly. Several studies have investigated the potential of TCLs to participate in demand response (DR) [12][13], For the time constant of temperature field is pretty large, aggregated rooms along with TCLs can be regarded as a super energy storage device and serve as the kinetic energy of the synchronous generators. Comparing to the other kinds of energy storage devices, aggregated TCLs have the advantages of flexibility and environmental protection property. So, it is of great significance to promote system inertia by designing a virtual inertia control strategy in order to implement the reversible interconversion of virtual kinetic energy of imaginary rotors and thermal energy of temperature field, which motivates this study.

In this paper, the power system virtual inertia is implemented by TCLs based on a virtual inertia controller. To reject the fluctuation of the aggregated TCLs power consumption and preserve the performance of virtual inertia control strategy, a PI controller-based tracking control scheme is proposed. The rest of this paper is organized as follows: the model of power system with virtual inertia controller and PI controller is formulated in section II. The control strategy is described in detail in section III. Simulation results are exhibited in section IV, followed by conclusions.

II. PROBLEM FORMULATION

A. Power system model

Considering a single-area power system with ancillary serve of virtual inertia, the frequency response model is shown in Fig.1.

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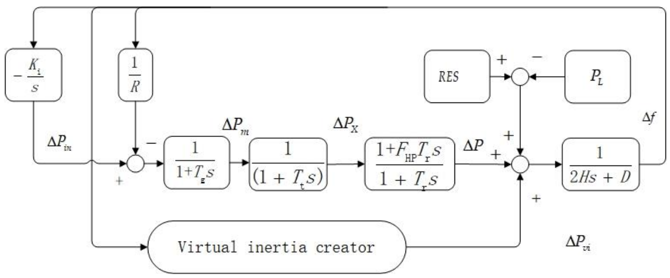


Fig.1 Frequency response model with ancillary serve device

where R is the governor's adjustment coefficient. ΔP_{vi} is the power consumption variation of the aggregated TCLs. T_g is the time constant of the speed regulator. H is the inertia time constant of the generator. Δf is the system frequency deviation value. D represents the damping coefficient of the system. T_t is the time constant of the steam turbine. T_r represents the time constant of the generator. K_i represents the integral gain of the secondary frequency modulation.

B. An Equivalent thermal parameters model of TCL

The mentioned TCL in the virtual inertia control scheme is periodically turned on and off to preserve the users' comfort level, which causes the uncertainty of the power consumption. In this paper, the TCL in cooling mode is mainly studied. Let $S_i(t)$ be the on/off state (1 referring to on state and 0 referring to off state) of the t h TCL, and $T_i(t)$ be the temperature of the corresponding room. Then $S_i(t)$ can be written by

$$S_i(t^+) = \begin{cases} 0 & T(t) \le T_{\min} \\ 1 & T(t) \ge T_{\max} \\ S_i(t) & otherwise \end{cases} \quad (1)$$

$$\dot{T}_i(t) = -\frac{1}{C_i R_i}[T_i(t) - T_a + S_i(t) R_i Q_i] \quad (2)$$

where $C_i(t)$, $R_i(t)$, $Q_i(t)$ represent the equivalent heat capacity, equivalent thermal resistance and equivalent heat rate, respectively. The total power consumption of aggregated TCLs is formulated as following

$$p(t) = \sum_{i=1}^{n} p_i(t) S_i(t) = \sum_{i=1}^{n} \frac{Q_i(t) S_i(t)}{\eta_i} \quad (3)$$

where coefficient η_i describes the efficiency of the device.

III. DESIGN OF THE CONTROL SCHEME

The virtual inertia creator consists of virtual inertia controller (VI), PI-based load tracking controller (PILTC), and s saturation module as depicted in Fig.2.

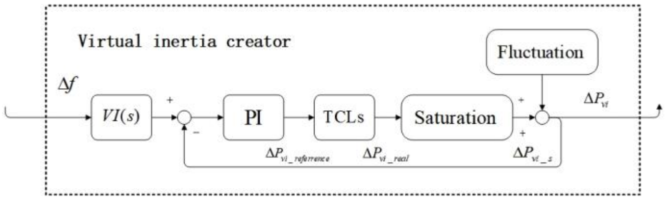


Fig.2 Details of the virtual inertia creator

VI controller can be formulated as

$$VI(s) = -k_{vi} s \quad (4)$$

where k_{vi} is the virtual inertia coefficiency. Considering the response uncertainty of the TCLs, which is assumed to subject to Bernoulli distribution, the real response ΔP_{vi_real} corresponding to the output of the PI based load tracking controller $\Delta P_{vi\_referrence}$ is given as

$$\Delta P_{vi\_real} \sim B(n_{feasible}, \frac{\Delta P_{vi\_referrence}}{p_{feasible}}) \quad (5)$$

$$\begin{cases} n_{feasible} = n_{on} \quad p_{feasible} = p_{on} & if \quad \Delta P_{vi\_referrence} < 0 \\ n_{feasible} = n_{off} \quad p_{feasible} = p_{off} & if \quad \Delta P_{vi\_referrence} \ge 0 \end{cases} \quad (6)$$

where n_{on} and n_{off} are the sum of the TCLs which are in on state and off state respectively. p_{on} and p_{off} are the corresponding total power. And $B(n,p)$ refers to Bernoulli distribution. Owing to the saturation module, the relationship between ΔP_{vi_real} and ΔP_{vi_s} is shown as following

$$\Delta P_{vi\_s} = \begin{cases} p_{on} & \Delta P_{vi\_real} \ge p_{on} \\ -p_{off} & \Delta P_{vi\_real} \le -p_{off} \\ \Delta P_{vi\_real} & otherwise \end{cases} \quad (7)$$

The power consumption fluctuation results from the natural switching action of each TCL between.

IV. SIMULATION RESULTS

In this section, a single area power system in Fig. 1 is applied as a case study. The values of the parameters of single area power system and TCLs are presented in TABLE I and TABLE II respectively. The changes of ambient temperature, the changes of the load and power fluctuation of the RESs are exhibited in Fig 3. The Monte Carlo simulation method is used to imitate the dynamics of the TCLs. The corresponding simulation results are shown in Fig. 4.

TABLE I. Parameters of the single area power system

R=0.05	T_g=0.2s	H=5s	D=1	T_t=0.3s	T_r=7s
K_i=2	P_{base}=2000MW	k_{vi}=10	f=50Hz		

TABLE II. TCL Parameters

Parameter	*Value (expectation)*	*Distribution*
T_{set}	21°C	Normal distribution
T_a	29°C	——
C	2kWh/°C	Normal distribution
R	2°C/kWh	Normal distribution
η	2.5	——
Q	14	Normal distribution

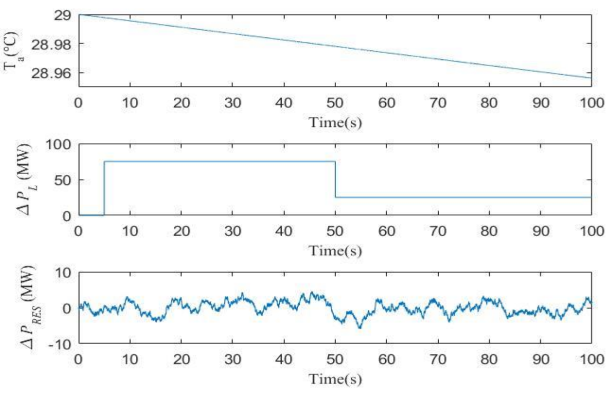


Fig.3 The variation of ambient temperature and power fluctuation of Loads and RESs.

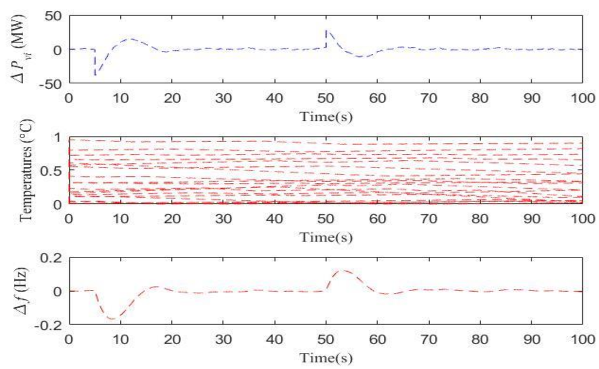
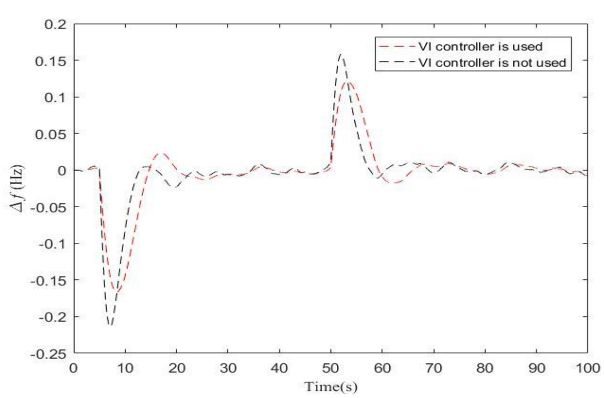


Fig.4 The variation of ambient temperature and power fluctuation of Loads and RESs.

A. *Case 1*

At this stage, the performance of the virtual inertia controller is compared with that without it, which is depicted in Fig 6, and a PI based load tracking controller is adopted. As it is clear from Fig.5, the power system virtual inertia is successfully implemented. The disturbance in Fig. 3 is considered.



111Fig.5 Frequency response according to the power fluctuation of Loads and RESs

B. *Case 2*

At this stage, the performance of PI based load tracking controller is shown in Fig 6, comparing to that without it. It is obvious that the performance of virtual inertia controller without PI based load tracking scheme will degenerate. The disturbance in Fig. 3 is considered.

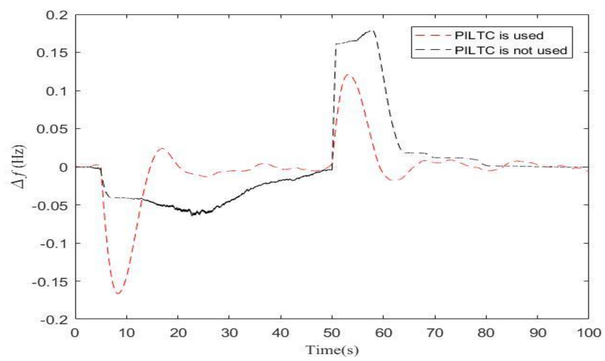


Fig.6 Frequency response according to the power fluctuation of Loads and RESs

V. CONCLUSION

This paper presented an approach to implementing power system virtual inertia by TCLs. A virtual inertia controller is used to create reference signal. And a PI based load tracking controller is used to optimize the performance of the virtual inertia control scheme. The simulation results indicate that the proposed virtual inertia control method has better performance that the virtual inertia controller without PI based load tracking.

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