Game Theory Applied in System of Renewable Power Generation with HVDC Out-sending Facilitated by Hundred Megawatts Battery Energy Storage Station

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***Abstract*—Battery Energy Storage Station (BESS) is the most effective way to facilitate transmission of large scale hybrid power generation that includes unpredictable renewable energy sources. In this paper we consider a wind-solar-thermal power system with high voltage direct current (HVDC) transmission and propose a novel power imbalance adjustment scheduling strategy based on game theory method. We propose a cooperative approach to maximize the total benefits by developing an optimal power adjustment distribution scheduling method. First use frequency deviation to determine the required total power adjustment and then according to cooperative game model the distributed power adjustment orders are decided. To incentivize the self-interested subsystem to take the system optimal action, we design a punishment protocol which each agent would be punished due to decreased sale price and subsidy. We exam the impact of proposed cooperative strategy through a simulation model and demonstrate that our analysis provides useful insight for designing incentive-compatible game schemes for the hybrid power system with HVDC transmission.**

Keywords—Renewable Power; Battery Energy Storage System; HVDC; Game Theory

I. Introduction

Renewable energy especially wind power and PV power have been rapidly developed since the environment issue caused by fossil fuel consumption is intensified. Since 2011 China has been the country with largest installed wind power capacity, and the wind power capacity continues increasing significantly every year [1]. China also ranked first in photovoltaic (PV) generation in 2015 [2]. But the regions with the most resourceful renewable power locate far from the load center. At present, accommodation capability of wind power in Northwest, Northeast and North China tends to be saturated. With the planned integration of large-scale PV power, it is urgent to transmit redundant renewable power to loads of other regions. The feasibility of transmitting large-scale renewable power located in Northeast and Northwest to North, East and Central China grid through HVDC projects was systematically researched [3]. In order to successfully transmit large-scale renewable energy through line commutated converter based high voltage direct current (LCC-HVDC) system, at sending end the thermal power plants are built to provide voltage support [4]. Thus, formed a wind-solar-thermal bundled power sending system.

However, the intermittent renewable power can cause serious power imbalance in the sending end. To ensure power system operate stably, the most likely choice is to curtail wind power. China had the most serious wind power curtailment in recent years. In 2015, the annual abandoned wind power was 33.9 billion kWh, and the average rate of abandoned wind was 15% [5]. Northwestern China is the area that holds most rich wind power resource but also suffer the most serious wind power curtailment. Gansu province discarded wind power 8.2 billion kWh and the wind curtailment rate was as high as 39% last year. One reason is that the regional power grid is relative weak, which means lacking of enough peak shifting ability. Another important reason for the large amount of wind curtailment is lacking of cooperation among the sub-generation systems.

The power imbalance caused by uncertain renewable power is still highlight research issue. [6] presented the method for calculation of maximum wind power penetration in an island power system with voltage-source converters based high voltage direct current (VSC-HVDC) or LCC-HVDC, but it didn't propose specific control strategy to inhibit power imbalance. Some work focused on transient stability study. [7] made the initial high-frequency generator tripping strategy adaptive to different faults for wind-PV-thermal transmitted by AC/DC system. The operating characteristics of HVDC, the operational conditions of both grid-connecting and islanding modes in the transition period and the imbalanced power distribution in weak sending end network is studied in [8]. Some research is mainly about power and voltage control. [9]

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has proposed an DC power modulation strategy which uses wind farm power as input. [10] also proposed an additional control strategy to the ultrahigh-voltage direct current (UHVDC) system, which changes the power or current order according to the variation of system frequency. Most researches on large-scale renewable power HVDC transmission didn't consider BESS to facilitate stable operation at sending end. In micro-grid, energy storage has been widely used and proved to be very effective in regulating power fluctuation. Since the power batteries price keeps decreasing, applying large scale BESS to hybrid power generation with HVDC out-sending is possible [11].

This paper considered not only adding large BESS but also HVDC additional control to facilitate frequency regulation. This hybrid system is complicated since the integration of distributed renewable generations, battery energy storage station and HVDC. The most challenge work is to find optimal strategy for each agent such as to make balance and optimize benefits of every subject in power system. The traditional single decision making based optimization system hardly resolve this problem. However, game theory as a method for multiple objects optimization can be very promising in dealing with it [12].

We propose cooperative game as method to optimize operation of renewable generation with HVDC out-sending system facilitated by hundred megawatts level's BESS. That is through maximizing benefits of the agent alliance and reasonably distributing game payoff to optimize individual benefit. We use frequency deviation to determine the required total power adjustment and then determine power order for each subsystem according to cooperative game model. Finally, this paper made a simulation for selected weight factor control coefficient to verify the control strategy is applied effectively.

II. System Model

A. Problem Formation

We consider an electric power system which consists of thermal generation units, wind farms, BESS and HVDC as in. Each thermal unit is equipped with thermal generator control system (TGCS); the wind farm is equipped with wind farm control system (WFCS); the PV station is equipped with photovoltaic control system (PVCS); HVDC is added the HVDC control system (HCS); the BESS is also equipped with battery control system (BCS). All the control systems can communicate with their own subsystem and the control center, controlling the scheduling of energy input or output in each subsystem.

This paper the entire scheduling interval (e.g. 2 hours) is divided into T time-slots with equal duration, whose set is denoted by $\tau = (1,2,\cdots T)$ (e.g. T=120 time-slots in 2 hours). We assume that the power scheduling is determined at the beginning of the entire scheduling interval. The output power of thermal generation unit i and renewable generation unit during time slot t is denoted by the variable $P_{Ti}(t)$, $P_{WFj}(t)$ and $P_{Pk}(t)$. Compared with thermal and renewable power generation, BESS is capable of charging and discharging energy in/from the batteries. As we define energy inputting into BESS as positive, the power consumption of BESS at time slot t is denoted by $P_{BESS}(t)$. And the power consumption of HVDC transmission at time slot t is denoted by $P_{HVDC}(t)$.

The most challenge issue for a hybrid generation system with uncertain renewable energy is frequency stability. The active power fluctuation of renewable generation can cause power imbalance in the sending system, thus threatening system frequency stability. Therefore, an objective function for frequency control is formulized as [13]:

$$\Delta P(t) = P_S(t) - P_L(t) \rightarrow 0 \tag{1}$$

$$P_S(t) = P_T(t) + P_{WF}(t) + P_{PV}(t) \tag{2}$$

$$P_L(t) = P_{BESS}(t) + P_{HVDC}(t) \tag{3}$$

Due to physical constraints, there are both maximum and minimum amount of energy for thermal generations, BESS and HVDC transmission at each time slot,

$$P_T^{\min}(t) \le P_T(t) \le P_T^{\max}(t) \quad \forall t \in \tau \tag{4}$$

$$P_{WG}^{\min}(t) \le P_{WG}(t) \le P_{WG}^{\max}(t) \quad \forall t \in \tau \tag{5}$$

$$P_{PV}^{\min}(t) \le P_{PV}(t) \le P_{PV}^{\max}(t) \quad \forall t \in \tau \tag{6}$$

$$P_{BESS}^{\min}(t) \le P_{BESS}(t) \le P_{BESS}^{\max}(t) \quad \forall t \in \tau \tag{7}$$

$$P_{HVDC}^{\min}(t) \le P_{HVDC}(t) \le P_{HVDC}^{\max}(t) \quad \forall t \in \tau \tag{8}$$

where $P_T^{\min}(t)$, $P_{WG}^{\min}(t)$, $P_{PV}^{\min}(t)$, $P_{BESS}^{\min}(t)$, $P_{HVDC}^{\min}(t)$ are separate lower bound of thermal generation, wind generation, PV stations, BESS and HVDC transmission; $P_T^{\max}(t)$, $P_{WG}^{\max}(t)$, $P_{PV}^{\max}(t)$, $P_{BESS}^{\max}(t)$, $P_{HVDC}^{\max}(t)$ are separately upper bound of thermal generation, wind generation, PV stations, BESS and HVDC transmission.

B. Power Adjustment Control System

The power control diagram for wind-thermal generation HVDC out-sending with BESS is show in Fig. 1.

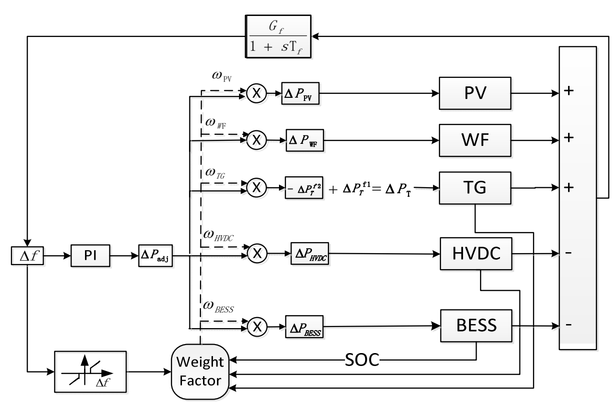

Fig. 1. Power control diagram

Power output or input of each subsystem should be:

$$P_{PV}(t) = \sum_{k=1}^{p} P_{PVk}(t) \quad (9)$$

$$P_{WF}(t) = \sum_{j=1}^{m} P_{WFj}(t) \quad (10)$$

$$P_{T}(t) = \sum_{i=1}^{n} P_{Ti}(t) \quad (11)$$

Since thermal generators have the characteristic of primary frequency regulation. When participating in system power regulation, we not only take advantage of this characteristic but also implement secondary frequency regulation, thus

$$\Delta P_T(t) = \Delta P_T^{f1}(t) + \Delta P_T^{f2}(t) \quad (12)$$

It is difficult to accurately forecast renewable power especially for wind power, so here uses frequency deviation as control objective. Through the PI controller, a total active power adjustment order can be obtained. Then weight factor model is used to decide the adjustment weight factors. In such complicated hybrid generation system, in order to fulfill optimal benefit of the whole system we propose a game theory based cooperative approach. In section III a weight factor model will be explicitly described.

III. Power Adjustment Weight Factor Game

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Finally, complete content and organizational editing before formatting. Please take note of the following items when proofreading spelling and grammar:

A. *Coopeprative Approach for hybrid generation system afflicated by BESS with HVDC sending*

There are five participators, including wind farm (WF) generations, photovoltaic (PV) generations, thermal generations (TG), battery energy storage station (BESS) and HVDC. Since PV and WG are uncertain power generation, although there are total 16 alliance combinations for cooperative game with five participators, we choose the following alliance combination:

[{PV, WG}, {TG, BESS, HVDC}]

The weight factor strategy of each subsystem is denoted as

$\omega_{WG} \in [0,1]$, $\omega_{PV} \in [0,1]$, $\omega_{TG} \in [0,1]$, $\omega_{BESS} \in [0,1]$, $\omega_{HVDC} \in [0,1]$ and

$$\omega_{WG} + \omega_{PV} + \omega_{TG} + \omega_{BESS} + \omega_{HVDC} = 1 \quad (13)$$

The strategy's continuous spaces are

$$\omega_{WG}\Delta P_{ad}(t) \in \{S_{WG} = [\Delta P_{WG}^{\min}(t), \Delta P_{WG}^{\max}(t)]\} \quad (14)$$

$$\omega_{PV}\Delta P_{ad}(t) \in \{S_{PV} = [\Delta P_{PV}^{\min}(t), \Delta P_{PV}^{\max}(t)]\} \quad (15)$$

$$\omega_{TG}\Delta P_{ad}(t) \in \{S_{TG} = [\Delta P_{TG}^{\min}(t), \Delta P_{TG}^{\max}(t)]\} \quad (16)$$

$$\omega_{BESS}\Delta P_{ad}(t) \in \{S_{BESS} = [\Delta P_{BESS}^{\min}(t), \Delta P_{BESS}^{\max}(t)]\} \quad (17)$$

$$\omega_{HVDC}\Delta P_{ad}(t) \in \{S_{HVDC} = [\Delta P_{HVDC}^{\min}(t), \Delta P_{HVDC}^{\max}(t)]\} \quad (18)$$

For participators {PV, WG}, {TG, BESS, HVDC}, the strategy sets are

$S_{WP} = [\Delta P_{WG}^{\min}(t),\ \Delta P_{WG}^{\max}(t) ; \Delta P_{PV}^{\min}(t), \Delta P_{PV}^{\max}(t)]$;

$S_{BTH} = [\Delta P_{BESS}^{\min}(t),\ \Delta P_{BESS}^{\max}(t) ; \Delta P_{HVDC}^{\min}(t), \Delta P_{HVDC}^{\max}(t) ; \Delta P_{TG}^{\min}(t), \Delta P_{TG}^{\max}(t)]$
and the information sets $v(t)$, $I(t)$, $SOC(t)$ and Δf separately represent wind speed, solar irradiance, state of charging of the BESS and frequency of sending system.

If this cooperative game model has the Nash Equilibrium point $\{\Delta P'_{WG*} + \Delta P'_{PV*}\}$ and $\{\Delta P'_{BESS*} + \Delta P'_{TG*} + \Delta P'_{HVDC*}\}$, it should be the optimal strategy as the other has the optimized strategy, that reaches the Nash equilibrium maximum payoff strategy under this game alliance.

B. *Power Adjustment Distribution in Wind farms and PV stations alliance*

We distribute power adjustment weight factor in wind-solar alliance according to their capacity. Thus,

$$\omega_{WG} = \omega_{WGPV} \cdot \frac{\sum_{j=1}^{m} C_{WGj}}{\sum_{j=1}^{m} C_{WGj} + \sum_{k=1}^{p} C_{PVk}} \quad (19)$$

$$\omega_{PV} = \omega_{WGPV} \cdot \frac{\sum_{k=1}^{p} C_{PVk}}{\sum_{j=1}^{m} C_{WGj} + \sum_{k=1}^{p} C_{PVk}} \quad (20)$$

in which C_{WGj} and C_{PVk} are capacity of each wind farm and PV station.

C. *Game in BESS and HVDC alliance*

Equilibrium point $\{\Delta P'_{BESS*} + \Delta P'_{TG*} + \Delta P'_{HVDC*}\}$ is corresponding to $\omega_{BTH} = \omega_{TG} + \omega_{BESS} + \omega_{HVDC}$. For the power adjustment weight factor distribution in BESS-thermal-HVDC alliance, considering secondary frequency regulation is normally decided by regional AGC (autonomous generation control), it is actually a constant

$$\omega_{TG} = \omega_{TG}^{0} \quad (21)$$

and total power adjustment weight factor of BESS and HVDC should be

$$\omega_{BESS} + \omega_{HVDC} = \omega_{BH} = \omega_{BTH} - \omega_{TG}^{0} \quad (22)$$

On the basis of game theory, weight factors distribution between BESS and HVDC are determined by economic benefits and operation stability. The following cases shows that weight factors of BESS and HVDC should be attributed according to the principles that HVDC power order should less frequently than BESS and to be more profitable when battery SOC at suitable condition BESS undertaking more power adjustment:

Case 1: When $\triangle f > 0.2$, SOC<0.4, then $\omega_{BESS}\uparrow$, $\omega_{HVDC}\uparrow$, Competitive;
Case 2: When $0.1<\triangle f \le 0.2$ SOC<0.4, then $\omega_{BESS}\uparrow$, $\omega_{HVDC}\downarrow$, Cooperative;
Case 3: When $-0.2\le\triangle f<-0.1$ SOC<0.4, then $\omega_{BESS}\downarrow$, $\omega_{HVDC}\downarrow$, Competitive;
Case 4: When $\triangle f<-0.2$ SOC<0.4, then $\omega_{BESS}\downarrow$, $\omega_{HVDC}\uparrow$, Cooperative;
Case 5: When $0.4\le SOC\le 0.6$ Or $-0.1\le\triangle f\le 0.1$, then $\omega_{BESS}\uparrow, \omega_{HVDC}\downarrow$, Cooperative.
Case 6: When $\triangle f>0.2$ SOC>0.6, then $\omega_{BESS}\downarrow$, $\omega_{HVDC}\uparrow$, Cooperative;
Case 7: When $0.1<\triangle f\le 0.2$ SOC>0.6, then $\omega_{BESS}\downarrow$, $\omega_{HVDC}\downarrow$, Competitive;
Case 8: When $-0.2\le\triangle f<-0.1$ SOC>0.6, then $\omega_{BESS}\uparrow$, $\omega_{HVDC}\downarrow$, Cooperative;
Case 9: When $\triangle f<0.2$, SOC>0.6,, then $\omega_{BESS}\uparrow$, $\omega_{HVDC}\uparrow$, Competitive;

In case 2,4,5,6,8 BESS and HVDC can work in cooperative way, while in case 1,3,7,9 BESS and HVDC are competitive. So we design the weight factors distribution principle as following.

Here we define a variable $\sigma_{\omega}^{SOC,f}$ as

$$\omega_{HVDC} = \frac{\omega_{BH}}{2} + \sigma_{\omega}^{SOC,f} \tag{23}$$

$$\omega_{HVDC} = \frac{\omega_{BH}}{2} - \sigma_{\omega}^{SOC,f} \tag{24}$$

$$\sigma_{\omega}^{SOC,f} = \begin{cases} -\frac{\omega_{BH}}{2} & \begin{matrix}(0.4\le SOC\le 0.6 \\ -0.1\le\Delta f\le 0.1)\end{matrix} \\ \alpha(SOC-0.5)\cdot\Delta f & \begin{matrix}(0.1<\Delta f\le 0.2 \\ -0.2\le\Delta f<0.1)\end{matrix} \\ \begin{matrix}\beta(\Delta f^2-0.04)+ \\ \alpha(SOC-0.5)\cdot\Delta f\end{matrix} & \begin{matrix}(\Delta f<-0.2 \\ \Delta f>0.2)\end{matrix} \end{cases} \tag{25}$$

Since there are both cooperative and competitive case in the alliance, the coefficient α, β is adaptive according to operating condition.

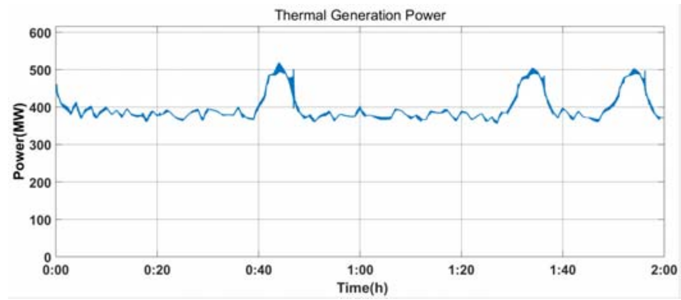
IV. Case Simulation

We build a model to demonstrate the power adjustment method that based on game theory of weight factor can effectively implemented in system of the renewable power generation with HVDC out-sending facilitated by BESS.

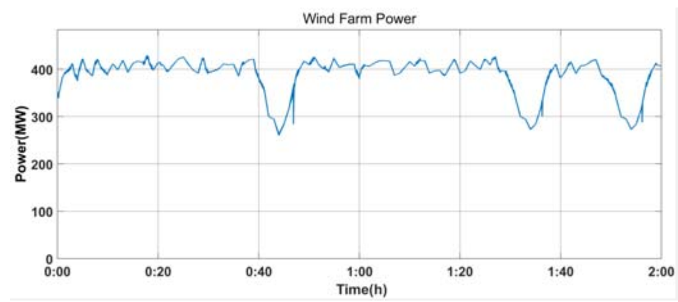
In this model, the cooperative approach aims take advantage of BESS power regulation capacity and HVDC coordination control to help integrate renewable power into power grid. So we designed the cooperative weight factor portion as ω_{WP}: ω_{BTH} =0.2:0.8; and according to the capacity of PV stations and wind farms, we get $\frac{\omega_{WG}}{\omega_{PV}}=8:1$, $\omega_{TG}^{0}=0.1$. Thus the weight factor of each subsystem is:

$$[\omega_{WG},\omega_{PV},\omega_{TG},(\omega_{BESS}+\omega_{HVDC})]=[0.02, 0.16, 0.1, 0.72]$$

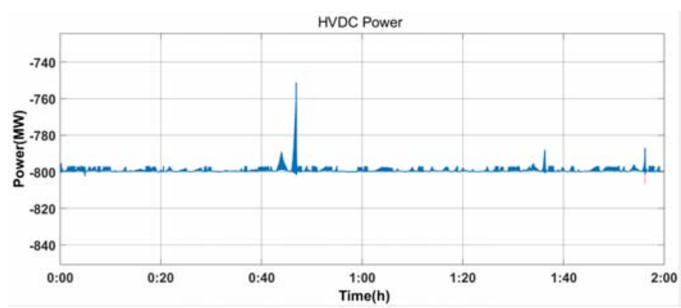
In the BESS and HVDC alliance, we make a simulation for the case α =1.5, β =5. Fig. 2 shows each subsystem power, and Fig. 3 and Fig.4 are SOC of battery energy storage station and power system frequency.



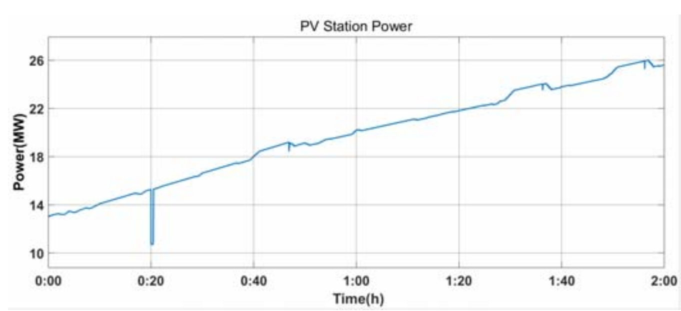
(a)Thermal Generator Power



(b)Wind Farm Power



(c) HVDC Power

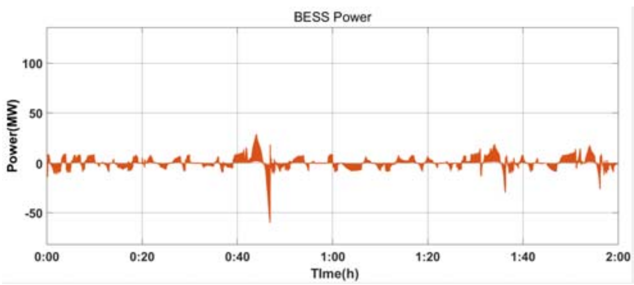


(d) PV Station Power

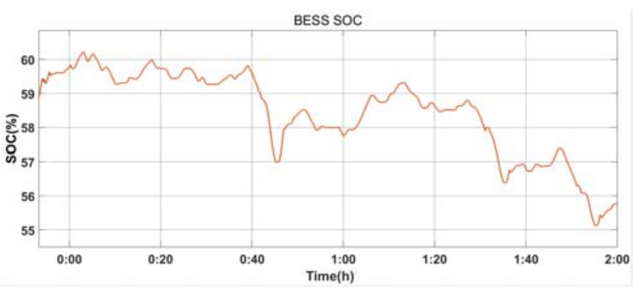
Fig. 2. Subsystem Power. (a)Thermal Generator Power (b)Wind Farm Power (c) HVDC Power (d) PV Station Power

The HVDC transmitted total power is 800MW, while the thermal power and renewable power ratio is closed to 1:1. The power capacity of BESS is 25MWh, which can keep work 15 minutes in maximum power 100MW.

During 2 hours' simulation time, wind farm power has large amount of drop and PV power has partial shadowing. As illustrated in Fig.6, renewable power imbalance caused frequency fluctuation are successfully reduced. The game theory determined weight factor can be applied to optimal whole system benefit as well as keep power system operating stably.



(a) Power



(b)SOC

Fig. 3. BESS (a)Power (b) SOC

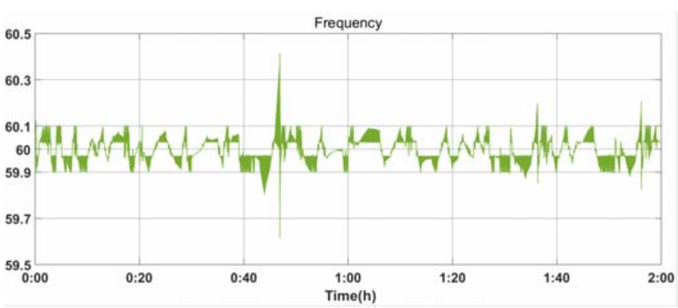


Fig. 4. System Frequency

V. CONDLUSION

This paper uses hundred megawatts BESS to help solve frequency stability problem in large-scale uncertainty renewable power with HVDC out-sending system. We propose control strategy based on game theory to find out optimal power adjustment order among each subsystem, and to design BESS and HVDC alliance power weight factors distribution method. The game between BESS and HVDC aims to ensure economic benefit and operation stability. Finally, based on designed control strategy we made a simulation model, verifying a good performance in keeping frequency stability.

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