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An Active Power Regulation Strategy for Wind Farm Considering Wake Effect

Xue Lyu[1,2], Youwei Jia[1], Zhao Xu[2], Xu Xu[2]

[1]Southern University of Science and Technology, Dept. of Electrical and Electronic Engineering, Shenzhen, China

[2]The Hong Kong Polytechnic University, Dept. of Electrical Engineering, Hong Kong, China

***Abstract*—To address the supply-demand imbalance issue in a system with high penetration of wind power, wind farms are required to follow the dispatch command to adjust their outputs, known as load sharing. In this context, this paper proposes a coordinated active power regulation strategy for wind farms in presence of wake effect. In the proposed control scheme, the kinetic energy storage potential and pitch angle adjusting capability of the wind turbine are exploited to extend its output. To reduce the activation frequency of pitch angle control and enhance total kinetic energy storage during the load sharing process, the load sharing ratio of each wind turbine in the proposed control strategy is allocated in a hierarchical manner based on the evaluation of their respective kinetic energy storage charging range/discharging range. Simulation results demonstrate the effectiveness of the proposed control scheme.**

***Index Terms*—wind farm, kinetic energy, pitch angle, active power regulation.**

I. INTRODUCTION

Recent decades have witnessed the fast development of wind power for energy supply. The variable speed wind turbines (VSWTs) including the doubly-fed induction generator (DFIG)-based wind turbines (WTs), and the permanent-magnet synchronous generator (PMSG)-based wind turbines are widely installed in industry due to their high energy efficiency. However, using the maximum power point tracking (MPPT) control, VSWTs cannot provide any active power support to system when supply-demand imbalance disturbances occur. As a result, the growing wind power penetration poses severe challenges on system operation security and reliability [1].

In general, the power fluctuation is balanced by conventional synchronous generators (SGs). the frequent action of governor may result in reduced life cycle and increased costs. Problems would become severe with more traditional SGs replaced by the WTs. In this context, the wind farm (WF) is expected to provide ancillary services to participate in system load sharing. To fulfill this requirement, one feasible technique is to install energy storage system, such as pumped water, flying wheel or super-capacitors, in the wind farm[2-4]. However, it will lead to excessive investment. The other kind of technique is to develop advanced control algorithms to adjust the WTs output power in accordance with the dispatch demand.

Generally, there are two kind of methods to adjust the active power output of WTs, i.e., rotor speed control and pitch angle control. The rotor speed control can achieve either deloading or overloading by adjusting rotational speed of wind turbine[5-7]. Specifically, rotor speed acceleration can withhold wind power capture and store partial energy in the form of kinetic energy (KE) in its rotating mass. On the other hand, rotor speed deceleration can provide temporary extra power support via release the stored KE back to system. Pitch angle control is the other way to regulate wind power capture through adjusting blade pitch angle [8-10]. However, if without deloading in advance, this control can only reduce power output and is only applicable for deloading operation. Since the wind power is directly wasted during the actuation process, pitch angle control will inevitably bring energy loss. Moreover, frequent activation of blade pitch angle may increase mechanical stress and fatigue of WTs.

By far, most research about wind power regulation strategy is developed based on a single WT model or utilizing an aggregated model to present a WF, which has no difference with the individual WT. It is easy to understand that homogeneous control is straightforward yet is fundamentally flawed in terms of a significant discrepancy between simulation and reality. In fact, turning to a whole WF perspective, individual WTs that are collectively committed to load sharing shall not neglect the naturally occurring wake effect (i.e. As wind flow proceeds downstream, there exists a trail where wind speed is reduced). In light of non-negligible wake effect, we dedicate to investigating a coordinated active power regulation strategy for the WF, of which the concerned operating conditions of individual WTs and relevant load sharing ratio allocation are heterogenous.

To fill in the gap of this field, this paper proposes a coordinated control strategy for WF to provide load sharing support by exploring wake interactions. To better follow the dispatch order while reduce the activation frequency of pitch angle, a rule-based load sharing ratio allocation approach is developed. Specifically, the rotor speed control always has a

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high priority to utilize and the charging/discharging range of KE storage of each WT is real-time calculated. At the WF control level, the load sharing ratio of each WT is allocated in a hierarchical manner. Case studies are carried out in a DFIG-based WF considering wake effect to verify the effectiveness of the proposed control scheme.

The remainder of the paper is organized as follows. In section II, the DFIG-based WT model and the wake model are introduced. Section III presents the proposed coordinated load sharing control strategy for wind farm. Case studies are conducted and discussed in Section VI. Section V concludes the paper.

II. Wind Turbine Model and Wake Effect Model

A. *DFIG Model*

DFIG is a popular wind turbine as its power converter only needs to handle 25-30% of nominal generator power i.e. the slip power in the rotor circuit and remaining power is directly fed to the grid from the stator part. The system configuration of the DFIG-based WT is depicted in Fig. 1, whose main components include the wind turbine, gear-box, induction generator and back-to-back converter. It can be found that the stator is directly connected to grid, and the rotor is connected to grid via the back-to-back converter. The operation principle of the back-to-back converter is to synchronize the current with variable amplitude and frequency to the grid. The maximum power point tracking (MPPT) control is achieved in the rotor side converter (RSC) controller and the DC-link voltage is regulated by the grid side inverter (GSC) controller.

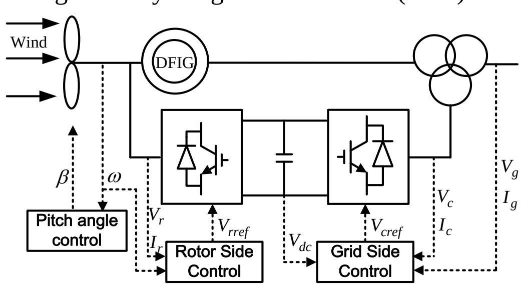

Fig. 1. Schematic diagram of DFIG-based wind turbine

For the wind turbine, the mechanical power extracted from the wind is defined as,

$$P_{wt} = \frac{\rho}{2}\pi R^2 v_w{}^3 C_p(\lambda,\beta) \tag{1}$$

where ρ is the air density, R is the rotor blade radius, v_w is the wind speed, λ is the tip speed ratio, β is the pitch angle, and C_p is the power coefficient. The power coefficient is a nonlinear function of tip speed ratio and pitch angle. According to[11], it can be expressed as,

$$C_p = 0.22(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{-\frac{12.5}{\lambda_i}} \tag{2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{3}$$

where the tip speed ratio is represented as,

$$\lambda = \frac{\omega R}{v_w} \tag{4}$$

where ω is the rotor speed. Normally, the pitch angle maintains at zero when v_w is below the rated value. In such a situation, C_p is the function of λ only. According to (4), there exists an optimum rotor speed that achieves the maximization of power coefficient for a given wind speed.

B. *Wake Effect Model*

Some existing wake models (e.g. kinematic, roughness, element and field models [12]) can hardly be incorporated in control frameworks due to the high complexity involved. In our work, a simplified yet effective model proposed in [13] is utilized, of which the modelling effectiveness is validated by extensive experiments in [14, 15]. The wake meandering is not considered in this wake model, and therefore the wind direction is assumed to parallel to the row of turbines at all times. According to this model, the wind speed $v_{w,n+1}$ reaching the WT_{n+1} can be calculated as,

$$v_{w,n+1} = v_{w,n} + k'(v_{w,1} - v_{w,n}) - k v_{w,1} C_{T,n} \tag{5}$$

where $v_{w,n}$ denotes the wind speed of the nearest upstream WT, k' and k are both distance parameters with k' corresponds to the recovered wind speed and k accounts for the wake effect of upstream WT. The values of k' and k are selected based on the actual data of the wind farm. $v_{w,1}$ is the free stream wind speed, $C_{T,n}$ is the thrust coefficient of the nearest upstream WT. The thrust coefficient C_T is a nonlinear function of tip speed ratio and pitch angle, which can be given via a look-up table or curving fitting[16]. Fig. 2 shows the relationship between C_T and λ, β .

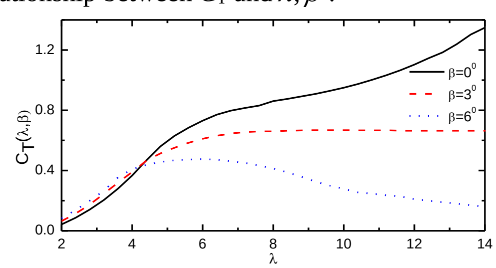

Fig. 2. Thrust coefficient of DFIG-based wind turbine

III. Proposed Control Scheme for Load Sharing

Wind farms are required to adjust power output to participate in load sharing. For example, when the required generation is less than the maximum power production of WF, the deloading control should be implemented. While when more production is needed, WF should possess the overloading capability. In this section, the deloading control and overloading control of the wind farm are discussed respectively for load sharing when wake effect is considered.

A. *Deloading Control*

When the deloading control is implemented, WTs should shift away from MPPT mode to a deloaded mode with a lower power coefficient. As shown in Fig. 3, the deloading can be realized by shifting the operating point from A to B through accelerating rotor speed, known as overspeed control. Though operating at a deloaded mode, the curtailed wind power can be stored in the rotational rotor in the form of kinetic energy. However, when rotor speed is accelerated to its upper limit, overspeed control is not applicable anymore. Under this circumstance, pitch angle control is another method to achieve deloading. As shown in Fig. 3, the operating point moves from A to C via increasing pitch angle. Different from overspeed control, pitch angle control cannot enhance wind power harvesting, since pitch angle does not possess energy storage capability and the curtailed wind power is directly wasted. As a consequence, overspeed control is usually preferable due to its fast response and its advantage on energy saving.

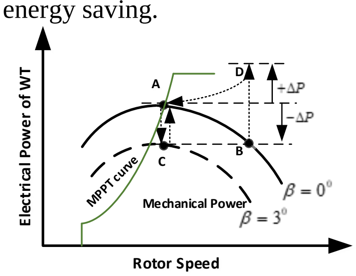

Fig. 3. Output power regulation of WT

Traditionally, a simple approach to allocate deloading requirement in the WF is to equally distribute the deloading ratio to each WT. However, when the wake effect is considered, this is no longer the optimal option since WTs in different locations operate in different status and wake interactions will inevitably affect the effectiveness of conventional uncoordinated load sharing strategy. For example, when load sharing ratio is equally distributed to each WT, the up-WTs may have to activate pitch angle control to achieve the deloading requirement as their KE charging range is samll due to their relatively high wind speed. In contrast, the KE based deloading capabilities of down-WTs are not fully exploited. Hence, to reduce the activation frequency of pitch angle control, the KE based deloading control always has a high priority to utilize for all WTs. However, the pitch angle control has to activate when rotor speeds of all WTs are accelerated to the upper limit. It should be noted that the increase of pitch angle leads to the decrease of thrust coefficient, as shown in Fig. 2. And then the wind speed reaching downstream WTs increases according to wake Eq. (5). As a result, pitch angle of downstream WTs inevitably increases. To avoid the above-mentioned problem, the downstream WTs has a high priority to activate their pitch angle control.

Base on the rotor motion equation, the relationship between rotor speed variation and dispatch command P_{comi} can be expressed as,

$$2H\omega_i \frac{d\omega_i}{dt} = P_{comi} - P_{wti} \tag{6}$$

where H is the inertia constant, P_{wti} is the mechanical power captured by the i-th WT.

Integrating (6) over time t_0 to t_1, we can obtain,

$$2\int_{t_0}^{t_1} H\omega_i d\omega = \int_{t_0}^{t_1} (P_{comi} - P_{wti})dt \tag{7}$$

$$H(\omega_{i1}{}^2 - \omega_{i0}^2) = (P_{comi} - P_{wti})\Delta t \tag{8}$$

where ω_{i0} and ω_{i1} denote the rotor speed of previous moment and current moment respectively.

It can be found that the deloading capability of overspeed control is depend on the rotational speed. Therefore, the charging power in the form of kinetic energy variation of each WT should be calculated according to its operation status. Taking into account the amount of available KE, in this work, the charging power of each WT is set to be proportional to the square of the rotational speed, which is given as,

$$\Delta P_{rot}^{de} = \Delta P_{rot\max}^{de} \frac{\omega_{\max}^2 - \omega^2}{\omega_{\max}^2 - \omega_{\min}^2} \tag{9}$$

where $\omega_{\max}$ and $\omega_{\min}$ are the maximum rotor speed and minimum rotor speed of WT, $\Delta P_{rot\max}^{de}$ is the maximum charging power, which is depend on the maximum KE that WT absorbs via rotor speed acceleration and this value is adjustable. The active power support ability is analysed in [17] and similarly, in this work, it is determined via our simulation results.

It can be seen from Fig. 2 that the rotor speed acceleration increases the thrust coefficient and leads to the decrease of wind speed reaching down-WTs and in turn their wind power capture. To store as much KE as possible, in the proposed control, only when rotor speed of down-WT accelerates to the upper limit, its neighborhood up-WT starts to activate overspeed control to compensate the remaining deviation between dispatch command and WF actual power output. When all WTs are charged full, the pitching based deloading control is activated from back row WTs to front row WTs in sequence. To this end, the load sharing ratio to each WT is assigned instantaneously based on the predefined activation and its charging range calculation. As a result, WTs in the WF response in a hierarchical manner.

Assuming there are n WTs in one row in the studied wind farm. The mismatch between the dispatch demand and wind power generation is denoted as ΔP and $\Delta P = P_{WF}^{act} - P_{WF}^{com}$. For the last down-WT, to exploit its deloading capability via overspeed control, the deloading ratio is defined as,

$$\Delta P_{wt,n} = \begin{cases} \min\left\{\Delta P, \Delta P_{rot}^{de,n}\right\}, \Delta P \ge \sum_{i=1}^{n} \Delta P_{rot}^{de,i} \\ \min\left\{\Delta P - \sum_{i=1}^{n-1} \Delta P_{rot}^{de,i}, P_{wt,n}^{act}\right\}, \Delta P \le \sum_{i=1}^{n} \Delta P_{rot}^{de,i} \end{cases} \tag{10}$$

where $P_{wt,n}^{act}$ is the actual power output the n-th row WT. Equation (10) guarantees that the KE based deloading control of all WTs has a high priority to utilize. If the deloading requirement is within the KE charging range of all WTs, the load sharing ratio of the last row WT is allocated according to the minimum value of the power deviation and its KE charging range. On the other hand, if the deloading requirement cannot be achieved by only utilizing the KE based control, the load sharing ratio of the last row WT is allocated according to the minimum value of remaining power deviation that cannot be stored in the form of KE variation and its actual power output.

As mentioned above, the remaining power deviation can be offset by the neighbor up-WTs. The deloading ratio for the i-th row WT is defined as,

$$\Delta P_{wt,i}=\begin{cases}\min\left\{\Delta P-\sum_{j=i+1}^{n}\Delta P_{wt,j},\Delta P_{rot}^{de,i}\right\},\Delta P\geq\sum_{i=1}^{n}\Delta P_{rot}^{de,i}\\ \min\left\{\Delta P-\sum_{j=1}^{i-1}\Delta P_{rot}^{de,j}-\sum_{j=i+1}^{n}\Delta P_{wt,j},P_{wt,i}^{act}\right\},\Delta P\leq\sum_{i=1}^{n}\Delta P_{rot}^{de,i}\end{cases} \tag{11}$$

Similarly, Eq. (11) ensures that the load sharing ratio allocation of the *i*-th WT is either within its charging range or its actual power output based on different operation scenarios.

B. Overloading Control

When over-consumption event occurs, system required generation may be larger than the maximum power production of WF. Accordingly, the stored KE should be released back to provide extra active power support. It can be seen from Fig. 2 that the thrust coefficient decreases along with rotor speed deceleration, which generates a positive influence on power capture of down-WTs. Hence, in the proposed control scheme, the first up-WT has the highest priority to response to the dispatch command. Similar to the deloading scenario, all WTs in the WF response in a hierarchical manner by instantaneously assigning the load sharing ratio to each WT based on the predefined activation priority and the discharging range calculation. It should be noted that the WT might stall if too much KE is extracted. To ensure the stable operation of each WT, the KE discharging range is defined as,

$$\Delta P_{rot}^{ov}=\Delta P_{rot\max}^{ov}\frac{\omega^2-\omega_{mpp}^2}{\omega_{\max}^2-\omega_{\min}^2} \tag{12}$$

where $\Delta P_{rot\max}^{ov}$ is the maximum discharging power, ω_{mpp} is the rotor speed at MPPT mode.

The overloading ratio that the first up-WT undertakes is expressed as,

$$\Delta P_{wt,1}=\min\left\{\Delta P,\Delta P_{rot}^{ov,1}\right\} \tag{13}$$

Similarly, overloading ratios for the *i*-th row WT is defined as,

$$\Delta P_{wt,i}=\min\left\{\Delta P-\sum_{j=1}^{i-1}\Delta P_{rot}^{ov,j},\Delta P_{rot}^{ov,i}\right\} \tag{14}$$

In case that load increment is larger than the overloading ability of WF and the reserve capacity of conventional generators is not enough, the presented load sharing scheme may not ensure system power balance. In such situation, the load curtailment should be applied.

Fig. 4 shows the proposed control scheme. It can be seen that the load sharing ratio that the *i*-th DFIG assumes is calculated according to (10-14). And then the modified active power is tracked as the new reference.

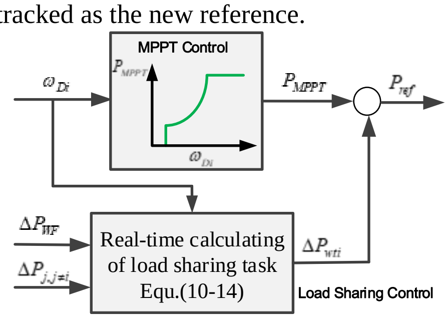

Fig. 4. Proposed load sharing control scheme for each DFIG

IV. Case Studies

To evaluate the performance of the proposed control strategy, a test system that contains two conventional synchronous generators (SGs), static loads, and a DFIG-based wind farm was modeled in DIgSILENT/PowerFactory, which is shown in Fig.5. The nominal capacities of two SGs are 30-MVA and 10-MVA, and the primary frequency droop parameter of the SGs are set as 4%. The wind farm consists of 4 units of 5-MW DFIG. The distance between each WT in a row is 14R. Power grid contains two local loads. L1 consists of a fixed load $P_{L1}+jQ_{L1}$ as 30MW+1Mvar, and the other switching in/out load L2, $P_{L2}+jQ_{L2}$.

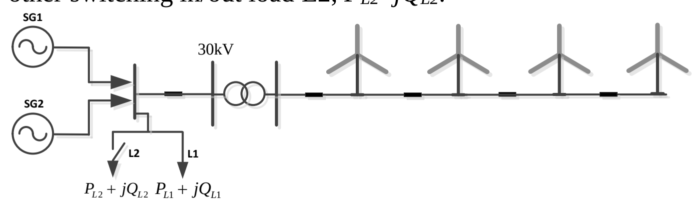

Fig. 5. Single-line diagram of test system

A. Deloading Control

The dump load $P_{L2}+jQ_{L2}$ as 2MW+0Mvar is switched off at t=10s. Three different scenarios namely with MPPT control, with conventional load sharing control and with the proposed control are compared in Fig. 6. It is assumed that the free wind speed v_{w1} is 12m/s.

It is clearly seen from Fig. 6(b) that the output power of WF remains unchanged with MPPT control throughout the simulation process. System frequency rises when load disturbance occurs with the frequency peak is 50.316Hz and the quasi-steady state frequency is 50.117Hz as shown in Fig. 6(a). In the conventional load sharing control scheme, each WT reduces 0.5-MW output power, which reduces the instant frequency to 50Hz and the quasi-steady state frequency to 50.054Hz as shown in Fig. 6(a). It can be seen from Fig. 6(b) that the total reduced power of the WF at the quasi-steady state is not equal to 2MW, as the activation of pitch angle control of up-WTs (Fig. 6(d)) leads to the increase of power capture of down-WTs. In contrast, with the proposed control, power mismatch between load and generation is completely compensated by WF and system frequency maintains at 50Hz throughout load disturbance as shown in Fig. 6(a). The rotor speed of each WT is accelerated to 1.22p.u. as shown in Fig. 6(c) no matter with the conventional load sharing control or the proposed control since the KE based deloading control always responses firstly. However, only utilizing overspeed control cannot fulfill the required deloading level. And then pitch angle control of each WT activates to continue curtail power output with the conventional load sharing control as shown in Fig. 6(d). By comparison, only DFIG 4 activates the pitch angle control to reduce power output with the proposed control and pitch angle of other WTs maintains at zero. It shows from Fig. 6(e) that the output power of SGs remains almost unchanged with the proposed control as WF offsets the total power gap. It can be seen from Fig. 6(f) that wind speed reaching back row WTs is affected by the operating points of up-WTs due to wake interactions, just as illustrated in wake equation (5).

B. *Overloading Control*

The dump load $P_{L2}+jQ_{L2}$ as 4MW+0Mvar is switched on at t=100s. Fig. 6 shows the dynamic response of DFIGs and SGs after sudden load changes. It is clearly seen from Fig. 6(a) that with the proposed control, the system frequency deviation is the smallest and system frequency recovers fastest. Specifically, the rate of change of frequency decreases significantly and frequency nadir increases to 49.803Hz. This is because more KE is stored via the proposed load sharing control compared with the conventional control. When load disturbance appears, all WTs move to MPPT mode with the reserved power released back to system. In addition, WF provides temporary extra power support during rotor speed deceleration period (Fig. 6(b)). The SG output power curve in Fig. 6(e) indicates that in the proposed control scheme, the

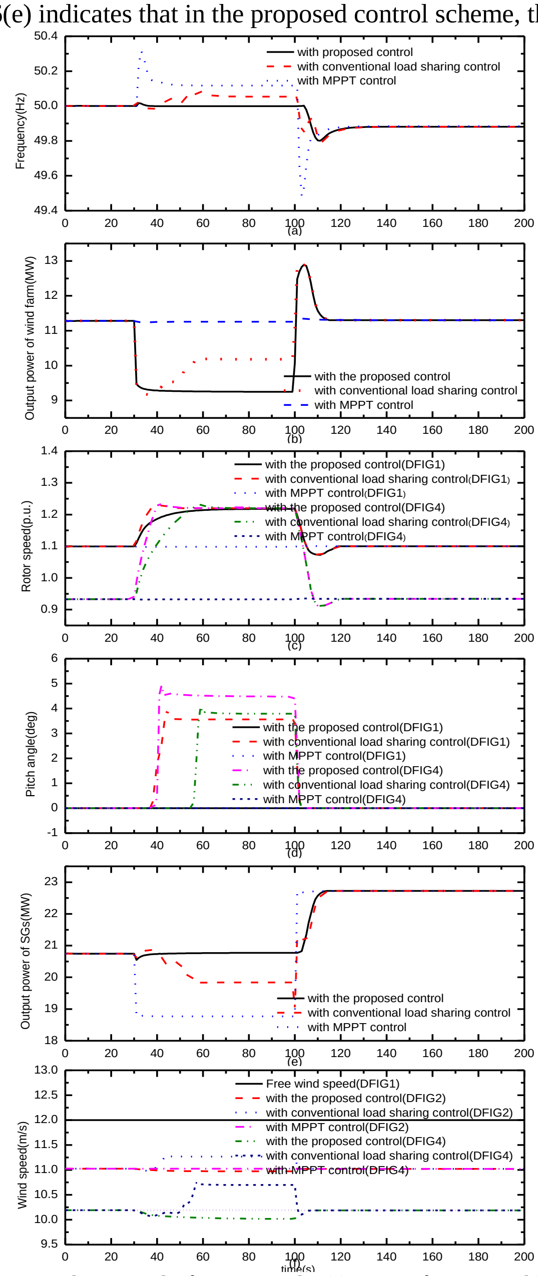

Fig. 6. Simulation results for Case Study. (a) System frequency, (b) WF output power, (c) DFIG rotor speed, (d) DFIG pitch angle(e) SGs output power, (f) Wind speed

mechanical power from governor increases slower than that with conventional load sharing control as WF provides more contribution for system load sharing.

V. CONCLUSION

A coordinated active power regulation strategy of wind farm considering wake effect inside is proposed in this work. To reduce the activation frequency of pitch angle and enhance total KE storage while fulfilling the dispatch command, a rule-based load sharing ratio allocation approached is developed. Specifically, at WT control level, the KE charging range and discharging range of each WT is real-time calculated. At WF control level, the power regulation priority of each WT is determined according to the wake interaction characteristic. Finally, the superiority of the proposed control is verified by simulation results.

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