

# Comprehensive inertia control for hybrid AC/DC distribution system

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**Abstract:** In this study, a comprehensive inertia control strategy is proposed for the distribution system consisting of AC/DC sub-grids. The coupling relationship of the AC and DC systems is analysed, and the comprehensive inertia control method of hybrid AC/DC system is proposed. More specifically, the operational characteristics of the wind turbine generator (WTG) are utilised to design the virtual inertial response strategy, which enables the WTGs in distribution network to provide flexible voltage and frequency support. Further, since the distributed energy storage (DES) is taken into account, the virtual inertial response of WTGs can be more controllable, which fully utilises the capacity of DES without the risk of halt of the WTGs. In addition, the mutual power support is designed based on the coupling relationship of the hybrid system, which can enhance the overall inertia of the distribution network. Finally, the effectiveness of the proposed strategy is verified by the simulation studies, which shows that the strategy can enhance the power quality and dynamics of the hybrid AC/DC system and thus improves the robustness of the distribution network.

## 1 Introduction

With the increasing demand for environmental-friendly resources and the development of power electronics technology more and more renewable energy sources (RESs) are integrated into distribution network [1, 2]. To further reduce the power loss caused by multi-step power conversion, some distributed sources and loads, which share the same electricity format (i.e. all AC power or DC power), are clustered together. In the same cluster, the loads can utilise the power provided by the sources and there is no need to perform the AC/DC conversion, which can significantly improve the efficiency of RESs and bring about larger economic revenue. Therefore, the hybrid AC/DC distribution network will be the developing trend in future smart grid architecture [3, 4].

The energy storage (ES) devices are usually adopted to track the net power variation due to the unpredictable output of RES [5, 6]. The conventional design is to install the ES units near the RES or important loads and buses, which features distributed location [7, 8], and form the concept of distributed energy storage (DES). The existing control strategy for DES is focused on local power variation and without the concern to contribute to the overall system stability. In [9], the DES is of high vacancy rate since it is just activated when the utility grid is unable to provide enough active power for the microgrid. In [10], the control strategy assigns the high-frequency power variation to DES, which is highly based on the load prediction and hard to respond to power variation quickly. Therefore, for the hybrid distribution network, there is great potential left for DESs to respond to the overall power variation. In other words, the DESs should not only be responsible for the local power demand but also capable of supporting power demand in other sections.

The wind turbine generator (WTG) has a rotating part, which can provide short-term inertial support. Since its rotor speed is decoupled from the system frequency or DC voltage. The capability of WTG providing additional inertial support can only be realised by the additive control strategy. However, the additional active power is acquired by reducing the rotor speed, thus releasing the kinetic energy, so a second power disturbance might occur during the rotor speed recovery [11]. Therefore, the cooperation with the DES would be a proper way to better utilise the WTG's inertial support ability.

Nowadays, a few researchers focus on the overall inertial improvement of hybrid AC/DC distribution network. The research works are mostly focused on the single AC grid or DC grid. Thus, we propose a comprehensive inertial control strategy for the hybrid network, which can fully utilise the power support ability of DES and WTG, and contribute to the overall power quality, i.e., the enhancement of both frequency and voltage stability. The simulation results show the effectiveness of the proposed strategy.

## 2 Topology of hybrid distribution network

A topology of the hybrid network prototype is described in Fig. 1, which is composed of three typical parts: an AC section, a DC section and an interlinking converter (IC). In the AC part, the AC generators, such as diesel turbine generator (DTG), motor loads (high proportion in factories) and wind turbine generator (WTG), are included. The photovoltaic system is implemented in the DC section with other DC loads, which can reduce the power transition loss compared with that in the AC section.

It should be noted that the hybrid distribution network is integrated into the utility grid in the AC section. By reasonable employment of RES, the absorbed power of distribution network can be reduced significantly, and the negative influence imposed by the net power disturbance can be smoothed in the network, which is realised based on the cooperation of the RES and DES in network and will be discussed in the following.

## 3 Proposed comprehensive inertia control method

### 3.1 Inertial response of WTG with DES

The WTG is able to release kinetic energy while it is necessary. More specifically, the WTG works in MPPT mode in order to make full use of wind power and may slow down the mechanical rotor speed, denoted as  $\omega_r$ , to release certain amount of kinetic energy to provide short-term inertial support (STIS) when there is net power vacancy.

The available amount of energy that can be obtained from WTG when supporting frequency is limited, since the rotor speed will drop due to the extra output of active power. Therefore, the

equivalent inertia of WTG serving for frequency support can be defined as

$$H_{WTG}^{STIS} = \frac{\frac{1}{2}J_W(\omega_{MPPT}^2 - \omega_r^2)}{S_{WTG}} = \frac{\Delta P_{WTG}^{STIS}}{S_{WTG}} \Delta t \quad (1)$$

where

$$\Delta P_{WTG}^{STIS} = -\frac{dW_{WTG}}{dt} = -J_W \omega_r \frac{d\omega_r}{dt} \quad (2)$$

where  $H_{WTG}^{STIS}$  is the equivalent inertia constant of the WTG,  $\omega_{MPPT}$  is the initial rotor speed,  $\Delta P_{WTG}^{STIS}$  is the additional power increment of the WTG and  $\Delta t$  is the duration time.

It can be seen from (1) that the larger the rotor speed drops, the higher the inertia value we can acquire. However, considering the safety requirements of WTG's operation, it is improper to reduce the rotor speed. Therefore, the DES unit is assigned to be cooperated with the WTG during the STIS. Assuming  $\Delta P_{ES}^{STIS} = k_{ES} \times \Delta P_{WTG}^{STIS}$ , then the inertia response power of WTG will be shared in part by ES by adjusting the value of coefficient  $k_{ES}$ , which will lead to

$$\frac{1}{2}J(\omega_0^2 - \omega_{WTG}^2) = (1 - k_{ES})\Delta P_{WTG}\Delta t \quad (3)$$

$$\Delta\omega = \omega_0 - \omega_{WTG} = \omega_0 - \sqrt{\omega_0^2 - \frac{2(1 - k_{ES})\Delta P_{WTG}\Delta t}{J}} \quad (4)$$

It is clear that with the increase of  $k_{ES}$ , the decrease of rotor speed is gradually reduced under the fixed  $\Delta P_{WTG}$ , because the ES unit takes more proportion of response power for supporting frequency and releases the burden of WTG, and vice versa. Therefore, (4) can serve as the guide when determining the value of  $k_{ES}$  under different operational conditions of WTG.

For the inertial response of a synchronous generator (SG), the fast power support is realised by responding to the differential terms of frequency in the AC network, of which the DC network is operating in the similar way. Besides, the system will activate the voltage and frequency droop control regulation method to stabilise the transient power quality. Based on what is discussed above, the inertial response power for WTG with DES is defined in (5), and Fig. 2 shows the schematic of the proposed coordinated controller:

$$\Delta P_{WTG}^{STIS} = \begin{cases} k_{ac}^{WTG} \left[ \frac{df}{dt} + (f_0 - f) \right], & \text{for AC section} \\ k_{dc}^{WTG} \left[ V_{dc} \frac{dV_{dc}}{dt} + (V_{ref} - V_{dc}) \right], & \text{for DC section} \end{cases} \quad (5)$$

where  $k_{ac}^{WTG}$  and  $k_{dc}^{WTG}$  are the droop coefficients for AC and DC sections, respectively.

### 3.2 Cross-sectional inertial support in a hybrid network with DES

As for the AC system, the power balance is represented by a swing equation described as

$$\frac{T_J}{\omega_n} \frac{d\omega}{dt} = P_T - P_E \quad (6)$$

where

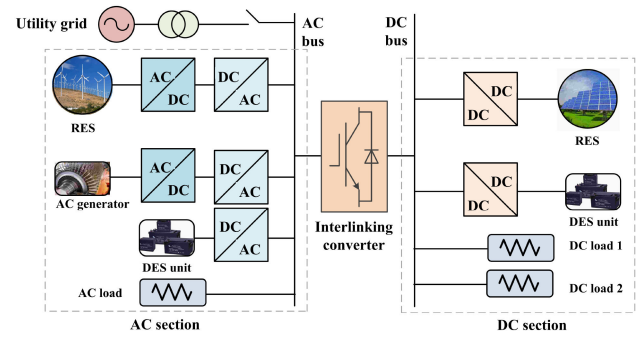


Fig. 1 Structure of the hybrid AC/DC distribution network

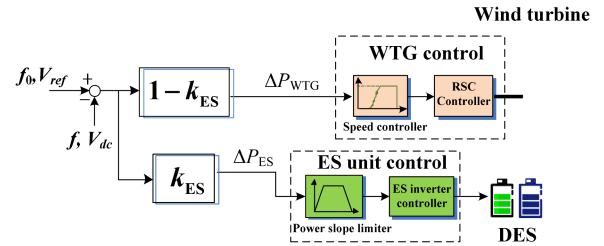


Fig. 2 Coordinated control scheme for WTG and ES systems

$$\begin{cases} T_J = \frac{2W_K}{S_B} \\ \omega_n = 2\pi f_n \end{cases} \quad (7)$$

Substituting (7) into (6), one can obtain

$$\frac{T_J}{\omega_n} \frac{d\omega}{dt} = P_T - P_E \quad (8)$$

where  $W_K$  is the kinetic energy of rotor at rated speed;  $S_B$  is the rated power;  $T_J$  is the time constant of generator;  $f_n$  is the rated frequency of the AC system;  $P_T$  and  $P_E$  are the input mechanical power and output power, respectively.

As for the DC system, the power balance is represented by the voltage variation described as

$$\frac{C_{dc}V_{dc}}{S_{VSC}} \frac{dV_{dc}}{dt} = P_1 - P_2 \quad (9)$$

where  $C_{dc}$  is the capacitance of DC capacitor;  $S_{VSC}$  is the rated power of IC;  $P_1$  and  $P_2$  are the equivalent input power and output power of the DC capacitor, respectively.

When active power is transmitted from the DC section to the AC section, the DC grid can be treated as the power source and IC is operating as an inverter, providing inertial support to the AC system, which can be regarded as a virtual synchronous machine. The same analysis can be utilised for the reverse operation, in which the AC grid is responsible for the DC voltage variation, working as a virtual capacitor. Therefore, it can change the operation states and direction of power flow IC, and thus, combining (8) and (9) leads to

$$\frac{T_{J,vir}}{f_n} \frac{df}{dt} = \frac{C_{vir}V_{dc}}{S_{VSC}} \frac{dV_{dc}}{dt} \quad (10)$$

where  $T_{J,vir}$ ,  $C_{vir}$  represent the virtual inertial constant and virtual capacitance, respectively.

Integrating both sides of (10), one can obtain

$$V_{dc} = \sqrt{\beta(f - f_n) + V_{dc,ref}^2} \quad (11)$$

where

$$\beta = \frac{2T_{J,vir}S_{VSC}}{f_n C_{vir}} \quad (12)$$

The coupling relationship of AC and DC grids is revealed in (11). Considering that the frequency variation is relatively small and abandons the high-order terms of its Taylor expansion, the linear relationship can be obtained as

$$V_{dc} = V_{dc,ref} + \frac{\beta}{2V_{dc,ref}}(f - f_n) \quad (13)$$

When there appears power shortage in the AC section, the virtual DC voltage variation can be acquired according to the relationship  $\Delta V_{dc}^{vir} = k_\beta(f - f_n)$ , which is derived from the above equation. Thus, we get the revised voltage reference defined as

$$V_{dc,ref} = V_{dc} - \Delta V_{dc}^{vir} \quad (14)$$

Considering the fact that the droop principle is usually adopted for the DES to respond to local power variation, we can rewrite the droop equation using the developed reference voltage and obtain

$$P_{dc,ref} = \frac{\beta}{2k_{dc}V_{dc,ref}}(f - f_n) + P_{dc}^0 \quad (15)$$

It shows that when the DC section provides active power support to the AC section (provided by the DES in the DC grid), the amount of cross-sectional power is determined by  $P_{dc,ref}$  and  $T_{J,vir}$ , whose the relationship is illustrated in Fig. 3. With the increase of frequency variation, the power is proportional to the frequency change, and the inertia constant also brings about the same influence on  $P_{dc,ref}$ .

Similarly, when the AC grid is providing active power to the DC section, the virtual frequency variation is accordingly obtained to develop the new droop equation shown in (16), and the characteristics are depicted in Fig. 4:

$$P_{ac,ref} = -\frac{2V_{dc,ref}}{k_{ac}\beta}(V_{dc,ref} - V_{dc}) + P_{ac}^0 \quad (16)$$

Assuming the power transmitted from the DC side to the AC side is at the positive direction, the difference between  $P_{dc,ref}$  and  $P_{ac,ref}$  is adopted as IC's reference power to avoid the power fluctuation in the hybrid network, which is shown in Fig. 5.

It should be noted that in order to avoid frequent action of IC when net power variation occurs, the dead zone is accordingly set as  $\Delta V_{dc} = \pm 0.02$  pu and  $\Delta f = \pm 0.1$  Hz. More specifically, the IC will not be activated within the dead zone, and the states of  $S_1$  and  $S_2$  are switched equal to 0, which can be defined as

$$S_1 = \begin{cases} 1, & |\Delta V| > 0.02 \\ 0, & |\Delta V| \leq 0.02 \end{cases} \quad (17)$$

$$S_2 = \begin{cases} 1, & |\Delta f| > 0.1 \\ 0, & |\Delta f| \leq 0.1 \end{cases} \quad (18)$$

## 4 Simulation results

To verify the effectiveness of the proposed control strategy, a hybrid AC/DC distribution network is modelling in DigSILENT/PowerFactory based on the topology in Fig. 1. Two typical operational cases are utilised for verification, in which the power is transferred from the DC section to the AC section or in the reverse case. The result without the comprehensive cross-zone power support is shown together for comparison. Basic simulation settings are shown in Table 1.

### 4.1 Case 1: power disturbance in the AC section

A step load power increment is activated in the AC section and leads to a sudden drop of frequency. Then, the frequency variation

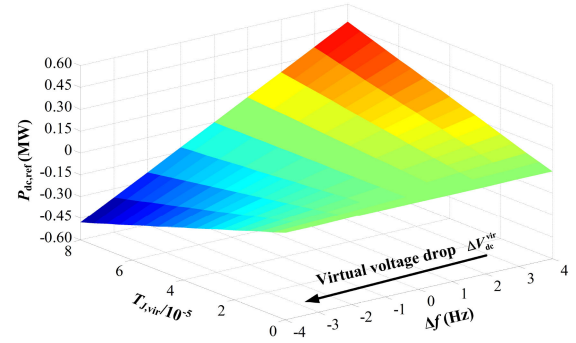


Fig. 3 Relationship between DC compensation AC power and virtual inertia and AC frequency variation

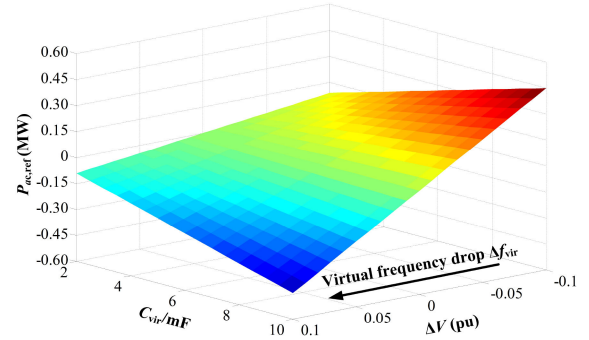


Fig. 4 Relationship between AC compensation DC power and virtual capacitor and DC voltage variation

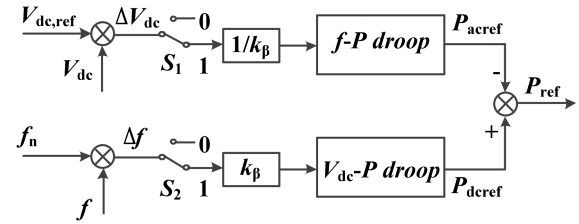


Fig. 5 Reference output power of IC converter

Table 1 System simulation parameters

Sub-section	Parameters	Value
AC section	rated voltage $V_{ac}^0$ , V	380
	rated frequency $f_n$ , Hz	50
	frequency droop coefficient $k_{ac}$ , (MW/Hz)	0.5
	virtual inertial constant $T_{J,vir}$ , s	$2 \times 10^{-5}$
	output power of DES, MW	0–10
DC section	AC load power, MW	5
	rated voltage $V_{dc}^0$ , V	700
	voltage droop coefficient $k_{dc}$ , MW/V	0.25
	DC capacitor $C_{dc}$ , $\mu F$	4000
	output power of DES, MW	0–5
IC converter	DC load power, MW	3
	rated capacity $S_{VSC}$ , MVA	2

is detected by the control system and the support power provided by the DC section is obtained according to the analysis above. The simulation results are shown in Figs. 6–8.

At the beginning, there is no active power transmitted between AC and DC grids, indicating the power balance is built in the distribution network. The step power increment of 5% in the AC section is activated at  $t = 1$  s. It can be seen from Fig. 6a that the DC section is not involved in the power support since the frequency deviation is limited to  $\pm 0.1$  Hz, in accordance with IC power being 0 shown in Fig. 8. During 4–10 s, the power

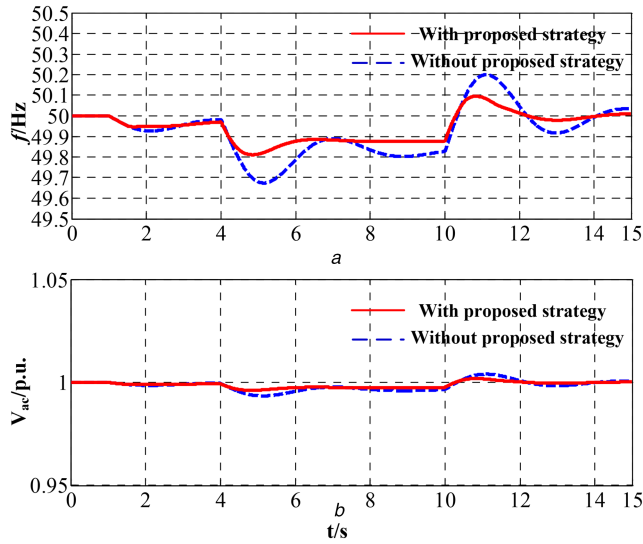


Fig. 6 AC section simulation results (Case 1)

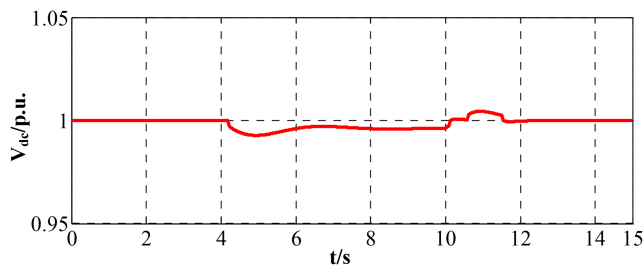


Fig. 7 DC section simulation results (Case 1)

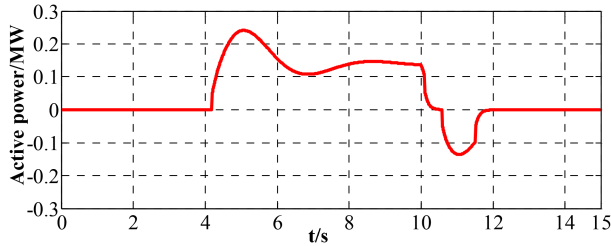


Fig. 8 IC power output simulation results (Case 1)

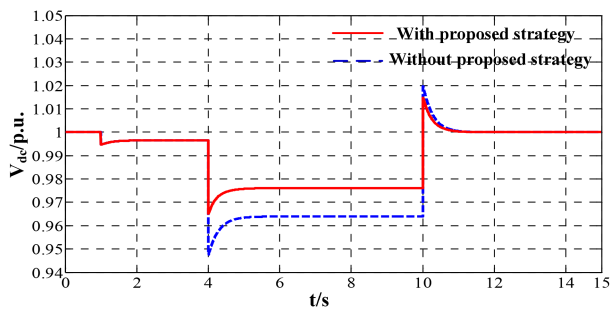


Fig. 9 DC section simulation results (Case 2)

increment reaches 20% of the rated load power and the frequency drops to 49.87 Hz, less than that of the low boundary of dead zone. The IC is activated as an inverter, and the additional active power is transmitted to the AC side, which is provided from DES of the DC section.

#### 4.2 Case 2: power disturbance in DC section

A step load power increment is activated in the DC section and leads to a sudden drop of DC voltage. Then, the voltage variation is detected by the control system and the support power provided by the AC section is obtained according to the control strategy described above. The simulation results are shown in Figs. 9–11.

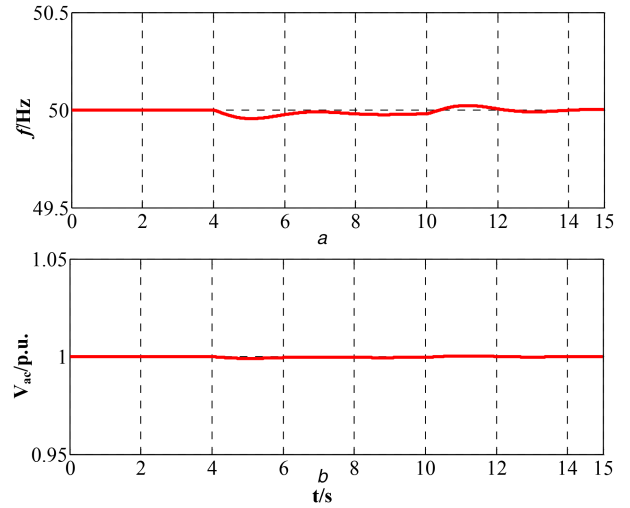


Fig. 10 AC section simulation results (Case 2)

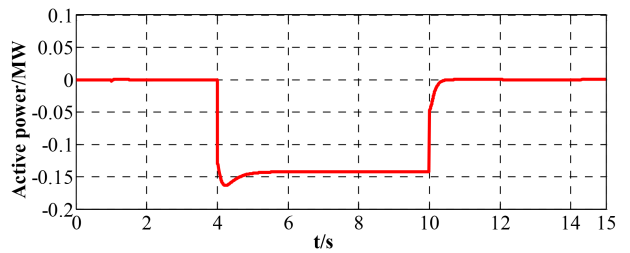


Fig. 11 IC power output simulation results (Case 2)

At the beginning, the power balance is built in the distribution network. Then, the step power increment of 5% in the DC section is activated at  $t=1$  s. It can be seen from Fig. 10a that the AC section is not involved in the power support since the voltage deviation is limited to 0.02 pu, in accordance with IC power being 0 shown in Fig. 11. During 4–10 s, the power increment reaches 50% pu and the voltage drops lower than 0.95 pu, less than that of the low boundary of dead zone. The IC is activated as a rectifier and the additional active power is transmitted to the DC side, which is provided from DES of the AC section.

## 5 Conclusion

In this article, a comprehensive inertia improvement strategy is proposed, which takes the power support potential of WTGs and DESs when the distribution network is confronted with power disturbance events. The proposed strategy sufficiently utilises the features of both the AC and DC sections with clear physical meaning and feasible to be implemented into practice. The strategy enables the DESs in the hybrid distribution network to respond to the net power demand without the limitation on where they are located. The performance of the proposed strategy is validated by the simulation results. In the future works, the coordination of different type of ES devices will be considered for the better performance of inertial support of the hybrid AC/DC distribution network.

## 6 Acknowledgments

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