



Fast frequency response of inverter-based resources and its impact on system frequency characteristics

Lining Su¹, Xiaohui Qin¹, Shang Zhang¹, Yantao Zhang¹, Yilang Jiang¹, Yi Han¹

1. China Electric Power Research Institute, Haidian District, Beijing 100192, P.R. China



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Abstract: The inertia response and primary frequency regulation capability of synchronous grids are declining owing to the increasing penetration of inverter-based resources. The fast frequency response (FFR) of inverter-based resources is an important mitigation option for maintaining grid security under the conditions of low inertia and insufficient primary frequency response capability. However, the understanding and technical characteristics of the FFR of inverter-based resources are still unclear. Aiming at solving the aforementioned problems, this paper proposes a definition for FFR based on the impact mechanism of FFR on system frequency. The performance requirements of FFR are clarified. Then, the effects of FFR on system frequency characteristics are further analyzed based on steady-state frequency deviation, the initial rate of change of frequency, and the maximum transient frequency deviation. Finally, the system requirements for FFR and its application effects are verified by simulating an actual bulk power grid, providing technical support for subsequent engineering application.

Keywords: Fast frequency response, Rate of change of frequency, Frequency deviation, ROCOF-based FFR, Deviation-based FFR.

1 Introduction

Conventional synchronous generators are being increasingly replaced by inverter-based resources such as wind turbines, solar photovoltaic batteries, and infeed HVDCs. As a result, the inertia response and primary

frequency regulation ability of synchronous grids are declining [1]–[6]. The frequency nadir of a grid with low inertia and frequency regulation ability decreases sharply during severe frequency disturbances such as generator tripping and polar blocking faults in DC transmission systems. In addition, involuntary under-frequency load shedding (UFLS) is more likely to occur in this case [7]–[10]. Therefore, frequency stability is becoming a major challenge owing to the high penetration of inverter-based resources.

As power electronics devices have the advantage of flexible control, the fast frequency response (FFR) of inverter-based resources during severe frequency disturbances is an important mitigation option of frequency instability for maintaining grid security in the conditions of low inertia and insufficient primary frequency response.

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✉ Lining Su
sulining@epri.sgcc.com.cn

Xiaohui Qin
qinxh@epri.sgcc.com.cn

Shang Zhang
zhangshang@epri.sgcc.com.cn

Yantao Zhang
ytzhang@epri.sgcc.com.cn

Yilang Jiang
ytzhang@epri.sgcc.com.cn

Yi Han
ytzhang@epri.sgcc.com.cn

In recent years, the FFR of inverter-based resources has been extensively investigated. In certain countries and regions, rules and standards that consider FFR are being designed and revised to address upcoming challenges, such as the enhanced frequency response in UK [11]-[15], the fast frequency reserve for the European Network of Transmission System Operators for Electricity [16]-[20], and the FFR in Australia [21]-[23], Ireland [24]-[25] and Texas [21], [26]. In China, national standards are being drafted and revised to regulate the frequency response of wind farms and energy storage systems.

However, there are no unified definitions of FFR in existing literature. FFR appears to have different meanings depending on the context. Moreover, the functional orientation, performance objectives, and technical implementation specifications of FFR are unclear and inconsistent. A few authors consider that FFR refers to inertia emulation (or several alternative terms such as inertia-based response and synthetic inertia), deloading technology, proportional (droop) response [27]-[29], and fast synchronous inertia [30], whereas others exclude synthetic inertia from the definition of FFR [19]-[21], [26], [30]. There is a requirement for a clear definition of the FFR of inverter-based resources for further study and application.

The objective of this study is to propose a clear and widely acceptable definition of FFR and analyze its impact on system frequency characteristics. For this purpose, a definition is proposed based on the impact mechanism of FFR on frequency. Then, the performance requirements of FFR are clarified. Furthermore, the effects of FFR on system frequency characteristics are analyzed based on the indicators of steady-state frequency deviation, the initial rate of change of frequency (ROCOF), and the maximum transient frequency deviation. Finally, the system requirements for FFR and its application effects are verified through the simulation of an actual power grid. This research provides a recognizable definition and classification system with clear physical meaning for FFR, thus providing a unified foundation for subsequent research and application.

2 Proposed definition of FFR and its impact mechanism on system frequency

The FFR of inverter-based resources is defined based on its impact mechanism on system frequency. The distinction between the FFR of inverter-based resources and primary frequency response (PFR) is clarified from the perspective of the impact mechanism on system frequency.

2.1 Clear definition of FFR

The proposed definition of FFR is as follows:

FFR is the controlled contribution of electrical power from a generating unit or power plant that rapidly responds to frequency changes to minimize the torque imbalance of synchronous generators by adding or subtracting the output power into a system, thus contributing towards arresting the frequency change and settling the frequency indirectly.

This definition focuses on performance requirements more than technical implementation to achieve the controlled performance objectives. Based on this perspective, various fast control strategies that achieve the performance objective in the definition can be termed as FFR. To clarify, synthetic inertia response, which is defined in consistency with [30], is a subset of FFR.

The significant characteristics of the proposed definition are as follows :

- (1) FFR is the controlled contribution of electrical power from various sources, unlike PFR, which considers the contribution of the mechanical power of synchronous generators.
- (2) The required response time is faster compared to PFR. This is particularly critical under low-inertia conditions.
- (3) Various controlled responses are collected from inverter-based resources, such as ROCOF-based FFR responding to the ROCOF, deviation-based FFR responding to frequency deviation, and fast power injection triggered by event detection.

2.2 Impact mechanism of FFR of inverter-based resources on system frequency

System frequency is naturally determined by the rotating speed of the synchronous generators connected to a grid. Load exceeds generation when a large generating unit in the system is abruptly lost. In the case of a synchronous generator in the system, the electromagnetic torque acting on the rotor immediately exceeds mechanical torque, thereby reducing the rotating speed of the rotor. Inertia, which is a significantly inherent physical characteristic of the rotor, provides synchronous inertial response (SIR) to arrest rotating speed decline. When the deviation between the current and the initial rotating speed exceeds the preset deadband, the governor automatic control system provides PFR to increase mechanical torque, thereby arresting and restoring the rotating speed of the rotor after a certain period. As indicated by the electrical parameters of the system, the frequency of voltage and current changes with the rotating speed of generators, declining in the first few

seconds and rebounding after the frequency nadir.

The impact mechanism of the FFR of inverter-based resources on system frequency is shown in Fig. 1. The blue and red colors represent the cases in which inverter-based resources provide FFR and do not provide FFR, respectively. Note that the figure is only a schematic and does not show simulation results. The frequency response of load is not considered to simplify the analysis.

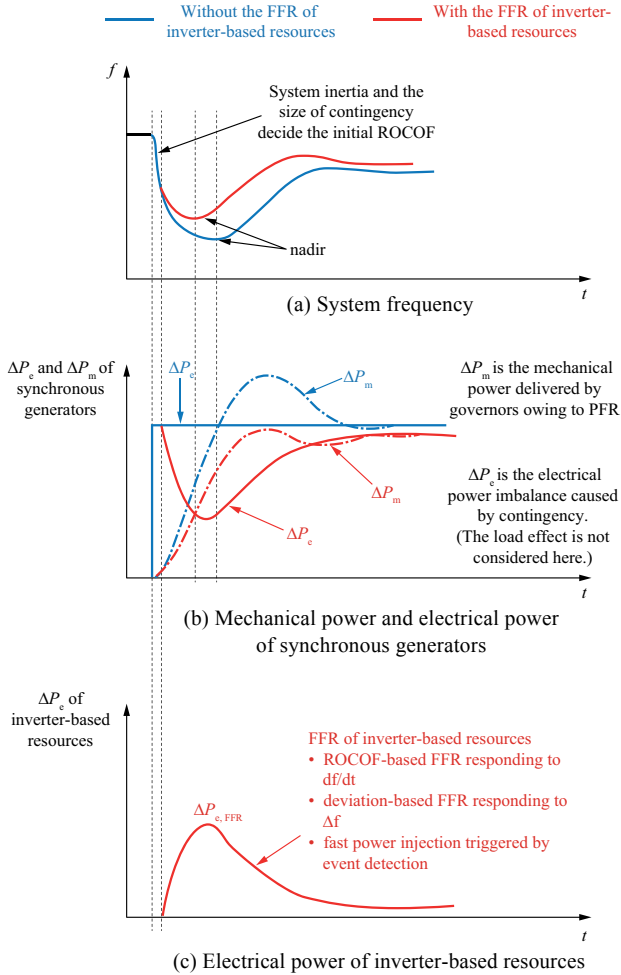


Fig. 1 FFR impact mechanism

The high ROCOF and frequency nadir improve when FFR is provided, as shown in Fig. 1(a).

The changes in the electrical power (ΔP_e) and mechanical power (ΔP_m) acting on the rotors of synchronous generators are shown in Fig. 1(b). If the time and space distribution characteristics of frequency are not considered, the system is equivalent to a single machine model. Thus, system frequency can be obtained according to the rotor motion equation, as given by.

$$2H_{\text{sys}} \frac{d\Delta f}{dt} = \Delta P_m - \Delta P_e \quad (1)$$

where Δf is the frequency deviation ($f - f_0$) in hertz and H_{sys} is the inertia constant of the system in seconds.

The controlled contribution of the electrical power of inverter-based resources ($\Delta P_{e,FFR}$) is shown in Fig. 1(c). Notably, the control objective of the FFR of inverter-based resources is the electrical power injected into the system to counteract part of the power imbalance of synchronous generators. Hence, ΔP_e is equal to the sum of the changes in external electromagnetic power, as given by

$$\Delta P_e = \Delta P_d + \Delta P_L - \Delta P_{e,FFR} \quad (2)$$

where ΔP_d is the electrical power imbalance owing to a disturbance. $\Delta P_d > 0$ for the abrupt loss of sources, and $\Delta P_d < 0$ for the abrupt loss of load. ΔP_L is the change in load in response to frequency. $\Delta P_{e,FFR}$ is the electrical power provided by the FFR of inverter-based resources.

When ΔP_L is neglected, the inversion of the curve in Fig. 1(c) is the same as the trend of the red curve in Fig. 1(b).

From (1) and (2), FFR and PFR achieve the same effect of reducing the imbalance between the mechanical power and electrical power acting on the rotors of synchronous generators. FFR contributes indirectly to reduce the electrical power on the grid side, whereas PFR contributes directly to increase the mechanical power on the prime mover side of the synchronous generator. In other words, FFR and PFR indirectly and directly affect the electrical power acting on synchronous generators, respectively.

When the frequency response of load is considered, ΔP_e must be superimposed on ΔP_L , as given by

$$\Delta P_L = K_L \Delta f \quad (3)$$

where K_L is the load frequency response coefficient. Typically, a change of 1% in frequency causes a change of 1–2% in load power [31]–[32].

Load frequency response slightly reduces the electrical power acting on the rotors; thus, system frequency response improves slightly.

It should be noted that the functional orientation of FFR is to be an alternative or supplement to PFR to help prevent rapid frequency decline and low-frequency load shedding. Hence, FFR can be designed to be withdrawn after the frequency nadir when PFR is sufficient for restoring system frequency to the steady-state region. This must be sufficiently gradual to ensure that frequency does not decrease again.

3 Performance requirements of FFR

The performance requirements of FFR, such as the response time, characteristics, and maximum response capacity, are discussed.

3.1 Response time of FFR

The functional orientation of FFR is to contribute towards arresting the change in frequency before the frequency nadir and settle frequency. The response time of FFR is critical under low-inertia conditions.

From the viewpoint of the implementation of FFR, the response time t_r is the total of the response times of control actions, including measurement time t_m , identification time t_i , signal processing time t_s , activation time t_a , and full response time t_f , as expressed in.

$$t_r = t_m + t_i + t_s + t_a + t_f \quad (4)$$

Owing to the fast control advantage of power electronics, the response time that can be technically achieved is as fast as hundreds of milliseconds. The summary of the response time is provided in Table 1.

Table 1 Summary of the response time for inverter-based resources [21], [33]–[34]

Inverter-based resources	Response time		
	Measure & Identify	Signal	Activate & Respond fully
Wind turbines	0.04–0.1 s	0.02 s	0.04–0.5 s
Solar photovoltaic batteries	0.04–0.1 s	0.02 s	0.1–0.2 s
HVDC systems	0.04–0.1 s	0.02 s	0.05–0.5 s
Lithium batteries	0.04–0.1 s	0.02 s	0.01–0.02 s
Flow batteries	0.04–0.1 s	0.02 s	0.01–0.02 s
Lead-acid batteries	0.04–0.1 s	0.02 s	0.04 s
Flywheels (inverters)	0.04–0.1 s	0.02 s	0.004 s

According to Table 1, the technically achievable response time is 0.07–0.62 s. However, the main challenge is to rapidly and accurately measure frequency or the ROCOF in the transient period when an active power shortage contingency occurs. In this case, a longer duration is required to ensure the accuracy of measurement. A balance between acting fast and making high fidelity decisions is vital.

Considering the aforementioned factors, the inertia level of the actual system, and the coordination of FFR with the conventional frequency response system, the recommended response time is less than 0.5–1.5 s. Generally, the response time decreases with system inertia.

3.2 Response characteristics and maximum response capability of FFR

Based on the different methods of implementation, FFR is categorized into ROCOF-based FFR (synthetic inertia) corresponding to the ROCOF, deviation-based FFR corresponding to frequency deviation, and fast power injection triggered by event detection.

Unlike the other two types, fast power injection triggered by event detection is a preset automatic strategy that is only applicable to specific events. This type of control technology is typically used in high voltage direct current (HVDC) power modulation and the automatic switching of power sources.

The controlled contributions of electrical power provided by ROCOF-based FFR and deviation-based FFR are calculated as shown in (5) and (6), respectively.

$$\Delta P_{\text{inertia}} = -T_J \frac{df/dt}{f_0} P_N \quad (5)$$

$$\Delta P_f = -K_f \frac{\Delta f}{f_0} P_N \quad (6)$$

where $\Delta P_{\text{inertia}}$ and ΔP_f are the electrical powers (in megawatts) provided by ROCOF-based FFR and deviation-based FFR, respectively, T_J is the equivalent per unit inertia constant of inverter-based resources due to control actions, f is the instantaneous frequency in hertz, f_0 is the system rated frequency in hertz, K_f is the frequency response coefficient due to control actions, P_N is the MVA rating capacity of inverter-based resources, and Δf is the frequency deviation ($f - f_0$) in hertz.

The physical characteristics of the inertia of synchronous machines are to prevent the rotor motion state from changing. This prevents frequency from deviating from the rated frequency and returning to the rated frequency. According to (5), during the decrease in frequency, where $\Delta f < 0$, $df/dt < 0$ and $\Delta P_{\text{inertia}} > 0$, that is, the inverter-based resources inject more active power into the system, thereby playing a positive role in preventing the decrease in frequency. During the recovery of frequency, where $\Delta f < 0$, $df/dt > 0$ and $\Delta P_{\text{inertia}} < 0$, that is, the inverter-based resources inject less active power into the system, thereby playing a negative role in restoring frequency.

Taking advantage of the flexible control characteristics of the inverter-based resources, ROCOF-based FFR can be designed to only operate under the conditions given by

$$\Delta f \frac{df}{dt} > 0 \quad (7)$$

Thus, ROCOF-based FFR only plays a positive role

in preventing frequency from deviating from the rated frequency. Furthermore, when frequency begins to recover, the inertia response is invalidated to avoid a negative impact on the recovery of frequency.

An active power reserve is required to ensure that FFR injects sufficient power into the system. It must be ensured that the maximum available response capacity is above a certain level.

The typical parameters of FFR are listed in Table 2.

Table 2 Typical control parameter ranges of FFR

Control parameters	Typical values		
	Wind turbine	Solar photovoltaic batteries	Electrochemical energy storage station
Equivalent per unit inertia constant T_f	4–12 s	4–12 s	4–12 s
Frequency response coefficient K_f	10–50	10–50	50–200
Maximum available response capacity	$\geq 6\%$	$\geq 6\%$	$\geq 10\%$

4 Impact of FFR on system frequency characteristics

The commonly used indicators for measuring system frequency stability include the maximum transient frequency deviation at the nadir ($\Delta f_{\max}$), ROCOF, and steady-state frequency deviation (Δf_{steady}). $\Delta f_{\max}$ is an important index, as the UFLS is triggered by the set value of frequency. The maximum ROCOF should not exceed the maximum withstand capability of power generation units and demand to prevent disconnection. Conventionally, SIR and PFR are two key elements in forming the dynamic frequency characteristics of the system. Inertia determines the rate of frequency decrease, immediately after a disturbance. PFR determines steady-state frequency deviation. SIR and PFR are involved in dynamic frequency response, and they affect the frequency nadir.

Based on the analysis of key system frequency response parameters, system frequency characteristics are studied based on the frequency stability indicators.

4.1 Key parameters of system frequency response

The key parameters of system frequency response include the system inertia constant, H_{sys} , the system frequency response coefficients, and the time constants of PFR and FFR.

The inverter-based resource penetration, p_{inv} , in a power

system is given by

$$p_{\text{inv}} = P_{\text{inv}} / S_{\text{sys}} \quad (8)$$

where P_{inv} is the output power of inverter-based resources (megawatts) and S_{sys} is the system load capacity (megawatts).

As inverter-based resources are a power substitute for synchronous generators, the output power of synchronous generators decreases during operation as p_{inv} increases.

Unlike synchronously connected rotating machines, inverter-based resources, such as wind turbines with rotating rotors, cannot directly affect frequency because the kinetic energy of the wind turbine is on the DC side and is indirectly released to an AC system via a converter. In doubly fed induction generators, which have an AC connection to a system, physical inertia is negligible compared to the rotational inertia of synchronous generators.

Inertia arrests frequency decline by injecting kinetic energy from synchronously rotating devices into a system during a power imbalance. The main contribution to H_{sys} is from synchronously connected rotating generators, as given by (9) [35]–[37]

$$\begin{aligned} H_{\text{sys}} &= \sum H_{\text{SG}}^i S_{\text{SG}}^i / S_{\text{sys}} \\ &= \left(\sum S_{\text{SG}}^i / S_{\text{sys}} \right) \left(\sum H_{\text{SG}}^i S_{\text{SG}}^i / \sum S_{\text{SG}}^i \right) \quad (9) \\ &= \left(\sum S_{\text{SG}}^i / S_{\text{sys}} \right) \bar{H}_{\text{SG}} \end{aligned}$$

where S_{sys} is the system load capacity (megawatts), H_{SG}^i is the per unit inertia constant of the i -th synchronously connected rotating generator, S_{SG}^i is the MVA rating capacity of the i -th synchronously connected rotating generator, and $\bar{H}_{\text{SG}}$ is the average per unit inertia constant of synchronously connected rotating generators.

According to (5), system inertia is proportional to the total capacity of conventional synchronous generators in the system. Generally, $\bar{H}_{\text{SG}}$ is approximately equal, therefore H_{sys} increases with the number of generators. Typically, the H_{SG} for a conventional synchronous generator is of the order of 3–6 s and varies according to the generation profile.

To simplify the analysis, it is assumed that synchronous generators are turned off as p_{inv} increases and there is no spinning reserve in the system. In this condition, relative inertia decreases as p_{inv} increases, as given by

$$H_{\text{sys}} = (1 - p_{\text{inv}}) \bar{H}_{\text{SG}} \quad (10)$$

The system frequency response coefficient, K_{sys} , consists of K_L and the frequency response coefficient of generators, K_G , in conventional synchronous-generator-dominated power systems. K_G is generally expressed as the inverse of the governor speed regulation droop, R .

The typical values of the aforementioned parameters

are shown in Table 3. These values are used to analyze and intuitively display the frequency dynamic characteristics after large power imbalance disturbances.

Table 3 Typical values of parameters

Parameters	Typical values
$\bar{H}_{SG}$	5 s
K_L	1.0
R	0.05
T_R	8 s
T_J	10
T_H	0.5 s
K_f	20
T_f	0.5 s

4.2 Steady-state frequency deviation

The steady-state frequency deviation of the system is related not to system inertia, but only to the frequency response coefficients of the system.

According to static frequency characteristics, the per unit steady-state frequency deviation, $\Delta f_{\text{steady}*}$, is obtained from.

$$\Delta f_{\text{steady}*} = -\frac{\Delta P_{d*}}{K_L + (1 - p_{\text{inv}})\frac{1}{R} + p_{\text{inv}}p_f K_f} \quad (11)$$

where p_f is the ratio of the rated capacity of the inverter-based resources that provide deviation-based FFR to the total output power of inverter-based resources.

Based on (11), steady-state frequency deviation is determined by K_L , R , and the frequency response coefficient, K_f , of the deviation-based FFR of inverter-based resources.

In the absence of the deviation-based FFR of inverter-based resources, that is, $p_f = 0$, steady-state frequency deviation is obtained from.

$$\Delta f_{\text{steady}*} = -\frac{\Delta P_{d*}}{K_L + (1 - p_{\text{inv}})\frac{1}{R}} \quad (12)$$

According to (12), steady-state frequency deviation increases with the penetration of inverter-based resources in the absence of the deviation-based FFR of inverter-based resources.

Fig. 2 shows the trend of steady-state frequency deviation with the penetration of inverter-based resources when a power imbalance disturbance occurs in the system with the parameters listed in Table 3. The per unit

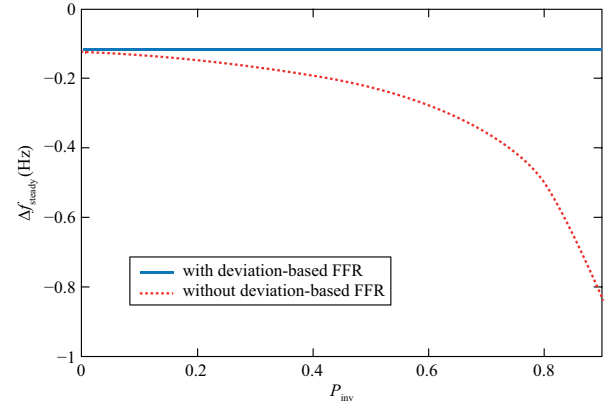


Fig. 2 Relationship between steady-state frequency deviation and the penetration of inverter-based resources for different control strategies

disturbance electrical power, ΔP_{d*} , is assumed as 5%. Under the condition of deviation-based FFR in Fig. 2, the value of p_f is set as 1.

As K_f is equal to K_G , which is the inverse of R , the steady-state frequency deviation with FFR remains constant as the penetration of inverter-based resources increases. In contrast, in the absence of the deviation-based FFR of inverter-based resources, the absolute value of steady-state frequency deviation increases nonlinearly with the penetration of inverter-based resources. Therefore, deviation-based FFR plays an important role in improving steady-state frequency, particularly with a high penetration of inverter-based resources.

4.3 Initial ROCOF

The ROCOF is defined as the time derivative of the power system frequency (df/dt). It is a measure of the rate of decline of the system frequency.

As FFR is not an instant response but a control function, it takes time to measure and identify signals. Thus, FFR cannot affect the initial ROCOF at time $0+$. The initial ROCOF is only determined by system inertia and the amount of power imbalance, as given by (13).

$$\left. \frac{df_*}{dt} \right|_{0+} = -\frac{\Delta P_{d*}}{2(1 - p_{\text{inv}})\bar{H}_{SG}} \quad (13)$$

where $*$ represents the per unit quantity.

Therefore, when the penetration of inverter-based resources is high, the decrease in relative inertia leads to a nonlinear increase in the initial ROCOF in the power system, as shown in Fig. 3. The rate of increase in the initial ROCOF increases with the penetration of inverter-based resources.

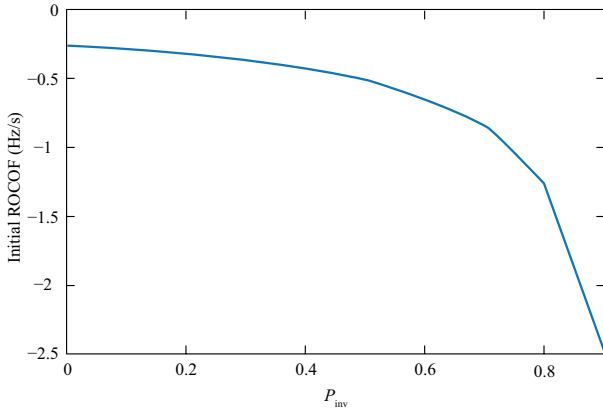


Fig. 3 Relationship between the initial ROCOF and the penetration of inverter-based resources

4.4 Maximum transient frequency deviation

The maximum transient frequency deviation is obtained at the frequency nadir, which occurs when the mechanical power and electrical power acting on the rotor become equal for the first time.

The increase in mechanical power is attributed to the PFR of the governor automatic control system. PFR helps arrest frequency and interacts with inertia to determine the frequency nadir. PFR requires about 15-30 s to respond fully. In conventional synchronous-generator-dominated systems, the impact of PFR on the frequency nadir is stronger than that of system inertia [38]. The decrease in electrical power is primarily caused by load frequency response and the FFR of inverter-based resources.

The relationship between the maximum transient frequency deviation and the penetration of inverter-based resources for different control strategies is shown in Fig. 4.

ROCOF-based FFR and deviation-based FFR contribute towards improving the maximum transient frequency

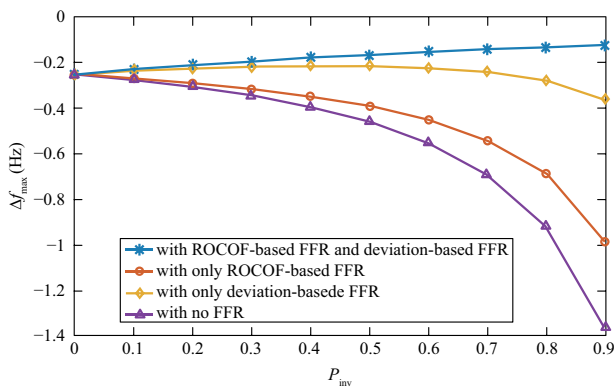


Fig. 4 Relationship between the maximum transient frequency deviation and the penetration of inverter-based resources for different control strategies

deviation. Among different FFR control strategies, the effect of deviation-based FFR is better than that of ROCOF-based FFR, and the combined effect of these two strategies is the best.

When only the deviation-based FFR control strategy is adopted, the absolute value of the maximum transient frequency deviation decreases as the penetration of inverter-based resources increases because of the higher response speed compared to a system with no penetration of inverter-based resources. However, when the penetration of inverter-based resources is high, the absolute value of the maximum transient frequency deviation increases with the penetration of inverter-based resources owing to a higher ROCOF under lower inertia. Therefore, ROCOF-based FFR is considerably necessary when the penetration of inverter-based resources is high.

5 Simulation case study

5.1 System requirements and conditions for FFR

We simulated a bulk receiving end grid with a load capacity of 350 GW. The frequency characteristics under a severe active power shortage contingency with various penetrations of inverter-based resources are compared in Fig. 5. After an ultra HVDC bipolar blocking fault, the active power loss of the system is 12 GW, which is approximately 3.4% of the load capacity. As the penetration of inverter-based resources increases, the dynamic characteristics of system frequency gradually deteriorate, which is indicated by the worse frequency nadir and higher ROCOF.

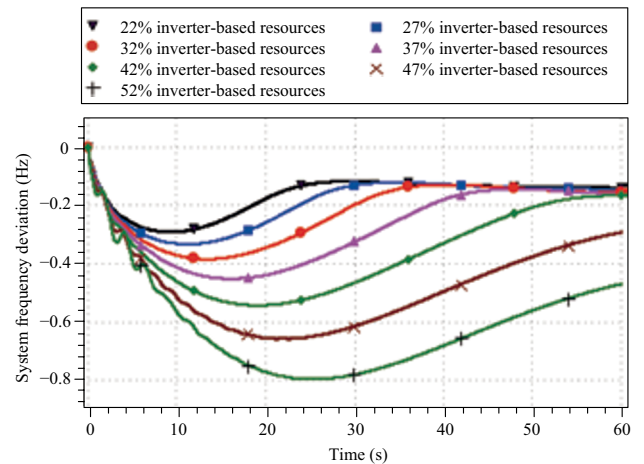


Fig. 5 Frequency characteristics under the same disturbance and various penetrations of inverter-based resources

The initial ROCOF immediately after the disturbance is the highest, and increases with the penetration of inverter-

based resources. Then, the ROCOF gradually decreases with time owing to the comprehensive effects of frequency on system frequency response. The frequency nadir occurs when the ROCOF becomes zero initially. The frequency nadir worsens as the penetration of inverter-based resources increases.

The figure shows that in the case of a large power imbalance disturbance in the system, the ROCOF increases and the frequency nadir worsens as the penetration of inverter-based resources increases. This increases the risk of UFLS and the disconnection of distributed renewable energy sources. Therefore, the conventional method of relying only on synchronous generators to maintain and regulate system frequency is insufficient, and the system requirements for FFR are crucial when the penetration of inverter-based resources is high.

5.2 Application effects of FFR

In the simulation case, the FFR is required the most when the penetration of inverter-based resources is 52%. ROCOF-based FFR and deviation-based FFR are implemented separately via additional frequency control, with the parameters provided in Table 2.

Considering the same disturbance as earlier, the frequency characteristics are improved to varying degrees by different types of FFR, as shown in Fig. 6.

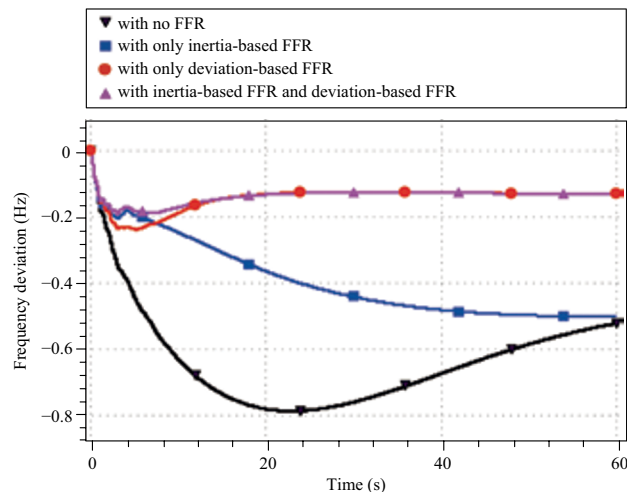


Fig. 6 System frequency deviation for different types of FFR

Fig. 6 shows that ROCOF-based FFR arrests frequency decline and improves the frequency nadir but does not contribute to frequency recovery. Deviation-based FFR demonstrates outstanding frequency support by rapidly arresting frequency decline and contributing to the settlement of frequency. The combination of the two types of FFR forms a collaborative response strategy and provides

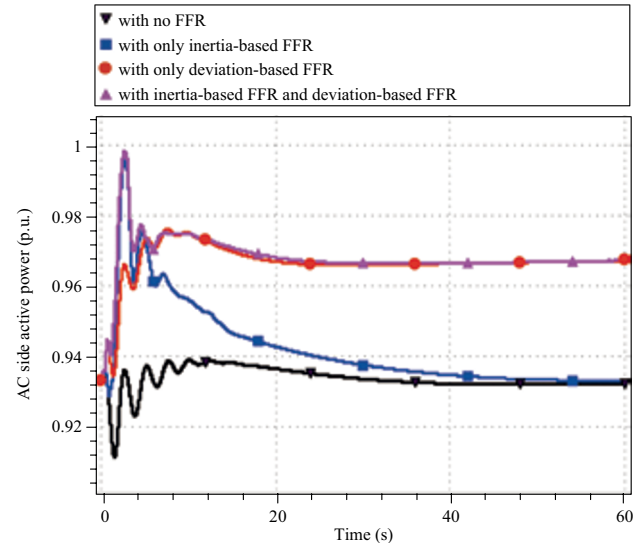


Fig. 7 The output power by the inverter-based resources with different FFR

the best effect.

The output active power on the grid side of the inverter is shown in Fig. 7. The power injection provided by ROCOF-based FFR reaches the peak in an extremely short period and then decreases gradually. Deviation-based FFR subsequently dominates and continuously injects power into the system. The power injected into the system increases when both types of FFR are used simultaneously.

6 Conclusions

The increasing penetration of inverter-based resources makes FFR a profound strategy for frequency security and stability of the future power systems. A recognizable definition with clear physical meaning for FFR has been presented to provide a unified foundation for subsequent research and application. In addition, the performance requirements from the system perspective have been proposed and verified. The following conclusions are obtained through simulation and comparison.

(1) FFR is clearly defined as the controlled contribution of electrical power from a generating unit or power plant that rapidly responds to changes in frequency to minimize the torque imbalance of synchronous generators by adding or subtracting the output power into a system, which contributes towards arresting the change in frequency and settling frequency indirectly.

(2) PFR directly affects the mechanical input power acting on the rotors of synchronous generators because system frequency is directly determined by the rotating speed of the synchronous generators connected to a grid.

In contrast, the FFR of inverter-based resources indirectly affects the electrical output power acting on the rotors of synchronous generators. FFR and PFR achieve the same effect of minimizing the imbalance between the mechanical power (torque) and electrical power (torque) acting on the rotors of synchronous generators.

(3) The FFR response time is recommended to be less than 0.5–1.5 s. Generally, the FFR response time decreases with system inertia. The maximum available response capacity should be ensured to be above a certain level to ensure that FFR injects sufficient power into the system.

(4) Deviation-based FFR plays an important role in the improvement of steady-state frequency, particularly when the penetration of inverter-based resources is high. Steady-state frequency deviation is determined by the load frequency response coefficient, governor speed regulation droop, and the frequency response coefficient of the deviation-based FFR of inverter-based resources.

(5) ROCOF-based FFR and deviation-based FFR cannot affect the initial ROCOF at the moment of a disturbance because FFR is not an inherent characteristic, unlike inertia, which achieves instant response. The control function of FFR requires time to measure and identify signals before activation. The initial ROCOF is only determined by system inertia and the amount of power imbalance.

(6) ROCOF-based FFR and deviation-based FFR contribute towards limiting the maximum transient frequency deviation. ROCOF-based FFR arrests frequency decline by temporarily injecting a large amount of power into the system in an extremely short period after a disturbance. This is required when the penetration of inverter-based resources is high to compensate for the lack of system inertia. Deviation-based FFR shows favorable frequency support effects by continuously injecting power into the system as long as the system frequency deviation exceeds the dead band. The combination of the two types of FFR forms a collaborative response strategy and provides the best effect.

This paper focuses on the FFR impact mechanism and performance requirements for the inverter-based resources from the system perspective. The control implementation details to achieve FFR have not been involved. There are still many technical problems to be solved in the application and realization of FFR, such as frequency signal extraction, the coordination between source-side active power control and inverter-side active power control strategies.

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Declaration of Competing Interest

We declare that we have no conflict of interest.

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Biographies



Lining Su received bachelor and master degree at North China Electric Power University, Beijing, in 2012 and 2015. She is working in China Electric Power Research Institute, Beijing. Her research interests include grids operation technology and renewable energy integration.



Xiaohui Qin received Ph.D. degree at North China Electricity Power University, Beijing, in 2008. He is working in China Electric Power Research Institute, Beijing. His research interests include power system plan and operation, application of FACTS and energy storage, power system transient stability, WAMS and its application.



Shang Zhang received bachelor and Ph.D. degree at North China Electric Power University, Beijing, in 2013 and 2018. She is working in China Electric Power Research Institute, Beijing. Her research interests include power grid planning, renewable energy integration, and energy storage technology.



Yantao Zhang received bachelor and master degree at Xi'an Jiaotong University, Xi'an, 2002 and 2005. He is working in China Electric Power Research Institute, Beijing. His research interests include power system simulation, power grid planning and operation, etc.



Yilang Jiang received bachelor, master and PhD degree at Tianjin University, Tianjin, in 2008, 2010 and 2015. He is working in China Electric Power Research Institute, Beijing. His research interests include the technology of grid planning and HVDC transmission.



Yi Han received bachelor and master degree at Xi'an JiaoTong University, Xi'an, in 1995 and 2000. She received Ph.D. degree at China Electric Power Research Institute, Beijing, in 2011. She is working in China Electric Power Research Institute, Beijing. Her research interests include power grid planning and renewable energy integration.

(Editor Yanbo Wang)