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Impact of renewable energy penetration rate on power system frequency stability

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Abstract

The construction of large-scale renewable energy sources has caused challenges to frequency stability of power system. This paper presents a method to evaluate the frequency stability of power system with high penetration of renewables. Based on input-to-state stability (ISS) theory, security/stability indices reflecting the frequency stability of the system are established. In addition, a simplified analysis method of local input-to-state stability (LISS)/ local input-to-output stability (LIOS) attributes is proposed based on System Frequency Response (SFR) model. Case studies are performed to verify the validity of the proposed method, and the corresponding security/stability indices are calculated.

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Keywords: Frequency stability; ISS theory; SFR model; Renewable energy

1. Introduction

With the rapid expansion of renewable energy power generation [1] and the wide application of high-voltage direct current (HVDC) transmission technology [2], the inertia response of power system reduces significantly, which will endanger the stable operation of the system [3]. With renewable energy penetration rate increasing [4], the system frequency stability will gradually deteriorate. This brings challenges to frequency stability and security which causes more attention to the analysis method of frequency stability [5].

To simplify frequency stability analysis, a second-order SFR model was applied in [6]. A simplified method that aggregates the SFR model with multiple machines to a single-machine model was proposed in [7]. However, it is unclarified how to consider model parameter changes when system contains high penetration of renewable energy. Several indices were proposed to measure dynamic behavior of system frequency, such as the frequency nadir (f_{nadir}), rate of change of frequency (RoCoF), and time to reach frequency nadir (t_{nadir}). However, indices

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above do not give a margin index and critical index to measure frequency stability and security. Therefore, due to complex working conditions [8] and the influence of various factors [9], it is significant to propose a quantitative evaluation method for frequency stability and security of power system with high-penetration renewables. A novel stability analysis approach based on the ISS theory was proposed [10]. ISS concept was applied to analyze the impact of external disturbances on the state quantity and quantify the maximum disturbance that the system can withstand, which can give margin indices to evaluate transient voltage stability [11].

Based on ISS theory, this paper proposes a quantitative evaluation method for the frequency stability influenced by high-penetration renewables. First, a quantitative evaluation scheme for frequency stability suitable for power system with high-penetration renewables is proposed. Second, a simplified analysis method for the LISS/LIOS attributes of subsystems based on the SFR model is proposed. Finally, case studies for the influence of renewable energy penetration rates on the frequency dynamic response are verified.

2. Problem formulation

To achieve quantitative frequency stability analysis, the ability of the system to withstand external disturbances should be researched.

The power system can be divided into subsystems. Neglecting the smaller time constants of the generating units, a low-order SFR model was proposed which can reckon the frequency behavior. The low-order SFR model is shown in Fig. 1(a). The parameters are listed in Table 1. Based on the low-order SFR model, a simplified method of subsystem partitioning can be proposed. In the SFR model, single machine and load are divided into two subsystems to simplify the division of subsystems.

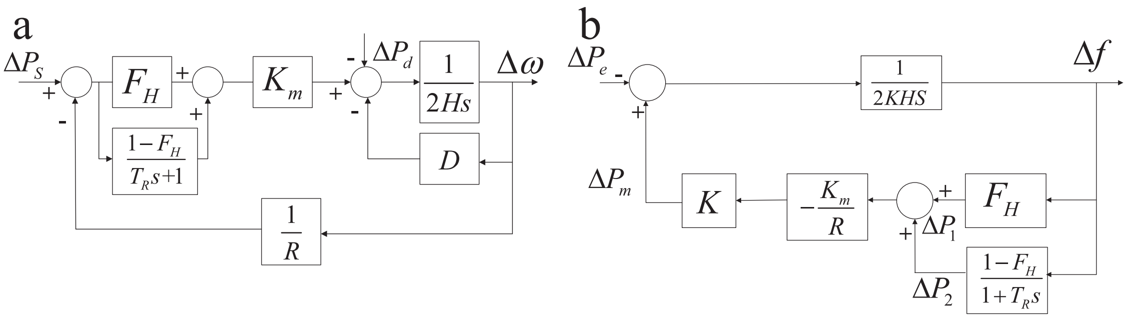

Fig. 1. (a)SFR model (b) Adjusted SFR model.

Table 1. Parameters of SFR model.

Parameter	Typical value
Reheat time constant T_R	6∼14 s
High-pressure turbine fraction F_H	0.15∼0.4
Inertia constant H	3∼9 s
Governor speed regulation R	0.04∼0.1
Load damping factor D	0∼2%

The research scheme of quantitative frequency stability analysis is proposed. At the subsystem level, by analyzing the subsystem response to external disturbances, the stability indices of subsystems can be got. At the level of subsystem, according to the stability indices of subsystems and the connections between subsystems, the stability of the entire system can be analyzed. Based on the stability criterion, the security/stability indices can be obtained. By using security/stability indices, system's security and stability operation margin can be obtained, which can achieve quantitative frequency analysis.

3. Quantitative frequency stability assessment framework

A nonlinear system with external inputs is represented as follows.

$$\begin{aligned} \dot{x} &= f(x) + g(x)u \\ y &= h(x, u) \end{aligned} \tag{1}$$

where $x \in D \subset R^n$, $u \in U \subset R^m$, $f : D \to R^n$, $g : D \to R^{n\times m}$. $f(0,0) = 0$, $h(0,0) = 0$, D and U represent domains of state variables and regions of external inputs respectively.

Definition 1. System (1) is LISS, if there exist $\beta^{LISS} \in KL$, $\gamma^{LISS} \in K_\infty$, so that for any $x_0 \in \Omega^{LISS} \in R^n$, $u \in U^{LISS} \in R^m$,

$$|x(t)| \le \beta^{LISS}(|x_0|, t) + \gamma^{LISS}(\|u\|_\infty) \quad \forall t \ge 0 \tag{2}$$

Definition 2. System (1) is LIOS, if $\beta^{LISS} \in KL$, $\gamma^{LISS} \in K_\infty$, so that for any $x_0 \in \Omega^{LISS} \in R^n$, $u \in U^{LISS} \in R^m$,

$$|y(t)| \le \beta^{LIOS}(|x_0|, t) + \gamma^{LIOS}(\|u\|_\infty) \quad \forall t \ge 0 \tag{3}$$

Considering the interconnected system with external inputs, the model of the ith subsystem is as follows.

$$\begin{aligned} \dot{x}_i &= f_i(x_i, u_i, \omega_i) \\ y_i &= h_i(x_i, u_i, \omega_i) \end{aligned} \tag{4}$$

where $x_i \in R^{n_i}$ denotes state variable; $u_i \in R^{m_i}$ and $y_i \in R^{p_i}$ represent the inputs and outputs; ω_i is the external disturbance.

Based on the stability criterion of the interconnected system, the quantitative evaluation indices reflecting the frequency stability and security of the interconnected system is proposed:

$$m = 1 - \rho\left(G^{LIOS}\right) \tag{5}$$

$$n = \min\left(\frac{\tau_i - b_i}{\tau_i}\right) \tag{6}$$

where $G^{LIOS} = \Gamma^{IOS}Z$; $\Gamma^{IOS} = diag\left(\gamma^{IOS}\right)$, Γ^{IOS} is input/output gain matrix; γ^{IOS} is the input/output gain; Z is input/output connection matrix; $\rho\left(G^{LIOS}\right)$ is spectral radius of G^{LIOS}; $b = Z(I_d - G^{LIOS})^{-1}\beta^{LIOS}$.

When stability index $m < 0$, the small-gain condition is not satisfied and the system is unstable; when $m > 0$, the system is stable; the greater the value of m, the greater the stability margin of the system. When security index $n < 0$, the system is operating in an unsafe state; the larger the value of n, the greater the margin of security operation.

4. LISS/LIOS analysis based on SFR model

4.1. SFR model with high-penetration renewables

How to aggregate the multi-machine SFR model to aggregated SFR model has been demonstrated. SFR model simplifies the frequency dynamic response process of a multi-machine system into a single-machine.

It is assumed that the increase of renewable energy is achieved by shutting down synchronous generators. Generating coefficient of synchronous units is proposed.

Definition 3. Generating coefficient of synchronous units:

$$K = \frac{\text{Output of synchronous units}}{\text{System load power}} \tag{7}$$

The generating coefficient of synchronous units K will continue to decrease as the penetration rate of renewable energy increases.

When the generating coefficient of synchronous units is K, the generating coefficient of renewable energy units is considered to be $1 - K$. The gain A is simplified to express the renewable energy frequency modulation gain. Considering that when renewable energy sources are not fully involved in frequency modulation, K_N is defined to indicate the rate of renewable energy participating in frequency modulation. The adjusted SFR model is shown in Fig. 2.

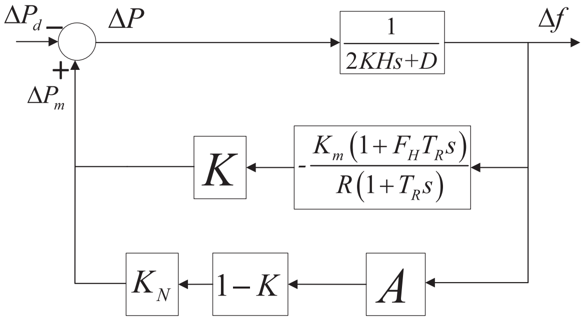

Fig. 2. System frequency response model under different renewable energy penetration rate.

4.2. Quantitative LISS/LIOS analysis based on SFR model

After getting the SFR model with renewable energy, the single-machine SFR model can be divided into two parts: a single generator and a load. LISS/LIOS analysis on the two parts is separately performed.

First, single generator LIOS attributes can be obtained. In order to construct the state equation, the second-order SFR model is changed as shown in Fig. 1(b).

According to Fig. 1(b), a single generator model is established.

$$\begin{bmatrix} \Delta \dot{f} \\ \Delta \dot{P}_2 \end{bmatrix} = \begin{bmatrix} -\frac{K_m F_H}{2HR} & -\frac{K_m}{2HR} \\ \frac{1-F_H}{T_R} & -\frac{1}{T_R} \end{bmatrix} \begin{bmatrix} \Delta f \\ \Delta P_2 \end{bmatrix} + \begin{bmatrix} -\frac{1}{2KH} \\ 0 \end{bmatrix} \Delta P_e \tag{8}$$

The system model can be simplified to $\dot{x} = Ax + Bu$, $y = Cx$. Where $x = \begin{bmatrix} \triangle f & \triangle P_2 \end{bmatrix}^T$, $u = \Delta P_e$, $y = \Delta f$.

$$A = \begin{bmatrix} -\frac{K_m F_H}{2HR} & -\frac{K_m}{2HR} \\ \frac{1-F_H}{T_R} & -\frac{1}{T_R} \end{bmatrix} \tag{9}$$

$$B = \begin{bmatrix} -\frac{1}{2KH} \\ 0 \end{bmatrix} \tag{10}$$

$$C = \begin{bmatrix} 1 & 0 \end{bmatrix} \tag{11}$$

The solution is as follows.

$$x(t) = e^{At} x_0 + \int_0^t e^{A(t-\tau)} Bu(\tau)\, d\tau \tag{12}$$

$$|x(t)| \le \left\| e^{At} \right\| |x_0| + \|u\|_\infty \left\| \int_0^t e^{A(t-\tau)} B d\tau \right\| \tag{13}$$

Since A is a Hurwitz matrix, the LISS attribute of subsystems can be estimated with the following formula.

$$\gamma^{ISS} = \sup \left\| \int_0^t e^{A(t-\tau)} B d\tau \right\| \tag{14}$$

$$\beta^{ISS} = \sup \left| \left(e^{At} x(0) \right)_1 \right| \tag{15}$$

The LIOS attributes of subsystems are estimated as follows.

$$|y| \le \|C\| \, |x| + \|D\| \, \|u\|_\infty \le \|C\| \, \beta^{ISS}(|x_0|, t) + \left(\|C\| \, \gamma^{ISS} + \|D\| \right) \|u\|_\infty \tag{16}$$

The LIOS attributes of single generator can be expressed as $\beta^{IOS}(|x_0|, t) = \|C\| \beta^{ISS}(|x_0|, t)$ and $\gamma^{IOS} = \|C\| \gamma^{ISS} + \|D\|$.

Second, load LIOS attributes can be obtained. Ignoring reactive power dynamics, load can be simplified to a model that only considers the effect of frequency regulation:

$$P_L = P_0(1 + K_p \triangle f) \tag{17}$$

Then we can get

$$\Delta P_e = K_p \Delta f + \Delta P_L \tag{18}$$

where ΔP_L is the unchanged active power, K_p is frequency index for real power, expressed as the percentage of the active power change caused by a frequency shift of 1%.

The input and output are respectively selected as frequency and power, the properties of LIOS are estimated as follows.

$$\gamma_L^{IOS} = K_p, \ \beta_L^{IOS} = 0 \tag{19}$$

Furthermore, the quantitative evaluation indices of security and stability of the whole system can be obtained.

5. Case study

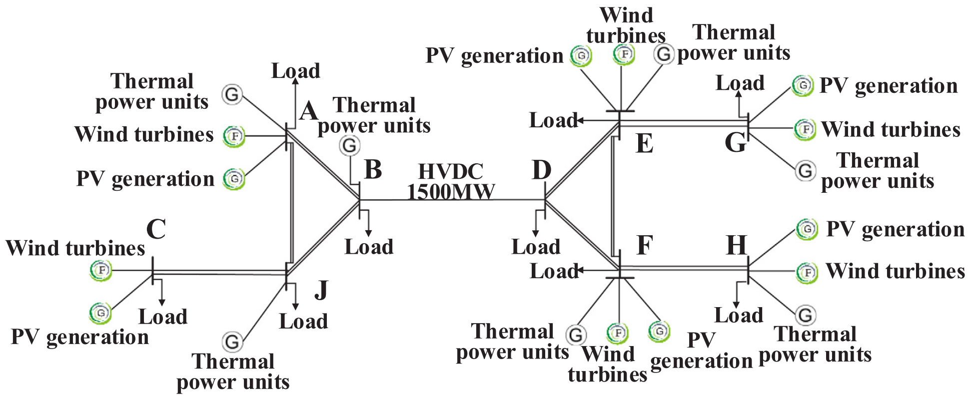

Fig. 3. Simplified Northwest Power Grid system.

The simplified Northwest Power Grid system is used to test the frequency stability of power system under different renewable energy penetration rates. The test system is shown in Fig. 3. In the simplified Northwest Power Grid system, there are synchronous generators and renewable energy generators in bus A, and there are only renewable energy units in bus C. The power is delivered from bus B to bus D of the infeed grid through HVDC system. The renewable energy penetration rates of the test system are changed by changing the installed renewable energy resources at bus A and bus C. Renewable energy penetration rate of test system is changed to analyze its influence on the frequency stability and verify the practicability of indices.

Case 1: Evaluate the impact of renewable energy on frequency dynamics when the ratio of power disturbance is 10%. Setting the renewable energy penetration rate is 20%, the frequency dynamics can be analyzed when the Northwest Power Grid simplified system has a DC unipolar blocking fault. First, the LIOS attributes of the generator and the load are $\gamma_G = 0.103$ and $\gamma_L = 1.871$ respectively. Second, based on the frequency stability quantitative evaluation method, it is calculated as $\rho = 0.453 < 1$, the small gain condition is met which verifies that the system can return to a stable state after being disturbed, and the stability quantitative evaluation index is 0.547. Finally, on the basis of satisfying the small gain condition, formula (5) is used to judge whether the system is operating safely. The security and stability constraints are met, the system operation has not exceeded the limit, and the security quantitative evaluation index is 0.735. Then, the stability/security indices under different renewable energy penetration rates can be recalculated according to the above process. The results are shown in Table 2.

The results show that when the system has a DC unipolar blocking faults, with the increase in the penetration rate of renewables from 20% to 60%, the small gain conditions are always met, but the system stability quantitative

Table 2. Calculation of m and n when penetration rates range from 20% to 60%.

Renewable energy penetration rate (%)	m	n
20	0.547	0.735
30	0.503	0.563
40	0.467	0.317
50	0.421	0.103
60	0.375	−0.176

evaluation index and security quantitative evaluation index gradually decreases. The stability margin and security operation margin continue to decrease. Under different renewable energy penetration rate, the simplified Northwest Power Grid can eventually return to a new stable state when a DC unipolar blocking fault occurs. However, after the DC unipolar blocking fault occurred in the Northwest Power Grid, the system frequency deviation increased with the increase of renewable energy penetration rates. When the penetration rate of renewables is 60%, the system does not meet the security evaluation index, and the frequency deviation exceeds the limit. The analysis results are verified by simulation, and the frequency deviation of the bus B is shown in Fig. 4(a).

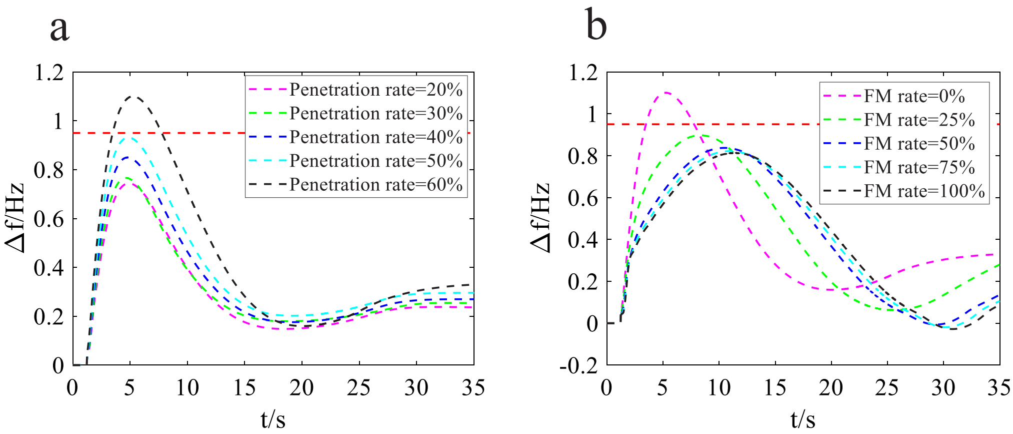

Fig. 4. (a) Dynamics of frequency under different penetration of renewable energy rates (b) Dynamics of frequency under different renewable energy frequency modulation rates.

Case 2: Evaluate the frequency modulation scale of renewable energy on frequency stability when the ratio of power disturbance is 10%.

Setting the renewable energy penetration rate is 60% unchanged, the frequency dynamics are analyzed when the Northwest Power Grid simplified system has a DC unipolar blocking fault. By setting different frequency modulation rates of renewable energy, the stability/security indices under different rates of renewable energy participating in frequency modulation can be calculated. The calculation results of the system stability/security quantitative evaluation index under different rates of renewable energy participating in frequency modulation are shown in Table 3.

The results show that when the system has a DC unipolar blocking faults, as the rate of renewable energy participating in frequency modulation increases from 0% to 100%, the small gain conditions are always met, and the system stability quantitative evaluation index and security quantitative evaluation index gradually increase. The stability margin and security operation margin continue to increase. Under different rates of renewable energy participating in frequency modulation, the simplified Northwest Power Grid can eventually return to a new stable state when a DC unipolar blocking fault occurs. The system frequency deviation decreased as the rates of renewable energy participating in frequency modulation increases. The frequency deviation of the bus B is shown in Fig. 4(b).

6. Conclusion

A method to quantitatively evaluate the dynamic response of the renewable energy penetration rates to the system frequency is proposed. Security/stability indices reflecting the frequency stability are established. A simplified

Table 3. Calculation of *m* and *n* under different rates of renewable energy participating in frequency modulation.

Renewable energy participating in frequency modulation rate (%)	*m*	*n*
0	0.375	−0.176
25	0.387	0.121
50	0.407	0.241
75	0.432	0.275
100	0.447	0.304

analysis method of LISS/LIOS attributes is proposed based on SFR model. The impact of external disturbances on the frequency stability can be quantitatively evaluated through security/stability indices. The validity of the indices is verified by simulations.

The SFR model ignores the influence of factors such as installed locations of renewable energy on frequency dynamics. In the follow-up research, the influence of factors such as installed locations of renewables and different renewable energy types will be further discussed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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