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Probabilistic Assessment on Area-Level Frequency Nadir/Vertex for Operational Planning

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ABSTRACT Local heterogeneity of the frequency response of modern grids becomes more severe than ever before due to 1) weaker grid connection strength brought by the favorable grid interconnection, and 2) more uncertainties and less system inertia brought by the increasing renewable integration. This dominant characteristic is difficult to be accurately characterized and evaluated by the classic aggregated system frequency response (SFR) model. Therefore, this paper proposes a framework for assessing the risk of area-level frequency nadir/vertex (FN/FV) for operational planning in a practical and effective manner. Firstly, a multi-point sensitivity (MPS) is proposed based on the classical SFR model to evaluate the system FN/FV, where the impact of different Renewable Energy Sources (RESs) on system FN/FV are considered. The method can be extended for regional frequency evaluation, but the influence of generator frequency oscillation cannot be effectively considered, which might impact assessment accuracy. To address this issue, a multi-interval sensitivity (MIS) method is further proposed to calculate the probabilistic distribution of the area-level FN/FV. The probabilistic results are evaluated by the FN/FV RAM, i.e., Risk Assessment Matrix, to provide a two-dimensional analysis for system operational planners. The accuracy and efficiency of the proposed MPS and MIS methods are critically validated via scenario-based simulation (SBS) in a modified IEEE 16-machine 68-bus benchmark system.

INDEX TERMS Operational planning, probabilistic assessment, frequency nadir/vertex (FN/FV), multi-point sensitivity (MPS), multi-interval sensitivity (MIS).

I. INTRODUCTION

THE integration of various renewable energy sources (RES) reduces the synchronous system inertia and brings more active power uncertainties into the modern power system [1], [2]. Both factors lead to a larger frequency deviation than ever before [3], [4], which may easily violate the frequency limit set by grid code and trigger the protection scheme [5], such as under frequency load shedding [6], [7] and over frequency generator tripping [8], [9]. These protective measures largely impact the consumers and should be avoided in practice if possible. Therefore, it is vital to evaluate the risk of the frequency violation caused by stochastic outputs from RESs in operational planning.

To achieve this target, frequency nadir (FN) and frequency vertex (FV), representing the peak and bottom of the frequency response curves separately in a period of time, are employed as two important evaluating indicators [10]. Numerous investigations on FN/FV have been conducted. In [11], the classical system frequency response (SFR) model is proposed to derive the system FN/FV w.r.t a disturbance, which treats the whole system as a mass and ignores the impacts of the electric distance, generator excitation system, and the interaction among the outputs of individual generator in the system. Although these assumptions seem less accurate, the SFR model provides a clear understanding and foundation for frequency stability analysis and thus is widely adopted. Quite a few improvement methods are developed to achieve better performance. In [12], the short-term first-order model for governors and prime movers in the SFR model is approximated by an aggregated constant that considers the impacts of individual generators. On this basis, the maximal frequency deviation of a small isolated system is estimated, while the excitation system is not considered. In [13], the excitation system is involved in predicting the system FN after a large disturbance, where a constant ramp rate of the overall mechanical power response is approximated to fit the response of each governor response. However, only one disturbance is considered, and the impacts of disturbance locations, especially in a multi-RES penetrated power system, on system FN/FV have not been investigated. In [14], a multi-disturbance scenario is involved in assessing the probabilistic distribution of system FN/FV for operational planning considering the effects of disturbance locations and excitation systems, while the sensitivity is obtained using specific operating conditions of the wind power and the computational process of the employed Cumulant-based method is complex. To sum up, system FN/FV is investigated widely based on the SFR model, improved SFR model, and fitting method, in which the impact of frequency oscillation of individual generators can be offset when computing the system-level frequency response and thus can be ignored. Thus, the assessment accuracy of system FN/FV can be improved when considering the frequency response of individual generators.

The growing heterogeneity of the frequency response of the modern grid, mainly caused by 1) weaker grid connection strength brought by the favorable grid interconnection, and 2) more uncertainties and less system inertia brought by the increasing renewable integration, cannot be properly evaluated by a system-level frequency response model. For example, reference [15], [16] demonstrates that there is a big difference between system RoCoF (i.e., rate of change of frequency) and area-level RoCoFs in a large-scale power system. Thus, it is necessary to investigate and assess the area-level FN/FV considering the frequency oscillation among areas. The recently published literature [17] can address this issue by simplifying the whole system into two-machine equivalent model, and then, deriving associated closed-form solution. However, the response model can only deal with two-machine equivalent regions, which is also difficult to derive and obtain in practice. Hence, this method cannot directly assess the area-level FN/FV considering frequency oscillation among multiple regions (more than two regions). Moreover, few existing literatures have conducted the relevant research, i.e., evaluation of area-level FN/FV, which deserves further investigation.

Traditionally, the stability evaluation in operational planning is implemented according to the 'worst-case' scenario, while the 'worst-case' scenario caused by the stochastic output of multiple RESs in modern power systems rarely happens due to low spatiotemporal correlations among RES [15]. Furthermore, it is reasonable to ignore the event with a low probability and the relevant impact in the current practice [18], [19]. Thereby, a two dimensional (probabilistic) assessment considering both severity and the occurrence probability of an event is more attractive and practical for the system operator and planner, which is usually achieved by two steps: 1) Obtain the probabilistic distribution of the concerned index, i.e., FN/FV in this paper, and then 2) evaluate the risk by the established RAM [14], [20]. There are normally two main methods to calculate the probabilistic distribution.

1. Scenario-based simulation (SBS, a kind of Monte Carlo simulation) [21]. The SBS firstly generates a large number of the scenarios according to certain probability distributions and then obtains the concerned index of each scenario by the simulation, based on which the probability distribution of the desired index is acquired. The SBS method is accurate but time-consuming. Moreover, the acquisition of FN/FV in a single scenario is still time-consuming since a whole frequency response curve needs to be captured and then the minimal/maximal point (FN/FV) is selected. Therefore, SBS is preferably regarded as a verification tool for the analytical method.

2. Analytical method[22]: The sensitivity and series expansion are required to obtain the probability distribution of the concerned index, such as the cumulant-based method. The derivation process of the analytical method is more complicated and not straightforward.

Therefore, this paper proposes a practical scheme to evaluate the risk of area-level FN/FV violation for operational planning. The main contributions are summarized below.

1. The multi-point sensitivity (MPS) is established to characterize the relationship between the FN/FV and stochastic outputs of multiple RESs, considering the impacts of the RES locations and excitation systems. The calculation process is straightforward, which avoids a complex derivation compared with the analytical method, and only a limited number of simulations or historical data are required. It should also be noted that the proposed MPS calculation does not require specific operating conditions of the wind power.

2. A multi-interval sensitivity (MIS) based on MPS is proposed to consider the impact of frequency oscillation on area-level FN/FV evaluation from a new perspective, i.e., different combinations of RES outputs impact the FN/FV differently. The sensitivity employed for FN/FV evaluation is selected from the established sets of sensitivities according to different scenarios.

3. The proposed MPS and MIS-based assessment can achieve an efficient assessment on FN/FV compared with Monte Carlo-based time-domain simulation, which requires to capture the whole frequency response curve and then searches the maximal/minimal point, while both proposed methods can calculate the FN/FV directly. Moreover, either proposed method is more accurate than SFR model-based method when assessing the system FN/FV.

4. The two methods can be complementary for operational planning according to different requirements. The MPS aims to achieve a more efficient assessment requiring only a small amount of calculation, while the MIS can conduct a relatively more accurate assessment and hence demand more computational resources.

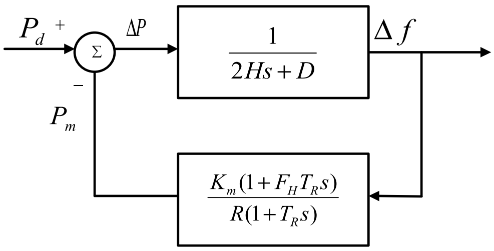

FIGURE 1. **A simplified SFR model with a single disturbance.**

The rest of the paper is organized as follows. In Section II, the MIS of area-level FN/FV is introduced. On this basis, the scheme of evaluating the risk of area-level FN/FV for operational planning is presented in Section III. The case study is conducted in Section IV, and the conclusions are drawn in Section V.

II. THE SENSITIVITY OF FN/FV

A. SENSITIVITY OF FN/FV BASED ON THE SFR MODEL

The SFR model is usually applied to derive the sensitivity of FN/FV w.r.t a single disturbance, where the disturbance can be regarded as an aggregated one at the system level, as illustrated in Fig. 1 [11], and the frequency response is derived as (1):

$$\Delta f = \left(\frac{R\omega_n^2}{DR+K_m}\right)\left(\frac{(1+T_R s)}{s^2+2\xi\omega_n s+\omega_n^2}\right)P_d \quad (1)$$

where,

$$\omega_n^2 = \frac{DR+K_m}{2HRT_R} \quad (2)$$

$$\varsigma = \frac{2HR+DRT_R+K_m F_H T_R}{2\,(DR+K_m)}\omega_n \quad (3)$$

where, K_m is mechanical power gain, T_R is reheat time constant, F_H is high-pressure turbine fraction, R is governor speed droop constant, D is load damping constant, and H is system inertia constant. P_d is the active power disturbance.

The sudden disturbance is most concerned, and the Laplace domain is expressed as

$$P_d\,(s) = \frac{\Delta P}{s} \quad (4)$$

where ΔP is the magnitude of the P_d. Substitute (4) into (1), which is further transferred into the time domain, as shown in (5).

$$\Delta f\,(t) = \frac{R\Delta P}{DR+K_m}\left[1+ae^{-\varsigma\omega_n t}\sin\left(\omega_r t+\phi\right)\right] \quad (5)$$

where,

$$a = \sqrt{\frac{1-2T_R\varsigma\omega_n+T_R^2\omega_n^2}{1-\varsigma^2}} \quad (6)$$

$$\omega_r = \omega_n\sqrt{1-\varsigma^2} \quad (7)$$

$$\phi = tan^{-1}\left(\frac{\omega_r T_R}{1-\varsigma\omega_n T_R}\right) - tan^{-1}\left(\frac{\sqrt{1-\varsigma^2}}{-\varsigma}\right) \quad (8)$$

The FN/FV occurs when the deviation of (5) equals zero. The time reaching the FN/FV and FN/FV are required as (9) and (10) separately.

$$t_{n/v} = \frac{1}{\omega_r}tan^{-1}\left(\frac{\omega_r T_R}{\varsigma\omega_n T_R-1}\right) \quad (9)$$

$$f_{n/v} = \left[\frac{R}{DR+K_m}\left(1+ae^{-\varsigma\omega_n t_{n/v}}\sqrt{1-\varsigma^2}\right)\right]\Delta P = S_{n/v}\Delta P \quad (10)$$

The equations (10) indicates that there is one linear relationship (i.e., $S_{n/v}$) between the FN/FV and a single active power disturbance, which is established based on two assumptions:

1) The system is aggregated as a mass, and the electric distance among different disturbance sources and the generators is ignored, which means the location of the disturbance has no impact on the derived results. For example, the system FN/FV caused by a single active power disturbance with the same size and different locations are evaluated as the same according to (10), but they are not the same in practice.

In a multi-disturbance system, the disturbance is aggregated by adding the stochastic output of individual disturbance sources, and thus, the system FN/FV can be expressed as (11).

$$f_{n/v} = S_{n/v}\Delta P = S_{n/v}\sum_{i=1}^{M}\Delta P_i \quad (11)$$

where, ΔP_i is the disturbance of the i^{th} disturbance source, M is the number of the disturbance sources.

When individual ΔP_i is not equal to zero, while the sum of ΔP_i equals zero. The assessment, according to (10), is zero, while in practice, it is not.

2) The excitation system is not considered, which is usually equipped in a traditional power plant in practice and impacts the FN/FV. Thus, the consideration of the excitation system can make the research more practical.

Therefore, the FN/FV evaluated by (10)-(11) can be improved via selecting a proper sensitivity considering the locations of disturbance sources and the response of the excitation system.

B. MULTI-POINT SENSITIVITY (MPS) OF SYSTEM FN/FV

The MPS considers the impacts of RES location and excitation system via selected FN/FV from the simulated frequency response curve. The frequency response curve can be regarded as a comprehensive reflection of all impact factors in the system, including the RES location, excitation system, governor control system, inertia of the generator, etc. Compared with conventional SFR model-based assessment, the impacts of RES location and the excitation system are additionally considered in MPS-based assessment. The proposed MPS is calculated based on the collected FN/FV containing the above-mentioned impacts, and thus, the impacts of RES location and the excitation system are considered in the evaluation.

The sensitivity is a link connecting the system FN/FV and the active power disturbance, while according to the above analysis, a single sensitivity is difficult to accurately reflect this relationship, especially in a multi-disturbance power system. Thereby, it is reasonable to use multiple sensitivities to describe the impact of the stochastic output of individual RES on system FN/FV, where the number of sensitivities is equal to that of the disturbance source. Thus, equation (12) is derived.

$$f_{n/v} = \sum_{i=1}^{\mathrm{M}} S_{n/v_i} \Delta P_i \tag{12}$$

where, $S_{n/v_i}$is the sensitivity of the FN/FV w.r.t the i^{th}disturbance which can consider the impacts from not only the electric disturbance but also the control system, including governor speed and excitation system. Compared with the (11), the equation (12) can achieve a more accurate FN/FV assessment since it additionally considers the impacts of the RESs locations and excitation system via M sensitivities corresponding to M RESs with different locations rather than a single sensitivity employed in (11).

The procedure of computing the sensitivity of the FN/FV is presented below.

1. Collect M sets of data, each of which contains the stochastic output of M disturbance sources and the corresponding FN/FV from historical data sets or simulations. [23]. For simulation method, the stochastic outputs of M disturbance sources are selected randomly between the minimal and maximal output of individual RES and then sent into the benchmark system for time-domain simulation to acquire the FN/FV from the simulated frequency response curve. The stochastic outputs of M disturbance sources and the FN/FV are recorded as one set of data. If the set of data can be obtained from historical data, the time-domain simulation can be avoided. Repeat the above process M times to acquire the M sets of data.

2. The collected M sets of data can be rewritten in matrix form as (13).

$$\begin{bmatrix} f_{n/v1} \\ \vdots \\ f_{n/v,\mathrm{M}} \end{bmatrix} = \left[\begin{pmatrix} \Delta P_{1,1} & \cdots & \Delta P_{1,\mathrm{M}} \\ \vdots & \ddots & \vdots \\ \Delta P_{M,1} & \cdots & \Delta P_{M,\mathrm{M}} \end{pmatrix} \right] \begin{bmatrix} S_{n/v,1} \\ \vdots \\ S_{n/v,\mathrm{M}} \end{bmatrix}$$
$$F_{N/V} = P_{DIS} S_{N/V} \tag{13}$$

where the $\Delta P_{i,j}$ refers to the stochastic output of the j^{th} disturbance source in the i^{th} collected set of data, $i, j = 1 \ldots \mathrm{M}$. The i^{th} line of the $F_{N/V}$ and P_{DIS} corresponding to $f_{n/vi}$ and $\Delta P_{i,1}, \Delta P_{i,2} \ldots \Delta P_{i,\mathrm{M}}$, respectively, are the i^{th} collected set of data. The $S_{N/V}$ are variables that need to be solved in the next step.

3. According to (13), the MPS is determined by (14).

$$S_{N/V} = P_{DIS}^{-1} F_{N/V} \tag{14}$$

The calculated sensitivity includes the impacts from the electric disturbance and excitation system and governor speed of individual plants in the system, which is assumed to be fixed after being determined in this paper. It is noted that the rank of the P_{DIS} in (13) based on selected data in Step 1 needs to be M, i.e., full rank, which refers to a low similarity among each set of data.

C. MULTI-INTERVAL SENSITIVITY (MIS) OF AREA-LEVEL FN/FV

The area-level FN/FV is also an important indicator for operational planning, especially in a large-scale power system, but nearly no effectively analytical model is derived. One reason is that the impact from frequency oscillation of each generator on FN/FV after disturbance can be ignored in evaluating system FN/FV (i.e., the local heterogeneity of frequency responses can be offset in system frequency calculation) but cannot in area-level assessment. However, the impact/heterogeneity is difficult to be expressed analytically due to strong nonlinearity.

Thus, the MIS based on MPS is proposed to quantify the impact of frequency/power oscillation on area-level FN/FV evaluation by using different sets of sensitivities w.r.t different combinations of the RES outputs. In detail, each RES has only two states according to the actual output, i.e., above and below the steady state. Thus, there are total 2^{M} combinations of RES outputs (M is the number of the RES in the system) corresponding to 2^{M} sets of sensitivities. Each set of sensitivities can be obtained using the method calculating MPS, and the difference from MPS is that RES outputs used for establishing the sensitivity can only be arbitrarily selected from either between minimal value and steady state value or between steady state value and maximal value rather than between minimal value and maximal value.

Three assessment methods considering different kinds of sensitivities, i.e., single sensitivity, MPS, and MIS corresponding to Method 1-3, respectively, are illustrated and summarized in Fig.2. Method 1 can achieve fast assessment on system FN/FV using a single sensitivity derived from the SFR model but fails to quantify the impact of RES locations and excitation system. To address this issue and improve the accuracy of estimated FN/FV, Method 2 is proposed, where the traditionally single sensitivity is replaced by the M sensitivities, defined as a set of sensitivity (M is the number of RESs). This method can be extended for area-level FN/FV evaluation but fails to comprehensively reflect the impact of frequency oscillation on FN/FV evaluation. Hence, Method 3 is proposed to achieve a more accurate evaluation of area-level FN/FV by using a set of sensitivity selected from the preset 2^{M} sets of sensitivities according to different combinations of the RES outputs. It is noted that the MPS is only one component of MIS which will be clearly presented in the Case Study.

III. PROBABILISTIC ASSESSMENT ON AREA-LEVEL FN/FV

A. STOCHASTIC MODELING OF THE DISTURBANCE

Frequency-related uncertainties mainly include the random output of the RES and system loads in the power system,

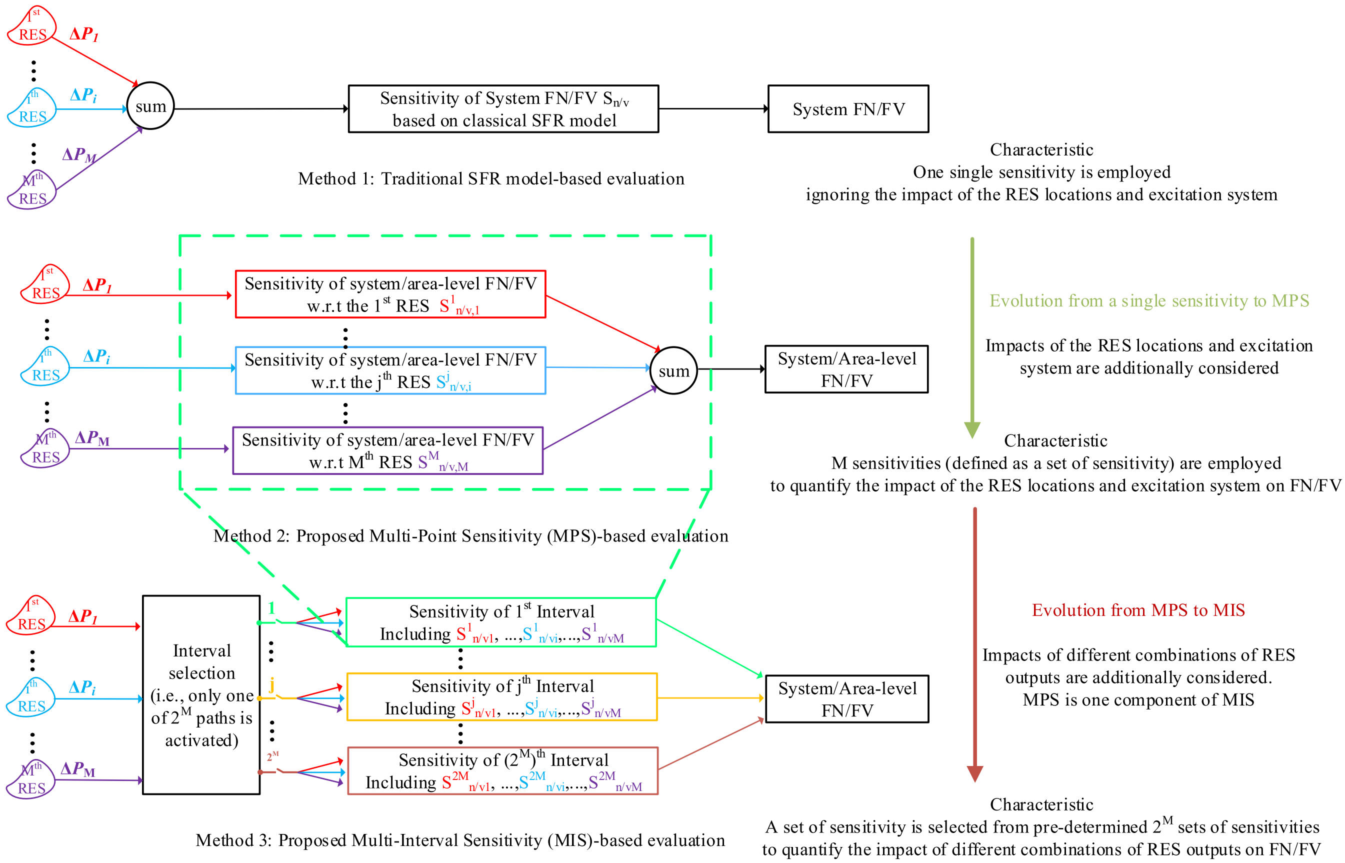

FIGURE 2. The comparison of the evaluation methods based on the traditional SFR-based single sensitivity and the proposed MPS and MIS.

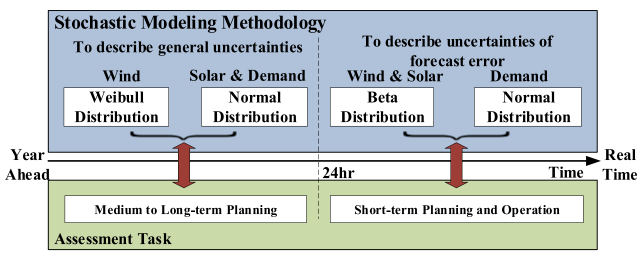

FIGURE 3. Stochastic modeling of uncertainties from different RESs and system loads in different assessment tasks/timescales.

the stochastic modeling of which is treated separately according to different assessment tasks/timescales as indicated by Fig. 3.

Although this paper focuses on analyzing the impact of RESs, the proposed method can also tackle other uncertainties, such as system loads. The spatiotemporal correlations between different RESs can be appropriately modeled by the correlation coefficient matrix [22].

B. RISK ASSESSMENT TOOL

The risk assessment matrix (RAM) can provide a two-dimensional assessment result with severity and occurrence probability comprehensively, which is a practical tool to evaluate the risk of an event. Three levels of risk are provided considering both the severity and the occurrence probability, which are labeled as 'L' (i.e., low risk in green part), 'M' (i.e., middle risk in yellow part), and 'H' (i.e., high risk in red part). The severity of FN/FV RAM is established according to an industrial standard [19], and the occurrence probability can be determined and adjusted manually according to grid code. In this paper, the FN/FV RAM is formed as Table 1 to evaluate the risk of area-level FN/FV.

TABLE 1. FN/FV RAM.

Probability \ Hz	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
0-1%	M	L	L	L	M
1%-30%	H	M	L	M	H
30%-100%	H	H	L	H	H

C. OPERATIONAL PLANNING BASED ON MIS/MPS OF AREA-LEVEL FN/FV

This section presents an overview of the evaluation process of area-level FN/FV based on MIS in a multi-RES power system for operational planning, as illustrated in Fig. 4.

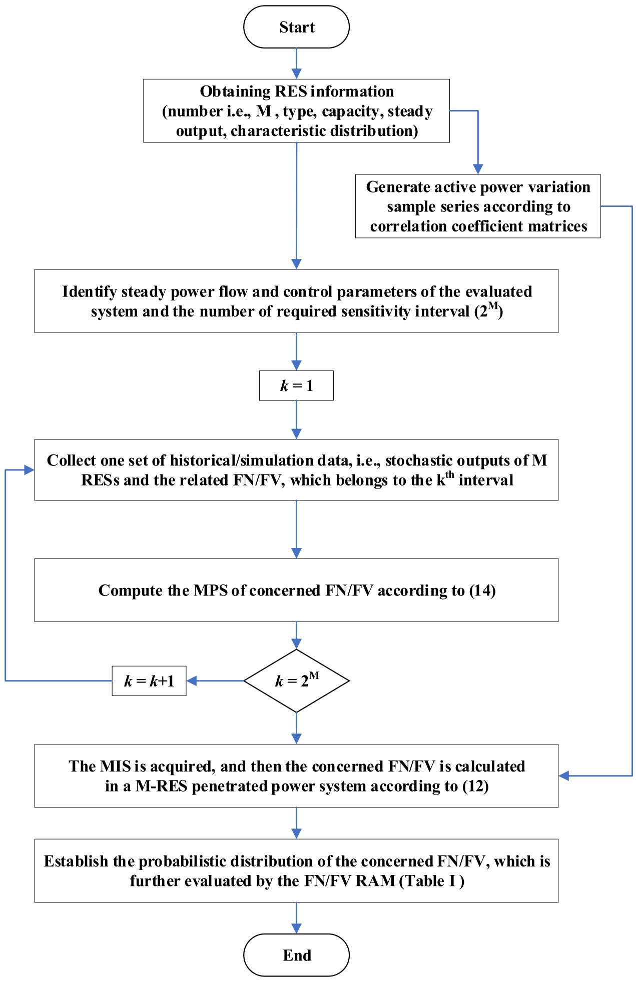

FIGURE 4. **Probabilistic assessment on area-level FN/FV for operational planning based on MIS in a multi-RES power system.**

1. Identify the information of the RESs, including the number (i.e., M), type, distribution of the natural source, and their correlation. Then, the stochastic and steady output of the individual RES is identified.

2. Based on the above information and the forecasted load, the operational planner can determine the generation of the individual plant in the system, which means the power flow of the system to be assessed is available.

3. Calculate MIS. Firstly, the number of the sensitivity interval is determined, i.e., 2^M, which is also the number of the cycles to acquire MIS. In each cycle/interval, one set of data are collected via historical information or simulation results, which contain the stochastic outputs of M RES and the corresponding FN/FV, and then the MPS of the concerned FN/FV is computed according to (14). After 2^M cycles, the MIS is obtained.

4. Compute the concerned FN/FV by (12) using the generated stochastic output of individual RES in Step 1 and the MIS in Step 3, which is further assessed by the FN/FV RAM.

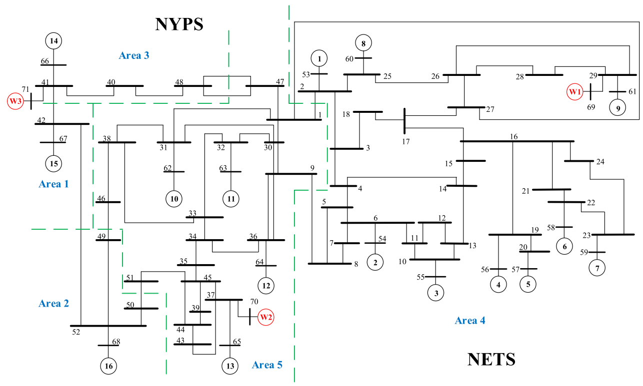

FIGURE 5. **Line diagram of a modified IEEE 5-area 16-machine benchmark system with three wind farms.**

It is noted that the MPS-based assessment is a special case of MIS-based assessment considering only one interval rather than 2^M intervals (in Step 3), and thus it is not presented here to avoid duplication.

It is noted that when M is large, the computational burden is quite heavy for MIS-based method. In this case, the MPS is recommended to be used as complementary. There is always a tradeoff between the assessment accuracy and efficiency, and thus two methods are provided in this paper, which can be flexibly chosen in the real application. Compared with traditional Monte Carlo simulations, the proposed methods can achieve satisfactory accuracy as well as efficiency.

IV. CASE STUDY

The effectiveness of the proposed framework is verified using a modified IEEE 5-area 16-machine 68-bus benchmark system with three Wind Farms (WFs) connected to buses 29, 37, and 41, respectively, as shown in Fig. 5 [24]. The benchmark system is perfectly suitable for the validation of three types of area-level FN/FV, including 1) system-level FN/FV, 2) area-level FN/FV (Area 4 and Area 5), 3) single-generator area-level FN/FV (Area 1-3).

The capacity of each WF is 2 p.u based on 100MVA, and the steady output is 2/3 of the capacity, which replaces the output of the adjacent generator, respectively. The Weibull distribution is employed for wind speed [25] and the correlation coefficient matrix is expressed as (15), the detailed calculation method of which is given in [26].

$$[\rho_{ij}]_{3\times 3} = \begin{bmatrix} 1 & 0.7 & 0 \\ 0.7 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (15)$$

A. SENSITIVITY ANALYSIS

According to the proposed scheme, eight intervals are classified in Table 2. The positive, i.e., the stochastic output is higher than the steady output of the WF, is labeled as "+." Otherwise, it is "−." For each interval, three sets of data, including the stochastic output of each WFs and correlated FN/FV are required via collecting historical data or

TABLE 2. The classified intervals based on the relationship between the steady output and stochastic output of three WFs.

Interval No	WF1	WF2	WF3
1	-	-	-
2	-	-	+
3	-	+	-
4	-	+	+
5	+	-	-
6	+	-	+
7	+	+	-
8	+	+	+

TABLE 3. The MIS of area-level FN/FV w.r.t WF1 within different intervals.

Interval No	System	Area 1	Area 2	Area 3	Area 4	Area 5
1	0.2414	0.2330	0.2554	0.2342	0.2330	0.2305
2	0.2269	0.2330	0.2298	0.2333	0.2331	0.2361
3	0.2393	0.2305	0.2444	0.2363	0.2345	0.2364
4	0.2377	0.2595	0.2512	0.2624	0.2569	0.2524
5	0.2359	0.2615	0.2487	0.2640	0.2573	0.2526
6	0.2329	0.2277	0.2413	0.2360	0.2307	0.2299
7	0.2365	0.2644	0.2494	0.2596	0.2547	0.2548
8	0.2359	0.2363	0.2446	0.2369	0.2404	0.2420

TABLE 4. The MIS of area-level FN/FV w.r.t WF2 within different intervals.

Interval No	System	Area 1	Area 2	Area 3	Area 4	Area 5
1	0.1798	0.1907	0.1749	0.1877	0.1972	0.2003
2	0.1957	0.2004	0.1931	0.1974	0.2006	0.2007
3	0.2017	0.1944	0.2017	0.1964	0.1991	0.1970
4	0.2012	0.1956	0.2021	0.1980	0.1996	0.1968
5	0.1919	0.2012	0.1955	0.2018	0.2025	0.1995
6	0.1962	0.1930	0.1979	0.1920	0.1853	0.1936
7	0.2039	0.2139	0.2044	0.2078	0.2104	0.2110
8	0.2060	0.2055	0.2069	0.2007	0.2108	0.2088

simulation. Then, the sensitivity of the individual area-level FN/FV w.r.t WF1-3 in each interval is calculated, shown in Tables 3-5 separately. The MPS of the individual area-level FN/FV w.r.t WF1-3 can be directly extracted from the specific line of the individual three tables since it is a special case/interval of the MIS. For example, the second line of Tables 3-5 is picked up as MPS in Table 6. It is noted that the selection of line/interval is arbitrary. Moreover, there is only one sensitivity of system FN/FV based on the derived SFR model, which is 0.2527, and the aggregation method of the SFR model is based on [27].

In order to improve the assessment accuracy, the impact of WF location is considered, and then the original sensitivity (i.e., 0.2527) is "expanded" to 0.2269, 0.1957, and 0.3060 (i.e., the second column of Table 6) for WF1-3 separately as the proposed MPS according to (14). Furthermore, the MPS can also be extended for area-level assessment, and the related sensitivities are also listed in Table 6. The different values of each line in Table 6 indicate that the same WF impacts system and area-level FN/FVs differently, which can be revealed by the proposed MPS. However, the MPS only considers the impact of one interval, i.e., interval 2, and ignores the impacts of other intervals. Thereby, the assessment accuracy can be improved by comprehensively considering the impact (i.e., MPS) of all intervals, and thus the 8 (i.e., 2^3) MPSs corresponding to different intervals are required to achieve better performance. In other words, each line of Table 6, including 6 values, is "expanded" to a table, including 48 values, shown in Tables 3-5, respectively. For each column of each three tables, the values are also various, which reflects the impact of different output ranges of three WFs on the same area-level FN/FV.

TABLE 5. The MIS of area-level FN/FV w.r.t WF3 within different intervals.

Interval No	System	Area 1	Area 2	Area 3	Area 4	Area 5
1	0.2776	0.2988	0.3017	0.3204	0.2874	0.2833
2	0.3060	0.2987	0.2860	0.2856	0.3038	0.3045
3	0.2756	0.2998	0.3022	0.3188	0.2870	0.2819
4	0.3002	0.3245	0.3265	0.3369	0.3150	0.3102
5	0.2752	0.3057	0.3020	0.3251	0.2915	0.2887
6	0.2993	0.3218	0.3253	0.3336	0.3086	0.3083
7	0.2740	0.3256	0.3044	0.3304	0.3064	0.2997
8	0.2945	0.3108	0.3199	0.3315	0.2972	0.2916

TABLE 6. The MPS of area-level FN/FV w.r.t three WFs.

WF	System	Area 1	Area 2	Area 3	Area 4	Area 5
WF1	0.2269	0.2330	0.2298	0.2333	0.2331	0.2361
WF2	0.1957	0.2004	0.1931	0.1974	0.2006	0.2007
WF3	0.3060	0.2987	0.2860	0.2856	0.3038	0.3045

TABLE 7. Assessment results of system FN/FV by the SBS, MIS, MPS, and SFR method.

Level \ **Hz**	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
SBS	9.08%	22.86%	44.62%	23.44%	0.00%
MIS	8.98%	22.78%	44.84%	23.40%	0.00%
MPS	9.76%	23.60%	43.94%	22.70%	0.00%
SFR	12.02%	22.40%	40.70%	21.86%	3.02%

B. VALIDATION OF MIS, MPS, AND SFR-BASED METHODS FOR SYSTEM FN/FV

After obtaining the required sensitivities, the probabilistic distributions of system FN/FV assessed by the SBS, the proposed MIS and MPS, and the traditional SFR method are presented in Fig. 6, and the assessment result and related absolute errors compared with SBS are in Table 7 and 8 separately.

The most concerning part is the 'red region,' assessed by SBS, i.e., frequency below 49.5 Hz. The probabilities of high risk evaluated by MIS, MPS, and SFR method are

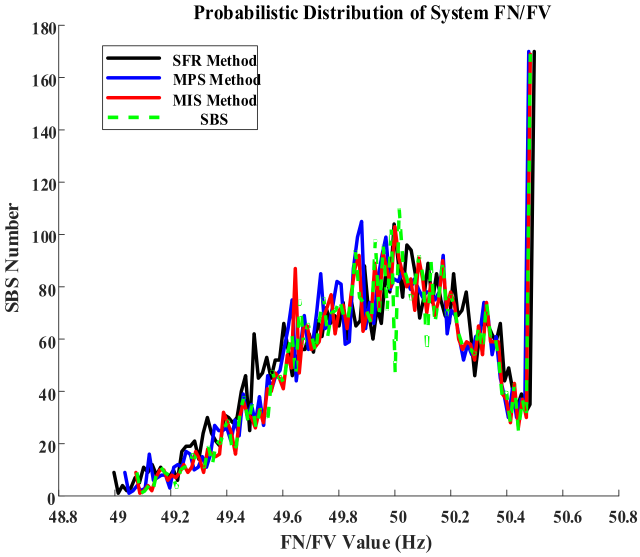

FIGURE 6. Probabilistic distributions of system FN/FV assessed by the SBS, MIS, MPS, and SFR-based methods.

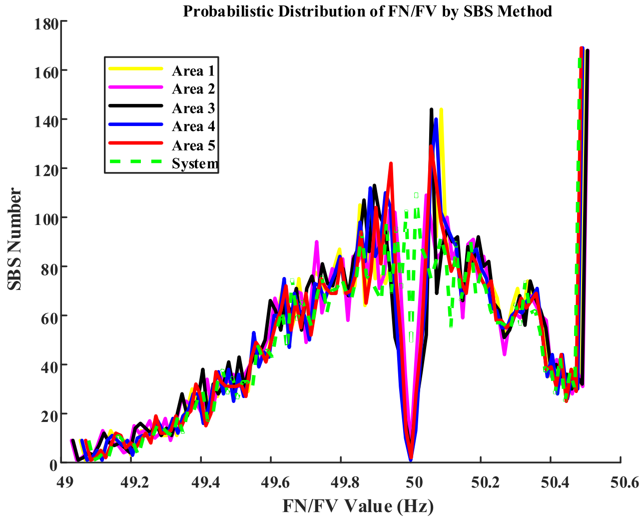

FIGURE 7. The probabilistic distribution of system and area-level FN/FV.

TABLE 8. Absolute errors of system FN/FV assessed by the MIS, MPS, and SFR method compared with SBS.

Area \ **Hz**	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
MIS	0.10%	0.08%	0.22%	0.04%	0.00%
MPS	0.68%	0.74%	0.68%	0.74%	0.00%
SFR	2.94%	0.46%	3.92%	1.58%	3.02%

TABLE 9. Assessment results of the system and area-level FN/FV by the SBS.

Level \ **Hz**	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
System	9.08%	22.86%	44.62%	23.44%	0.00%
Area 1	9.62%	24.14%	41.32%	22.14%	2.78%
Area 2	10.00%	23.54%	41.86%	21.26%	3.34%
Area 3	10.16%	24.36%	40.38%	21.86%	3.24%
Area 4	9.46%	23.52%	42.72%	24.30%	0.00%
Area 5	9.40%	23.42%	43.06%	24.12%	0.00%

8.98%, 9.76%, and 12.02% separately. Compared with the SBS-based assessment result, i.e., 9.08%, the errors of the three methods are 0.10%, 0.68%, and 2.94% subsequently. The assessment errors of the proposed MPS and MIS methods are below 0.7% and much smaller than that of the SFR method, i.e., 2.94%, where the MIS method performs much better.

It is also worth noting that the SFR-based assessment results in the frequency range above 50.5 Hz (bottom right corner of Table 7) is 3.02% and evaluated as high risk while the real occurrence probability is 0%. The large errors indicate that the SFR-based method cannot accurately assess the correlated risk due to large deviations, but both MPS and MIS methods can.

In other assessment ranges, i.e., 49.5-49.8, 49.8-50.2, and 50.2-50.5 Hz, the absolute errors of the MIS, MPS, and SFR methods change from 0.04% to 0.22%, from 0.68% to 0.74%, and from 0.46% to 3.92% separately. The maximal absolute error of the MIS method is smaller than the minimal absolute error of the MPS and SFR method separately, which further verifies the effectiveness of the MIS method in system-level evaluation. Moreover, the maximal error of the MPS method (i.e., 0.74%) is much smaller than that of the SFR method (i.e., 3.92%), which proves the MPS method is better than the SFR-based method in frequency assessment.

To sum up, the proposed MPS and MIS method can replace the SFR model-based method for risk assessment of system FN/FV violation in terms of accuracy.

C. THE HETEROGENEITY OF SYSTEM AND AREA-LEVEL FN/FV

The probabilistic distributions of the system and individual area-level FN/FV evaluated by SBS are illustrated in Fig. 7, and the detailed results are presented in Table 9.

As exhibited in Fig. 7, the probabilistic distribution of the system-level FN/FV is different from that of the area-level FN/FV. The most obvious difference occurs around 50Hz, (i.e., the steady state), where the occurrence number of area-level FN/FV (i.e., any of five areas) is nearly 0, while that of the system FN/FV is above 40. The main reason for this phenomenon is frequency oscillation, where the heterogeneity of the area-level frequency responses is offset in system frequency calculation, and this leads to a relatively large occurrence number of system FN/FV around the steady state, i.e., 50Hz. In other words, the system-level assessment is relatively conservative compared with area-level assessment due to a relatively high occurrence number around the steady state.

In Table 9, probabilistic distributions of frequencies below 49.5Hz and above 50.5Hz are more concerned since the

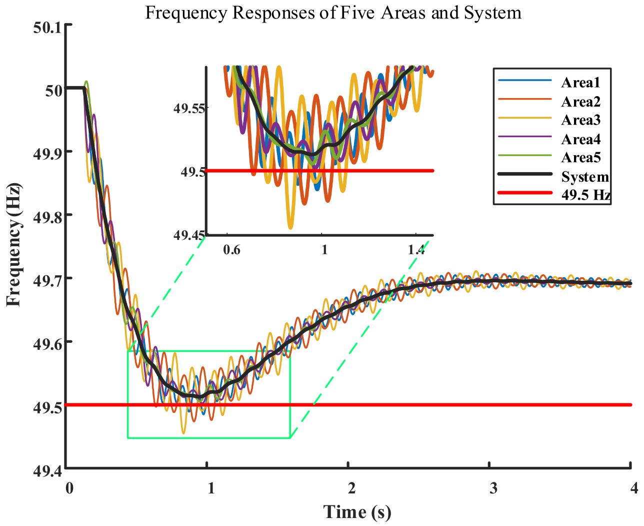

FIGURE 8. Frequency responses of five areas and the system.

frequency within either interval threatens the safe operation of power grids.

It is shown that in the frequency range below 49.5Hz, the occurrence probabilities of five areas vary from 9.40% to 10.16%, all of which are larger than the system-level assessment result, i.e., 9.08%, with a maximal deviation of 1.1%. Thus, the system-level assessment result is relatively conservative compared to the area-level assessment result due to a relatively low probability of occurrence below the lower limit (i.e., 49.5Hz). The reason for this phenomenon is also the frequency oscillation, where the heterogeneity of frequency responses is offset and covered in the system-level frequency but discovered in area-level frequency. As illustrated in Fig. 8, the regional frequency is below 49.5 Hz (e.g., 49.4547Hz for Area 3), while the system frequency, as an average response of the system, is still above 49.5Hz (i.e., 49.5126Hz), which leads to different risk assessment results of the system (i.e., middle risk) and areas (e.g., high risk for Area 3) with a boundary of 49.5Hz. Such frequency oscillation is mainly caused by the influence of the weak interconnecting ties and the difference in disturbance location, generator inertia, electrical distance, and deployed control system, such as excitation system and governor-speed droop control [28].

Moreover, the evaluation results of the system and five areas are the same, i.e., high risk, in the frequency range below 49.5Hz. However, the assessment results of the system and five areas are inconsistent in the frequency range above 50.5Hz. In detail, the system and Areas 4-5 are evaluated as low risk with 0%, whereas Areas 1-3 are assessed as high risk with probabilities of 2.78%, 3.34%, and 3.24%, separately. Therefore, the risk of area-level FN/FV violation cannot always be identified by a single system-level assessment result accurately due to the heterogeneity of frequency responses, which further necessitates the area-level FN/FV assessment.

TABLE 10. Assessment results of area-level FN/FV by the MIS method.

Level \ Hz	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
Area 1	9.66%	23.94%	42.00%	21.62%	2.78%
Area 2	9.82%	23.46%	42.38%	21.00%	3.34%
Area 3	10.18%	24.28%	41.18%	21.12%	3.24%
Area 4	9.52%	23.42%	43.10%	23.96%	0.00%
Area 5	9.48%	23.38%	43.20%	23.94%	0.00%

TABLE 11. Assessment results of area-level FN/FV by the MPS method.

Level \ Hz	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
Area 1	9.92%	23.54%	43.60%	22.94%	0.00%
Area 2	9.22%	23.34%	45.08%	22.36%	0.00%
Area 3	9.44%	23.46%	44.38%	22.72%	0.00%
Area 4	10.02%	23.62%	43.36%	23.00%	0.00%
Area 5	10.26%	23.56%	43.02%	23.16%	0.00%

TABLE 12. Absolute errors of area-level FN/FV assessed by the MIS method compared with SBS.

Area \ Hz	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
Area 1	0.04%	0.20%	0.68%	0.52%	0.00%
Area 2	0.18%	0.08%	0.52%	0.26%	0.00%
Area 3	0.02%	0.08%	0.80%	0.74%	0.00%
Area 4	0.06%	0.10%	0.38%	0.34%	0.00%
Area 5	0.08%	0.04%	0.14%	0.18%	0.00%

TABLE 13. Absolute errors of area-level FN/FV assessed by the MPS method compared with SBS.

Area \ Hz	<49.5	49.5~49.8	49.8~50.2	50.2~50.5	>50.5
Area 1	0.30%	0.60%	2.28%	0.80%	2.78%
Area 2	0.78%	0.20%	3.22%	1.10%	3.34%
Area 3	0.72%	0.90%	4.00%	0.86%	3.24%
Area 4	0.56%	0.10%	0.64%	1.30%	0.00%
Area 5	0.86%	0.14%	0.04%	0.96%	0.00%

D. VALIDATION OF MIS AND MPS-BASED METHODS FOR AREA-LEVEL FN/FV

The probabilistic distributions of individual area-level FN/FV evaluated by the MIS and MPS methods are presented in Table 10-11 separately, and the related absolute errors compared with the SBS-based results are given in Table 12 and 13, accordingly.

For overall quantitative analysis of both methods, the mean absolute error (MAE) of the MIS method (i.e., Table 12) is 0.2176%, and the maximal error is 0.8%, while the MAE of the MPS method (i.e., in Table 13) is 1.19%, and the maximal error is 4%. The errors of the MIS method are around five times smaller than those of the MPS method, which proves that the MIS method is better than the MPS method for the area-level FN/FV assessment.

Moreover, the assessment results demonstrate that when the heterogeneity of system and area-level FN/FV is not obvious (e.g., in the frequency ranges below 49.5Hz according to Table 9), both MPS and MIS methods can obtain a satisfying assessment result (i.e., high risk, middle risk, or low risk), but when the heterogeneity is obvious (e.g., the frequency ranges

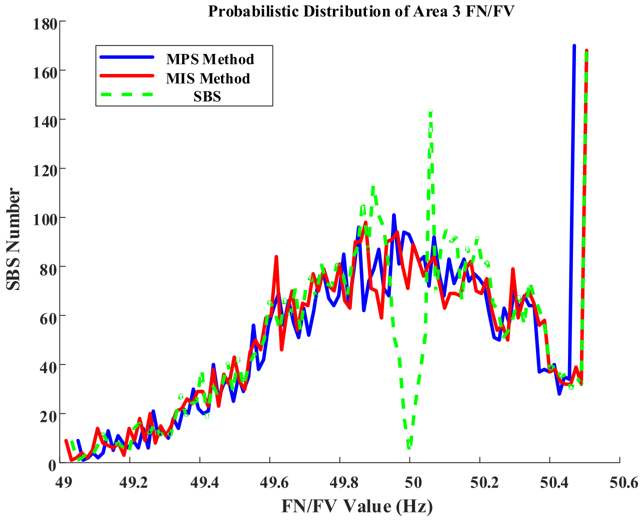

FIGURE 9. Probabilistic distributions of Area 3 FN/FV assessed by the SBS, MIS, MPS, and SFR-based method.

above 50.5Hz according to Table 9), only the MIS method can achieve an accurate assessment.

In detail, the heterogeneity of system and area-level FV (i.e., in the frequency range above 50.5Hz) can be reflected by the MIS method perfectly with no error in all areas, where Areas 1-3 are evaluated as high risk and the Areas 4-5 are low risk. However, the MPS method assesses the risk of all areas as low risk with occurrence probabilities of 0%, whereas the real values of Area 1-3 are 2.78%, 3.34%, and 3.24%, respectively. The large errors indicate the MPS method fails to achieve accurate assessment considering the heterogeneity of area-level frequency responses.

The reason for the inaccurate evaluation of the MPS method compared with the MIS method is that the MPS method fails to comprehensively consider the impact of frequency oscillation, while the MIS method does according to selecting the most suitable set of sensitivity from the established 2^M sets of sensitivities, i.e., MIS. The probabilistic distribution of Area 3 FN/FV assessed by SBS, MIS and MPS is exhibited in Fig. 9. The figure demonstrates that the MIS method approximates the SBS-based result better than the MPS method. Therefore, the MIS method is much more suitable for area-level assessment considering the heterogeneity of the frequency responses.

There is an interesting finding that MIS fails to approximate the SBS-based result around 50Hz accurately, as displayed in Fig. 9, but the assessed probability by the MIS method within the operational limit (49.8-50.2Hz) is accurate with an absolute error of 0.8% in Table 12. Therefore, the proposed MIS can achieve a proper approximation in statistics, which is suitable for operational planning.

E. COMPARISON OF COMPUTATIONAL TIME

In Table 14, the computational time of the SBS and the proposed MIS and MPS method is compared, and around

TABLE 14. Computational time.

	SBS	MIS Method	MPS Method
Computational Time	154875.3s	755.2s	101.4s

154120s (42.8 hours) and 154773.6 (42.9 hours) can be saved by the proposed MIS and MPS method separately, which proves the efficiency of the proposed methods. The MIS method is time-consuming compared with the MPS method but more accurate. If the required data for sensitivity calculation can be directly obtained from historical information, the MIS method would be more popular than the MPS method. Both methods can be selected according to different requirements for operational planning.

Therefore, the effectiveness and efficiency of the proposed MIS and MPS methods in calculating area-level FN/FV are verified by SBS.

V. CONCLUSION

In this paper, a framework for assessing the probabilistic distribution of the area-level FN/FV in a multi-RES power system is presented, and the MPS and MIS methods are proposed accordingly. The main conclusions are drawn below.

1. The heterogeneity of frequency responses leads to different assessment results of the system and area-level FN/FV. In this sense, the system-level assessment result is more conservative than the area-level assessment result due to a relatively high occurrence probability around the steady state and a relatively low occurrence probability of violating the upper and lower limits.

2. The proposed MPS and MIS methods can replace the classical SFR model for risk assessment of system FN/FV in operational planning due to much smaller errors validated by SBS since both methods consider the impact of RES locations and excitation systems.

3. Both MPS and MIS methods are suitable for the area-level FN/FV evaluation, while the MIS method performs much better than the MPS method, especially when the heterogeneity of system and area-level is obvious. The reason for the outstanding performance of the MIS method is that the impact of frequency oscillation on area-level FN/FV evaluation is considered and quantified from a new perspective.

4. The proposed methods are much more efficient than SBS since either of both estimates the FN/FV directly rather than firstly estimating the frequency response curve and then searching the maximal/minimal point. Thus, the proposed methods are suitable for fast operational planning of system and area-level FN/FV.

5. An interesting finding is that even though the value of the system and area-level FN/FV estimation at minor points (e.g., 50Hz) by the MIS method might not be quite accurate, the evaluated probabilistic distribution within the operational limit (e.g., 49.8-50.2Hz) is still precise with a maximal absolute error of 0.8%. Please note that in probabilistic assessment, the accuracy of the interval assessment (e.g., 49.8-50.2Hz) is more important than that of the point

assessment (e.g., 50Hz). Thus, the proposed MIS method is a practical and suitable probabilistic assessment for operational planning.

REFERENCES

[1] S. Q. Bu, W. Du, H. F. Wang, Y. Liu, and X. Liu, ''Investigation on economic and reliable operation of meshed MTDC/AC grid as impacted by offshore wind farms,'' *IEEE Trans. Power Syst.*, vol. 32, no. 5, pp. 3901–3911, Sep. 2017.

[2] V. Miranda, ''Successful large-scale renewables integration in portugal: Technology and intelligent tools,'' *CSEE J. Power Energy Syst.*, vol. 3, no. 1, pp. 7–16, Mar. 2017.

[3] P. Tielens and D. Van Hertem, ''The relevance of inertia in power systems,'' *Renew. Sustain. Energy Rev.*, vol. 55, pp. 999–1009, Mar. 2016.

[4] S. Li, Q. Liao, D. Liu, and B. Cen, ''Retraction note: An improved under frequency load shedding strategy based on dynamic power flow tracing,'' *Protection Control Mod. Power Syst.*, vol. 2, no. 1, p. 33, Dec. 2017.

[5] U. Rudez and R. Mihalic, ''Analysis of underfrequency load shedding using a frequency gradient,'' *IEEE Trans. Power Del.*, vol. 26, no. 2, pp. 565–575, Apr. 2011.

[6] V. V. Terzija, ''Adaptive underfrequency load shedding based on the magnitude of the disturbance estimation,'' *IEEE Trans. Power Syst.*, vol. 21, no. 3, pp. 1260–1266, Aug. 2006.

[7] S. Chandak, P. Bhowmik, and P. K. Rout, ''Load shedding strategy coordinated with storage device and D-STATCOM to enhance the microgrid stability,'' *Protection Control Mod. Power Syst.*, vol. 4, no. 1, p. 22, Dec. 2019.

[8] Z. Song, Y. Lin, C. Liu, Z. Ma, and L. Ding, ''Review on overfrequency generator tripping for frequency stability control,'' in *Proc. IEEE PES Asia–Pacific Power Energy Eng. Conf. (APPEEC)*, Oct. 2016, pp. 2240–2243.

[9] M. N. H. Shazon, H. M. Ahmed, and N.-A. Masood, ''Over-frequency mitigation using coordinated generator shedding scheme in a low inertia power system,'' in *Proc. IEEE Region Symp. (TENSYMP)*, Jun. 2020, pp. 560–563.

[10] J. Wen and S. Bus, ''Performance evaluation of coherency identification methods in frequency stability analysis based on a novel assessment index,'' in *Proc. IEEE 2nd Int. Electr. Energy Conf. (CIEEC)*, Nov. 2018, pp. 132–137.

[11] P. M. Anderson and M. Mirheydar, ''A low-order system frequency response model,'' *IEEE Trans. Power Syst.*, vol. 5, no. 3, pp. 720–729, Aug. 1990.

[12] I. Egido, F. Fernandez-Bernal, P. Centeno, and L. Rouco, ''Maximum frequency deviation calculation in small isolated power systems,'' *IEEE Trans. Power Syst.*, vol. 24, no. 4, pp. 1731–1738, Nov. 2009.

[13] L. Liu, W. Li, Y. Ba, J. Shen, C. Jin, and K. Wen, ''An analytical model for frequency nadir prediction following a major disturbance,'' *IEEE Trans. Power Syst.*, vol. 35, no. 4, pp. 2527–2536, Jul. 2020.

[14] S. Bu, J. Wen, and F. Li, ''A generic framework for analytical probabilistic assessment of frequency stability in modern power system operational planning,'' *IEEE Trans. Power Syst.*, vol. 34, no. 5, pp. 3973–3976, Sep. 2019.

[15] J. Wen, S. Bu, B. Zhou, Q. Chen, and D. Yang, ''A fast-algorithmic probabilistic evaluation on regional rate of change of frequency (RoCoF) for operational planning of high renewable penetrated power systems,'' *Energies*, vol. 13, no. 11, p. 2780, Jun. 2020.

[16] J. Wen, S. Bu, F. Li, and P. Du, ''Risk assessment and mitigation on area-level RoCoF for operational planning,'' *Energy*, vol. 228, Aug. 2021, Art. no. 120632.

[17] J. Shen, W. Li, L. Liu, C. Jin, K. Wen, and X. Wang, ''Frequency response model and its closed-form solution of two-machine equivalent power system,'' *IEEE Trans. Power Syst.*, vol. 36, no. 3, pp. 2162–2173, May 2021.

[18] M. Ni, J. D. McCalley, V. Vittal, and T. Tayyib, ''Online risk-based security assessment,'' *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 258–265, Feb. 2003.

[19] NationalgridESO. *Review of the NETS SQSS Criteria for Frequency Control that Drive Reserve, Response and Inertia Holding on the GB Electricity System*. Accessed: Apr. 1, 2021. [Online]. Available: https://www.nationalgrideso.com/industry-information/codes/security-and-quality-supply-standards-old/modifications/gsr027-review

[20] R. Preece and J. V. Milanović, ''Risk-based small-disturbance security assessment of power systems,'' *IEEE Trans. Power Del.*, vol. 30, no. 2, pp. 590–598, Apr. 2015.

[21] A. Younesi, H. Shayeghi, A. Safari, and P. Siano, ''Assessing the resilience of multi microgrid based widespread power systems against natural disasters using Monte Carlo simulation,'' *Energy*, vol. 207, Sep. 2020, Art. no. 118220.

[22] S. Bu, W. Du, H. Wang, Z. Chen, L. Xiao, and H. Li, ''Probabilistic analysis of small-signal stability of large-scale power systems as affected by penetration of wind generation,'' *IEEE Trans. Power Syst.*, vol. 27, no. 2, pp. 762–770, May 2012.

[23] K. Zhang, B. Wang, D. Liu, J. Zhao, Y. Guo, and Z. Wu, ''Prediction modeling of frequency response characteristic of power system based on historical data,'' in *Proc. IEEE/IAS Ind. Commercial Power Syst. Asia (I&CPS Asia)*, Jul. 2020, pp. 1486–1490.

[24] W. Du, S. Bu, and H. Wang., ''Effect of stochastic variation of grid-connected wind generation on power system small-signal probabilistic stability,'' *Proc. CSEE*, vol. 31, pp. 7–11, Jan. 2011.

[25] I. Abouzahr and R. Ramakumar, ''An approach to assess the performance of utility-interactive wind electric conversion systems,'' *IEEE Trans. Energy Convers.*, vol. 6, no. 4, pp. 627–638, Dec. 1991.

[26] L. Freris and D. Infield, *Renewable Energy in Power Systems*. New York, NY, USA: Wiley, 2008.

[27] Q. Shi, F. Li, and H. Cui, ''Analytical method to aggregate multi-machine SFR model with applications in power system dynamic studies,'' *IEEE Trans. Power Syst.*, vol. 33, no. 6, pp. 6355–6367, Nov. 2018.

[28] G. Rogers, *Power System Oscillations*. Berlin, Germany: Springer, 2012.

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