Location of Low-Frequency Oscillation Sources using Improved D-S Evidence Theory

Jiu Gu, Da Xie, Chenghong Gu, Jierong Miao, Yu Zhang

***Abstract*— This paper presents a method for localizing oscillation sources based on data fusion Dempster–Shafer (D-S) evidence theory. This study is based on data of each bus from the system collected by phasor measurement units (PMUs). Then the D-S evidence theory algorithm is employed to establish the mass function and the trust degree of each bus. Three traditional methods are used to locate the oscillation source and to provide the calculation results for structuring the mass function of the algorithm. Finally, the decision of oscillation sources localization is made according to synthesis decision value. The higher the synthesis decision value, the higher the possibility is of an oscillation source. The WECC179 bus power system is applied for verification, and the D-S evidence theory method is compared with the above traditional three methods. It is proved that the algorithm can significantly improve the accuracy of locating sources of negatively damped oscillations and forced power oscillations, effectively reduce misjudgment. Meanwhile, this algorithm is also effective for the positioning complex dual oscillation sources.**

***Index Terms*—Evidence theory, Low-frequency oscillation, Mass function, Oscillation source Location**

I. INTRODUCTION

As interconnected power system expands its scale over the decade, recurring low-frequency oscillations threatened safety and stability of large interconnected power systems operation [1]-[2]. Sources of oscillation events mainly include negatively damped oscillation and forced oscillation [3]. The source of negatively damped oscillation can be understood as a negatively damped unit, while the source of forced oscillation refers to the source of periodic disturbance that causes the oscillation. Generally, locating oscillation source is key to solving oscillation problems.

Besides, with the development of PMU, the wide-area measurement system (WAMS) of power systems can generate a large amount of operational monitoring data. It contains a large amount of information that can be mined, which includes power amplitude and angle of measured buses. According to Preece R et al (2012) and Chakrabortty A et al (2010), due to the wide distribution and wide monitoring range [4]-[5], these data plays an important role in solving the localization of oscillation sources.

There are four principles applied for the positioning of oscillation sources: travelling wave method, energy method, damping torque method and mode analysis method [6].

The traveling wave positioning method employs the propagation principle of electromechanical waves [7]. It was then revisited by Markham P N et. al. (2014), who described a method of judging the source of the oscillation through the phase difference. Liu Z et al. (2019) proposed a method based on WAMS to identify and track the center of oscillation [8]. It used the geometric relationship of the voltage phase to identify whether the generating unit is the source of oscillation. In [9], Zhang W et al proposed an on-line oscillation detection method for forced oscillation, which determined whether the power generation unit is an oscillation source based on the phase difference between electrical power and mechanical power; In [10], Wang M et al judged the location of the oscillation source based on the oscillation phase difference between the voltage angle of the bus and the adjacent bus.

The method based on energy applies Lyapunov function in power system stability analysis [11]. Li Y et al. (2012) established the energy function of generators based on port control Hamilton theory [12]. Chen L et. al. (2012) has established the calculation formula of the oscillation energy flow, but it may fail to identify all oscillation sources in multiple-source oscillation cases [13].

The modal analysis method based on small-signal eigenvalue analysis of the state space equation can obtain the frequency and damping information of the natural oscillation mode at a certain operating point of the system. However, this method may face "dimensional disaster" for complex models. It is difficult to obtain an accurate system model and thus is not suitable for online positioning [14]. Therefore, among the above four methods, travelling wave based and oscillating energy-based methods are more suitable for online monitoring.

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In addition, Dong Q et al used the propagation delay time of low-frequency disturbance traveling waves on transmission lines to calculate the location of low-frequency oscillation disturbance sources in the power grid [15][16]. Jiang P et al proposed a two-stage forced oscillation positioning method, which first located the bus of the oscillation source, and then located the control device according to the energy and phase [16]. Wu X et al proposed a distributed cooperative scheme for online positioning of forced oscillation sources [17]. For the positioning of multiple oscillation sources, an oscillation center identification method based on the variation trend of bus frequency was proposed [18].

A variety of intelligent information processing technologies, such as extension theory [19], support vector machine (SVM) method [20], fuzzy comprehensive evaluation method [21], etc. have applied to power systems based on the monitoring data of the power grid. These methods have achieved certain results in practical applications, but these methods have insufficient analysis in dealing with information uncertainty and information fusion. The advantage of information fusion technology is that it can reasonably coordinate multiple data sources and fully integrate a variety of useful information to make correct decisions in changing environment [22][23].

D-S evidence theory is one of data fusion methods, which can comprehensively deal with the uncertainties and multiple data sources fusion [24]. Based on D-S evidence theory, Jiao Z et. al. (2018) provided a fusion decision can be obtained and the trust range of the decision [25]. The application of evidence theory in power systems mainly includes fault monitoring and status recognition of power equipment. Many studies have contributed great efforts on fault diagnosis, optimal allocation and power flow analysis in power systems [26]-[30]. Therefore, D-S evidence theory is more suitable for the application scenario of oscillation source positioning.

The above methods of oscillating source positioning provide different application effects and scopes. This paper uses D-S evidence theory method to fuse the results of the traditional methods. Compared to traditional strategies, this paper has several innovations as follows:

1) Evidence-theoretic artificial intelligence algorithm is introduced to locate the oscillation source of low-frequency oscillation. It overcomes the shortcomings of a single traditional oscillation source localization method via multi-algorithm data fusion.

2) This algorithm synthesizes three traditional methods of oscillating source location and retains the potential oscillating sources obtained by each method to the greatest extent. It is beneficial to the location of multiple oscillating sources and has the effectiveness to deal with complex scenarios.

The rest of this paper is arranged as follows. The single oscillation source localization algorithm, evidence theory algorithm and algorithm flow are described in Section II. Practical diagnostic results and simulation diagnostic results are illustrated in Section III. Conclusions are in Section IV.

II. Localization Model Of Oscillation Source Based On D-S Evidence Theory

In this section, D-S evidence theory is used to fuse the results of the three methods to establish an on-line localization model of the oscillating source. The parameters of the model are trained through many cases to make the effect of the localization model more reliable.

A. *Principles of Evidence Theory*

D-S evidence theory is a type of artificial intelligence. It was first employed in expert systems and can handle uncertain information. The basic concept of evidence theory includes mass functions, confidence intervals, and composition rules[31]-[32] .

1) Mass Function

In the hypothesized space, the mass function is $2^{\Theta} \rightarrow [0,1]$, denoted as *m*. In the location problem, *m* is the probability function of the oscillation source. *m* satisfies:

$$m(\varnothing)=0 \quad \& \quad \sum_{A\subseteq\Theta} m(A)=1; \quad (m(A)>0) \tag{1}$$

The sum of the probabilities of oscillating source and the non-oscillating source is 1. The larger the value of $m(A)$, the higher the possibility that bus *A* is an oscillation source.

2) Trust Interval

In D-S evidence theory, the trust function is used to define the lower limit of probability, which is defined as:

$$Bel(A)=\sum_{B\subseteq A} m(B) \tag{2}$$

The likelihood function in D-S evidence theory can be used to define the upper limit of probability, defined as:

$$Pl(A)=\sum_{B\cap A\neq\varnothing} m(B) \tag{3}$$

The trust interval for the output of the combined trust function and likelihood function is $\left[Bel(A), \quad Pl(A)\right]$.

3) Synthesis Rules

The core of DS evidence theory is the rule of synthesis. $\forall A\subseteq\Theta$, The synthesis rule of n mass functions $m_1, m_2, \cdots, m_n$ on Θ is:

$$\left(m_1 \oplus m_2 \oplus \cdots \oplus m_n\right)(A) = \frac{1}{K} \sum_{A_1 \cap A_2 \cap \cdots \cap A_n = A} m_1\left(A_1\right) \cdot m_2\left(A_2\right) \cdot \ldots m_n\left(A_n\right) \tag{4}$$

$$K = \sum_{A_1 \cap \cdots \cap A_n \neq \varnothing} m_1\left(A_1\right) \cdot m_2\left(A_2\right) \cdot \ldots m_n\left(A_n\right) \tag{5}$$

K is called the normalization coefficient between multiple pieces of evidence and it can be used to define the degree of contradiction between various pieces of evidence. For the judgment of bus A as an oscillating source, combining the mass functions $\left(m_1 \oplus m_2 \oplus \cdots \oplus m_n\right)(A)$ can synthesize the results of each mass function $m_1, m_2, \cdots, m_n$ to improve the accuracy of the judgment.

B. Locating Oscillation Sources Using PMU Data

In this section, three positioning methods that can be used for on-line monitoring of the oscillation source will be introduced: the oscillation energy flow method, the voltage-based oscillation phase difference method, and the forced oscillation phase difference method. The first method is obtained by the principle of energy; the latter two methods are obtained by the traveling wave principle.

1) Oscillation Energy Flow Method

The detailed derivation process of the algorithm is shown in the references [11-12]. According to the theory of oscillation energy flow, the oscillation energy W_{ij} of a bus is defined as:

$$W_{ij} = \int \mathrm{Im}\left(I_{ij}^{*} \mathrm{d}U_i\right) \tag{6}$$

Where, U_i is the voltage of the bus, I_{ij}^{*} is conjugate current of the branch L_{ij}, and Im is the imaginary part.

Expand (6):

$$W_{ij} = \int \left(P_{ij} 2\pi \Delta f_i \mathrm{d}t + Q_{ij} \mathrm{d}\left(\ln U_i\right)\right) \tag{7}$$

Where, P_{ij} and Q_{ij} are the active power and reactive power of the branch L_{ij}, and f_i is the bus frequency. $\int Q_{ij} \mathrm{d}\left(\ln U_i\right)$ can be negligible, the oscillation energy can be approximated by $\int P_{ij} 2\pi \Delta f_i \mathrm{d}t$.

Assume that the current flowing out of the bus or cut set is positive. When the oscillation energy of a bus is positive and the oscillation energy curve has a positive slope, it indicates that the bus is outputting energy to the outside, so it is the source of oscillation.

2) Voltage-Based Oscillation Phase Difference Method

The angular difference between the two bus voltages is a prerequisite for power flow. When a bus in the power grid is a source of disturbance, the oscillation phase of the bus voltage is also delayed sequentially along the direction of the oscillation diffusion. Therefore, the angle oscillation phase of the voltage source oscillation angle is ahead of the angle oscillation phase of the bus voltage connected to the oscillation source. The detailed derivation process of the algorithm is shown in the reference [9].

In actual operation, when the oscillation occurs, the data measured by the PMU has a large interference, and the oscillation phase is always changing. It is impossible to judge the attribute of the oscillation source by a momentary oscillation phase difference. Therefore, (8) is generally used to define the phase difference index:

$$\Delta\varphi = \int \left(\varphi_1 - \varphi_2\right) \mathrm{d}t \tag{8}$$

Where, φ_1 is the voltage angle oscillation phase of the oscillation source bus, and φ_2 is the voltage angle oscillation of the adjacent bus.

In order to obtain this index, the HHT algorithm is introduced to find the instantaneous oscillation phase. The HHT algorithm consists of empirical mode decomposition (EMD) and hilbert transform (HT). The voltage angle data of the bus and the voltage angle of the adjacent bus are locked, and the EMD decomposition is performed on them to obtain the intrinsic modal function (IMF) components. HT is performed on the IMF component to extract the instantaneous phase. Based on the instantaneous phase difference, the phase difference index is obtained by integration. If the index is positive, the bus is judged to be an oscillation source; otherwise, it is a non-oscillation source.

3) Forced Oscillation Phase Difference Positioning

The motion equation of a generator rotor is shown in (9). The detailed derivation process of forced oscillation phase difference is in the literature [10].

$$\begin{cases} \dfrac{d\delta}{dt} = \Delta\omega \cdot \omega_0 \\ \dfrac{d\Delta\omega}{dt} = \dfrac{1}{2H}\left(\Delta P_{\mathrm{m}} - \Delta P_{\mathrm{e}} - D\Delta\omega\right) \end{cases} \tag{9}$$

Where, δ is the rotor angle. ω is the angular velocity. H is the inertia constant. ΔP_{m} is the mechanical input power. ΔP_{e} is the electrical output power, and D is the damping coefficient.

When $\Delta\dot{P}_{\mathrm{e}}$ and $\Delta\dot{\omega}$ are known, $\Delta\dot{P}_{\mathrm{m}}$ is calculated as in (10):

$$\Delta\dot{P}_m = j2H\Omega\Delta\dot{\omega} + \Delta\dot{P}_{\mathrm{e}} \tag{10}$$

Where, $\Delta\dot{P}_m$, $\Delta\dot{P}_{\mathrm{e}}$, and $\Delta\dot{\omega}$ are mechanical power fluctuations, electrical power fluctuations, and speed fluctuations in the form of phasors. Ω is the angular frequency of the power fluctuation. If the wave phase difference between ΔP_{m} and ΔP_{e} is greater than 0, the unit is an oscillation source.

C. Construction of Mass Function

According to the three methods of determining the source of oscillation mentioned in the introduction, the mass function of each method is established. When the slope of the oscillating energy flow method is the largest, the phase difference of the oscillating phase method or the phase difference of the mechanical and electrical oscillations is the largest. The probability of each method's decision result is set to 1, and the initialization probabilities *pp* of the remaining bus are set according to (11):

$$\begin{cases} pp(1)=1 \\ pp(k) = pp(k-1)\big/\left(0.8^k+1\right), \quad k=2,3,\ldots,n \end{cases} \tag{11}$$

In one case, the slopes of the oscillation energy flow curves, voltage angle oscillation phase differences, and mechanical and electrical oscillation phase differences of *n* bus are sorted from large to small, respectively. Assume that the slope of the oscillation energy flow curve at bus *i* is ranked at *j_m*1, the oscillation phase difference is ranked at *j_m*2, and the forced power oscillation phase difference is ranked at *j_m*3, Then define the mass function *p_m1* of the oscillation energy flow method, the mass function *p_m2* of the oscillation phase difference method, and the mass function *p_m3* of the forced oscillation phase difference method as shown in (12):

$$\begin{cases} p\_m1(i) = pp(j\_m1) \\ p\_m2(i) = pp(j\_m2) \quad i, j\_m1, j\_m2, j\_m3 \in 1,2,\cdots n \\ p\_m3(i) = pp(j\_m3) \end{cases} \tag{12}$$

D. Synthesis Rules

The result of the composition rule is equal to the product of all mass function values, divided by a normalization coefficient K. According to (11-12), the mass functions of three different methods are integrated to generate a combined quality function *P*1. According to the theoretical model of evidence, the formula for synthesizing evidence is derived in (13):

$$\begin{cases} P1 = \dfrac{1}{K}\left(p\_m1 \times p\_m2 \times p\_m3\right) \\ K = p\_m1 \times p\_m2 \times p\_m3 + (1-p\_m1)\times(1-p\_m2)\times(1-p\_m3) \end{cases} \tag{13}$$

Where, *K* is a normalization constant, and *P*1 is a synthesis decision value.

E. Optimization of Fusion Model for Two Kinds of Misjudgment Problems

After analyzing the results of the existing oscillation positioning methods, two typical misjudgment problems are found. The first type of misjudgment refers to the problem that none of the potential oscillation sources obtained by the oscillation source determination method are real oscillation sources. The second type of misjudgment refers to that although the oscillation source is located, its quality function is not the highest. Optimization of fusion model aims to reduce the occurrences of two types of misjudgments by using D-S evidence theory to train the results of the three sub-methods.

In this paper, the top three results of the mass function obtained by the discriminant method are used as potential sources of oscillation. Take the oscillating energy flow as an example. Assume that *pp*(1), *pp*(2) and *pp*(3) are the top three values in the mass function of the oscillating energy flow method, which correspond to buses *a*, *b* and *c*, respectively.

$$\begin{cases} pp(1) = p\_m1(a) \\ pp(2) = p\_m1(b) \\ pp(3) = p\_m1(c) \end{cases} \tag{14}$$

According to the definition of the first type of misjudgment, the three potential oscillation sources obtained are not correct results. the judgment is satisfied:

$$\forall\Theta(k) = No, k \in a,b,c \tag{15}$$

This kind of misjudgment indicates that the method is not effective in judging the oscillation source in some scenarios. In order to avoid that the comprehensive result is worse than the result of a single solution, the location methods with higher discriminant accuracy are selected for fusion. Through data fusion, the results of different methods are considered to reduce the probability of the first type of misjudgment.

According to the definition of the second type of misjudgment, the judgment is satisfied:

$$\begin{cases} \Theta(a) = No \\ \Theta(b) \cap \Theta(c) = Yes \end{cases} \tag{16}$$

In order to reduce the second type of misjudgment problems in the location submethod, it is necessary to increase the fusion decision value of the buses with more occurrences to be close to the value of the judgment result.

Suppose that the composite decision value of the number of occurrences greater than 2 in the potential oscillation sources obtained by the three single discriminant methods is $P1(x)$, the original positioning result $P1(y)$, and $P1(x)$□ $P1(y)$. The allowable acceptance coefficient ε is introduced so that the two values are within the acceptable range, then the objective function of optimization is:

$$\left| P1(x) - P1(y) \right| \le \varepsilon \tag{17}$$

By optimizing the fixed parameters of the synthesis decision value $P1$ and introducing the parameters α_1 and α_2 to the quality function and synthesis rules, the optimized model is:

$$\begin{cases} pp(1) = 1 \\ pp(k) = pp(k-1) \big/ \left(\alpha_1^{\ k} + 1\right), \qquad k = 2, 3, ..., n \end{cases} \tag{18}$$

$$K = p\_m1 \times p\_m2 \times p\_m3 + (\alpha_2 - p\_m1) \times (\alpha_2 - p\_m2) \times (\alpha_2 - p\_m3) \tag{19}$$

In this paper, the ANN method is used to solve (17-19), and the optimal solution set of α_1 and α_2 with different learning times can be solved. At the same time, when the operation mode or structure of the power system changes, the model needs to be solved again to ensure the adaptability of the training. After information fusion, the final confidence interval of α_2 is {0.68, 0.78}. α_1=0.8 and α_2=0.687 is used as a reference in the section III simulation.

F. Localization Fusion Model of Oscillation Source

The model of the oscillating source location fusion model algorithm is shown in Fig. 1. Its determination process is divided into three parts, which are using evidence theory; suppressing the oscillating source; comparing the suppression effect, the steps are as follows:

- Step 1: Firstly, PMU equipment is set at each generator bus in the system. Relevant electrical and mechanical quantities are obtained through the equipment.
- Step 2: Secondly, data is collected from generator buses by the PMU equipment set in the system. Parameters including the energy flow change of each generator bus, the voltage phase angle difference between the generator bus and the adjacent bus, and the electrical power and mechanical power phase angle difference can then be calculated from these data collected.
- Step 3: Thirdly, according to (11-13), the mass function of three oscillation location methods and the synthesis decision value $P1$ of each bus are generated.
- Step 4: Then, the synthesis decision value $P1$ in descending order are classified to generate M function. The bus with the largest synthesis decision value is considered as the source of oscillation. Then, this paper takes measures to improve the system damping by adjusting the scheduling operation mode of the bus i corresponding to $M(i)$. If the oscillation is found to be inhibited, it means that the bus i is the source of oscillation.
- Step 5: Thereafter, if system oscillation is inhibited, proceed to step 6; otherwise, we ignore the bus that have taken restraint measures and proceed to step 4 to continue to find other oscillation source until the system oscillation is been suppressed .
- Step 6: If it is cycled only once, it is determined that there is only a single oscillation source in the system, and it is the bus with the largest synthesis decision value; if the oscillation is inhibited after n cycles, there are n oscillation sources in the system.
- Step 7: Finally, the judgment result obtained by the evidence theory was then compared with the information of the oscillation source to verify the judgment effect.

The proposed method can give results when the source of oscillation is varying. From a space point of view, when the oscillation occurs, the oscillation source will not transfer to another place. From a time point of view, when the oscillation causes some wind turbines in the system to be disconnected from the network, the operating state of the power grid will change, which in turn causes the emergence or increase of new oscillation sources. The multiple oscillation source positioning strategy mentioned in Figure 1 of this article can realize the sequential positioning of multiple oscillation sources.

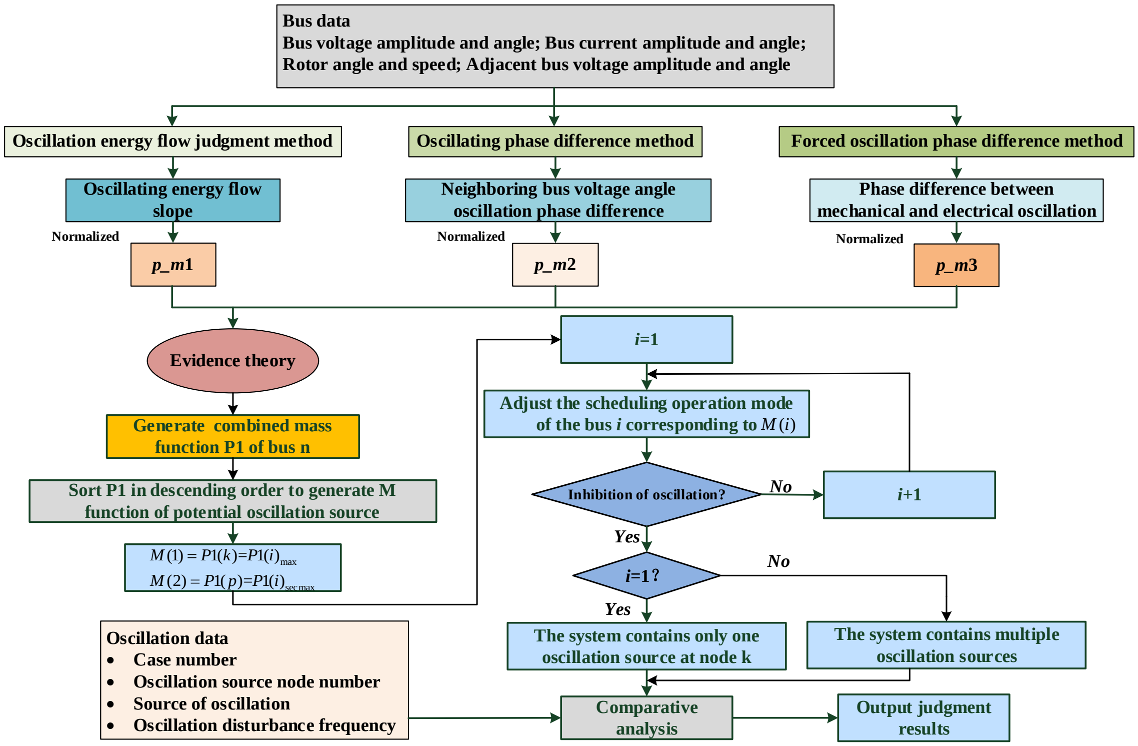


Fig. 1 Localization fusion model of oscillation source through evidence theory

III. Location Examples And Simulations Of Oscillation Sources

A. Simulation

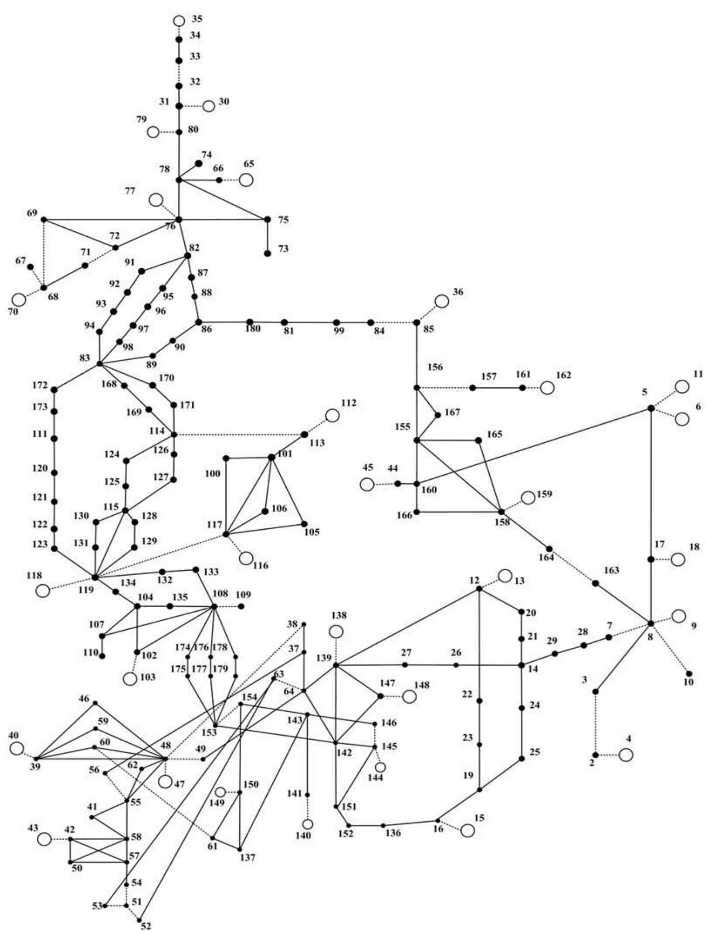


Fig. 2 WECC 179-bus power system

This paper uses a library of oscillation test cases developed by the University of Tennessee (UTK). The library includes simulation cases and actual oscillation events and is mainly applied to study the location of oscillation sources. All simulation cases are based on the WECC 179-bus power system, as shown in Fig. 2. The simulation cases are divided into forced oscillation simulation cases and negatively damped oscillation simulation cases. It includes different cases of multiple units with negative or weak damping, forced oscillation of governors and excitation systems, and complex cases with two oscillation sources. For specific oscillation information and bus information [33].

The data sampling frequency of the case set is 30Hz. Each case has 40 seconds of sampling data, and totally collects about 1200 data records. In the case of negatively damped oscillation, the large disturbance method of three-phase short-circuit fault is used to excite the negatively damped oscillation of the system. To avoid the impact of transient changes on the results, the last 1000 data records were taken for the analysis of the oscillation source location.

Due to the large number of cases in the case library, the location results obtained after applying the three methods are also different. Therefore, this article selects some of the typical cases for analysis. The specific oscillation information of typical cases is shown in Table I.

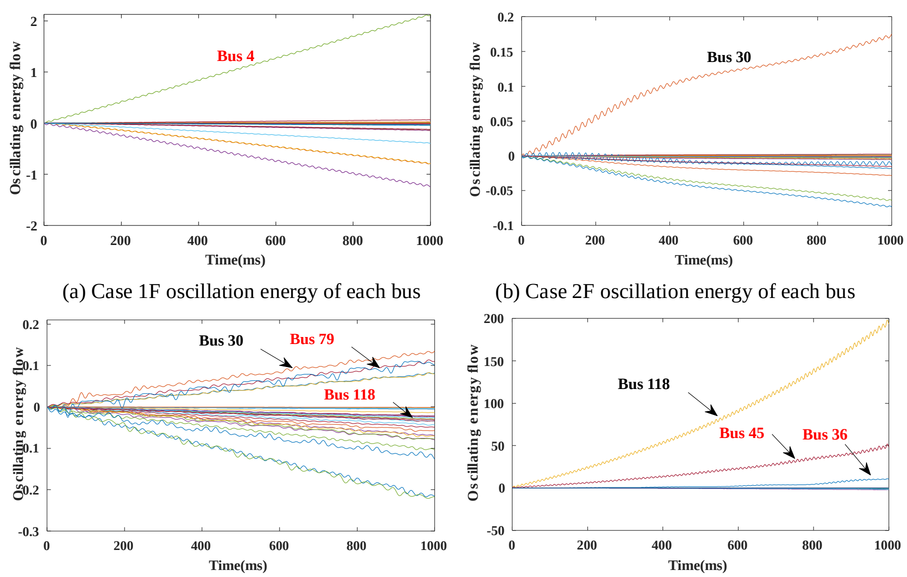
TABLE I
TYPICAL CASE SIMULATION DATA

Type	Oscillation source number	Case name	Signal Frequency /Hz	Oscillation source node
Forced power oscillation	1	Case 1F	0.86Hz	4
		Case 2F	0.86Hz	79
		Case 4F1	0.81Hz	79
	2	Case 7F1	118 bus: 0.43Hz, 79 bus: 0.65Hz	118 and 79
Negatively damped oscillation	1	Case 2ND	0.37Hz(0.02%)	65
		Case 3ND	0.46Hz(2.22%), 0.70Hz(1.15%), 1.63Hz(-0.54%)	11
	2	Case 8ND	1.27Hz(-1.06%), 1.41Hz(-0.22%)	45 and 36

B. Analysis of Three Oscillation Source Location Methods

1) Case analysis of oscillatory energy flow method

Cases 1F, 2F, 7F1, and 8ND are analyzed by the oscillation energy method. Among them, cases 1F, 2F, and 7F1 are forced oscillations; 8ND is a negatively damped oscillation. The oscillation energy of 29 generator buses is calculated, and the oscillation energy diagrams of all the generator buses are made as shown in Fig. 3. Among them, the red label indicates a correctly located oscillation source bus, the black label indicates a located but non-oscillation source bus; the brown label indicates an unlocated oscillation source bus, and the rest are not colored.



(a) Case 1F oscillation energy of each bus (b) Case 2F oscillation energy of each bus

(c) Case 7F1 oscillation energy of each bus (d) Case 8ND oscillation energy of each bus

Fig. 3. Case study of oscillating energy flow

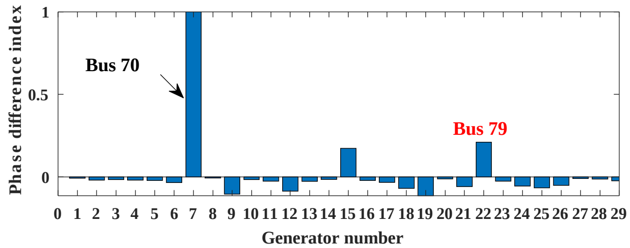
As shown in Fig. 3 (a), the output oscillation energy of bus 4 is positive and continues to increase, indicating that the bus outputs oscillation energy. In general, the bus with the largest slope is the bus that considers inhibiting the oscillation first. When the number of oscillation sources is uncertain, the oscillation source can only be suppressed according to the order of the bus's oscillation energy flow slope. Referring to Table I, it is found that bus 4 is positioned correctly. As seen from Fig. 3 (b), in this case, only one with a slope significantly greater than 0 is the bus 30, so it is judged as the source of oscillation. However, compared with Table I, it is found that the positioning result is wrong. The correct source of oscillation is bus 79. Comparing Fig. 3 (a) and (b), the oscillation energy flow method may determine the non-oscillation source as the oscillation source.

Case 7F1 is a complex oscillation situation with two oscillation sources. As can be seen from Fig. 3 (c), the output oscillation energy of bus 79 is positive and continues to increase, indicating that the bus outputs oscillation energy. However, the output oscillation energy of bus 118 is negative, and it is determined that it is not the oscillation source. In addition, the output of the oscillating energy flow of other buses continues to increase, and the slope is greater than that of bus 79 such as bus 30, which is considered in preference to bus 79. Therefore, this result is a typical second type of misjudgment.

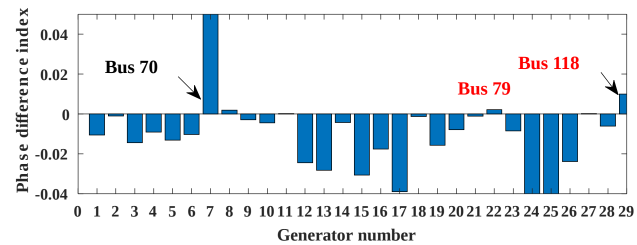
As seen from Fig. 3 (d), although the oscillation energy of the buses 45 and 36 is increased in the negatively damped oscillation, the slopes of the curves at the bus 45 and the bus 36 are respectively ranked second and third. The curve slope of bus 118 is the highest, and it is easier to misjudge it as the source of oscillation.

2) Case Analysis of Oscillation Phase Difference Method

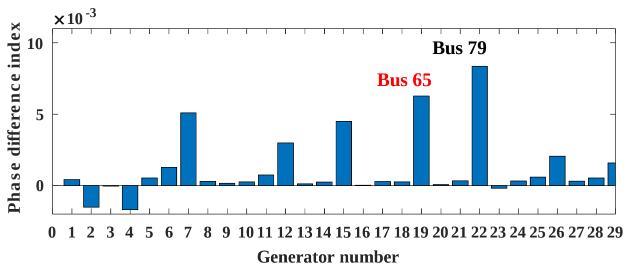
Cases 2F, 7F1, 2ND, and 8ND are analyzed by the oscillating phase method, of which case 2F, 7F1 are forced oscillations; case 2ND, 8ND are negatively damped oscillations. The voltage phase angle difference between the 29 generator buses and the adjacent buses is calculated, and the oscillation phase difference index of the generator buses is shown in Figure 4.



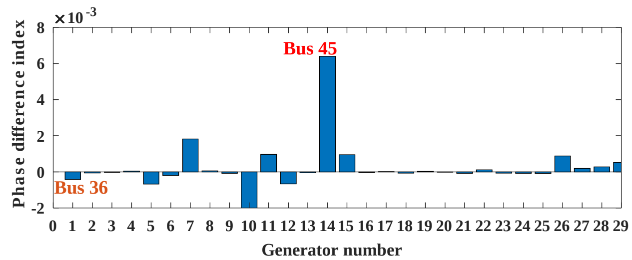
(a) Oscillation phase difference index for case 2F



(b) Oscillation phase difference index for case 7F1



Oscillation phase difference index for case 2ND



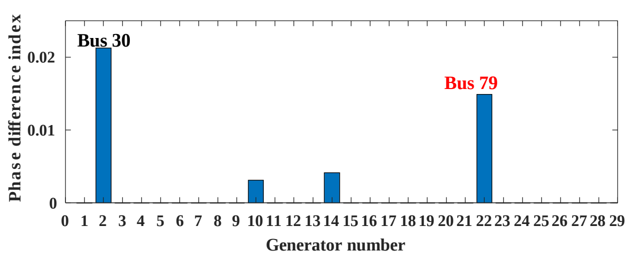
(d) Oscillation phase difference index for case 8ND

Fig. 4 Case analysis of oscillation phase difference method

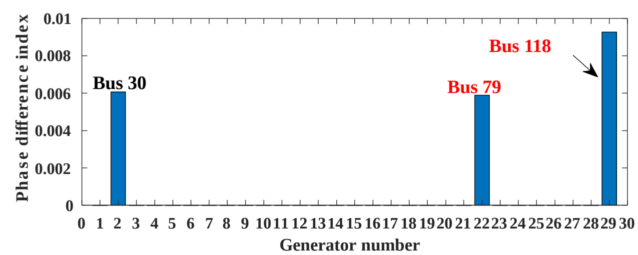
As shown in Fig. 4 (a), the phase difference between the bus 70 and the bus 79 is positive, which meets the determination condition of the oscillating phase difference method. Among them, the phase difference index of bus 70 is greater than bus 79, so it is prioritized in the determination of the oscillation source. However, compared with the source information, bus 79 is the correct source.In Fig. 4 (b), the two oscillation source buses 118 and 79 are effectively located by this method. However, the voltage phase difference index of bus 70 is much higher than others and it is prioritized as the correct oscillation source. In Fig. 4 (c), there are multiple buses with phase differences greater than 0. Bus 79 and bus 65 are the two buses with the highest index, and they are the first to be inhibited. However, bus 79 is not an oscillating source. In Fig. 4 (d), the oscillation phase difference method can only determine bus 45 as a correct oscillation source; for another oscillation source bus 159, it cannot be judged and is marked as brown.

3) Case analysis of forced oscillation phase difference method

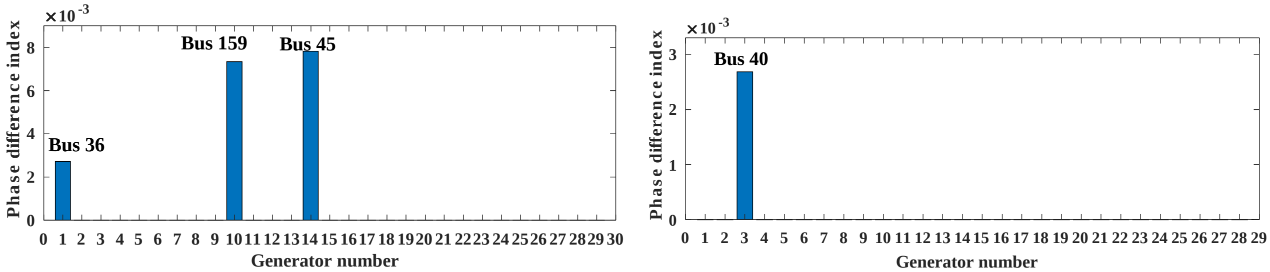
Cases 4F1, 7F1, 3ND, and 8ND are analyzed by the forced oscillation phase method. Among them, cases 4F1, 7F1 are forced oscillations; cases 3ND, 8ND are negatively damped oscillations. In the algorithm, the buses with negative phase difference index are filtered out, and only the generator buses with positive phase difference index are displayed, as shown in Fig. 5.



(a) Forced Oscillation Phase Difference Index for Case 4F1



(b) Forced Oscillation Phase Difference Index for Case 7F1



(c) Forced Oscillation Phase Difference Index for Case 3ND (d) Forced Oscillation Phase Difference Index for Case 8ND

Fig. 5 Case analysis of forced oscillation phase difference method

As shown in Fig. 5 (a), There are 4 buses with a phase difference between electrical power and mechanical power greater than 0. Among them, bus 30 and bus 79 are the two largest buses, and bus 30 is larger than bus 79, which is considered first in the determination of the source of oscillation. However, after comparing with the source information, it is found that bus 79 is the correct source. If the steps of inhibiting the oscillation source are adopted, other adverse effects may be generated in the system, thereby affecting the positioning of the bus 79. In Fig. 5 (b), using the forced oscillation phase difference determination method, both buses 118 and 79 are effectively located. However, the non-oscillating source of bus 30 is incorrectly located, and the phase difference index of bus 30 is slightly larger than bus 79. If the bus is preferentially inhibited, it may interfere with the effective positioning of bus 79. In Fig. 5 (c), the bus 11 as the oscillation source has not been effectively judged, and there is a serious misjudgment problem, indicating that the accuracy of the method for negatively damped oscillation is not high. In Fig. 5 (d), the bus 45 and bus 36 cannot be located by using the forced power oscillation phase difference method. In addition, there will be a misjudgment phenomenon-the bus 40 is misjudged as the source of oscillation.

4) Comparison of three oscillation positioning methods

Three oscillation positioning methods are proceeded to analyze all 29 cases to obtain the positioning results. Comparing the effects of the three methods on each case, the following outstanding issues are summarized:

1) The occurrence of the first type of misjudgment will cause the duration of oscillation to be extended, which will continue to affect the safety of the system. Judging from the judgment results, the first type of misjudgment includes the results of the oscillating energy flow method of case 2F, and the results of the forced power oscillating phase difference method of cases 3ND, 8ND.
2) The occurrence of the second type of misjudgment proves that the current method cannot find the source of oscillation in a short time, and other effective methods need to be adopted. The positioning results of the oscillation energy flow method for cases 7F1 and 8ND are typical second type of misjudgment.
3) The probability of incorrect localization for complex oscillations is extremely high. From the results of the above methods on the location of multi-source oscillations, the results are not very satisfactory.

Through above three categories, all cases of misjudgment are included. Among them, 1) and 2) are summaries of misjudgments for a single oscillation source, and 3) are summaries of misjudgments for double sources. Table II shows the classification of all cases that went wrong.

TABLE II
SUMMARIES OF MISJUDGMENTS ON FORCED POWER OSCILLATION AND NEGATIVELY DAMPED OSCILLATION

Types		Oscillatory energy flow	Oscillating phase difference	Forced oscillation phase difference
Forced power oscillation	The first type	2F,4F1,4F2	3F,6F1	5F3,6F1,6F2,6FM2
	The second type	4F3,6F1,6F2	2F,4F1,4F2,4F3,5F2,6FM2	4F1,4F2
	complex oscillation	7F1,7F2,7FM1	7F1,7F2,7FM1	7F1,7F2,7FM1
Negatively damped oscillation	The first type	\	1ND	1ND,3ND
	the second type	1ND	2ND	\
	complex oscillation	8ND	6ND,7ND,8ND	6ND,7ND,8ND

As shown in Table II, the applicability of the three methods for judgment differs. In the same case, certain methods can detect the source of oscillations, but others cannot. For forced power oscillation, the judgment effect of the three methods is not ideal, and the effect of the oscillation phase difference method is the worst. In addition, there are differences in the errors of various methods. In the same case, some methods can successfully locate the source of oscillation, and some methods cannot. For negatively damped oscillations, the oscillating energy flow method has a better positioning effect, while the oscillating phase difference and the forced oscillating phase difference both misjudge the complex oscillation.

The three methods are substituted into all 29 cases for analysis, and the three buses with the highest probability are used as potential oscillation sources, which are compared with the oscillation source information. The judgment result of one oscillation source by three methods.

TABLE III
JUDGMENT EFFECT OF THREE METHODS OF ONE OSCILLATION SOURCE LOCATION

Positioning method	Accuracy of forced power oscillation (%)	Accuracy of negatively damped oscillations (%)	Accuracy of low-frequency oscillation (%)
Oscillatory energy flow	66.7	100	59.3
Oscillating phase difference	83.3	55.6	40.7
Forced oscillation phase difference	72.2	44.4	48.1

It can be seen from the Table III that the oscillation energy flow method has the best effect on negatively damped oscillations, with an accuracy of 100%, and the worst effect on forced power oscillations; The oscillation phase difference method has the best effect on forced power oscillation, with an accuracy of 83.3%; the forced oscillation phase difference method is only applicable to forced power oscillation, and has the worst effect on negative damped oscillation, with an accuracy of 44.4%. For the complex situation of dual oscillation sources, the applicability of the judgments of the three methods is different. In the same case, some methods can monitor the oscillation source, and some methods cannot.

However, it is impossible to know the type of the oscillation in advance and choose a best method for locating the oscillation source. Therefore, the application scenarios of the oscillation source location method are various types of oscillation. Overall, the effect of the oscillatory energy flow method was the best, at 59.3% accuracy.

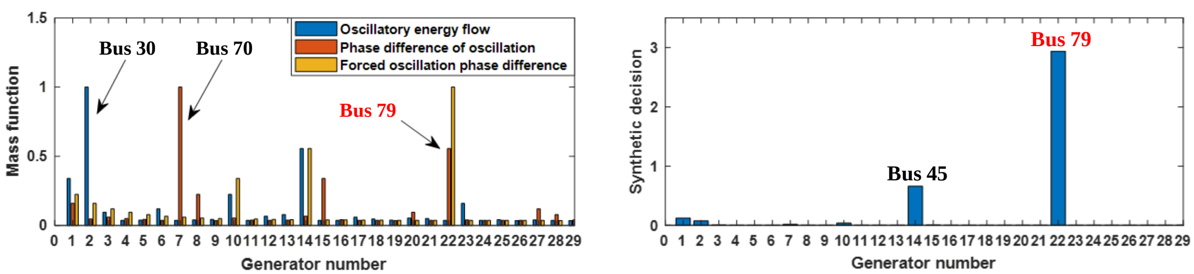
C. *Evidence Theory Modeling and Simulation Analysis*

This part mainly focuses on the three types of misjudgment problems generated by the three methods of locating oscillation sources in part B of Section III. Using the DS evidence theory data fusion model to solve the misjudgment problems that cannot be solved by three traditional positioning methods.

1) *The Solution to The First Type of Misjudgment*

Taking case 2F as an example, using the positioning model based on evidence theory, the quality functions of the three positioning methods are calculated according to (11-13), and then the combined decision is calculated using (14-21), as shown in Figure 6.

When the mass function of a bus is 1, the bus is the most likely source of oscillation It can be seen from Fig. 6(a) that bus 30, 70, and 79 are the most likely bus, because *p_m1*(30)=1, *p_m2*(70)=1, and *p_m3*(79)=1. At the same time, it was found that the mass functions obtained by bus 79 for the oscillating phase difference method and the forced oscillating phase difference method are both high, *p_m2*(79)=0.55 and *p_m3*(79)=1. Although the value of the mass function obtained by the oscillation energy flow method is not high, the probability of it being judged as an oscillation source after D-S evidence theory is therefore increased, P1(79)=2.91. However, for bus 30 and 70, the probability of their results after synthesis rules becomes very small, P1(30)=0.07 and P1(70)=0.017. Therefore, the potential oscillation sources obtained after data fusion are bus 79 and 45, of which bus 79 is the preferred oscillation source bus. After comparing with the information of the oscillation source, it proves that the judgment is correct.



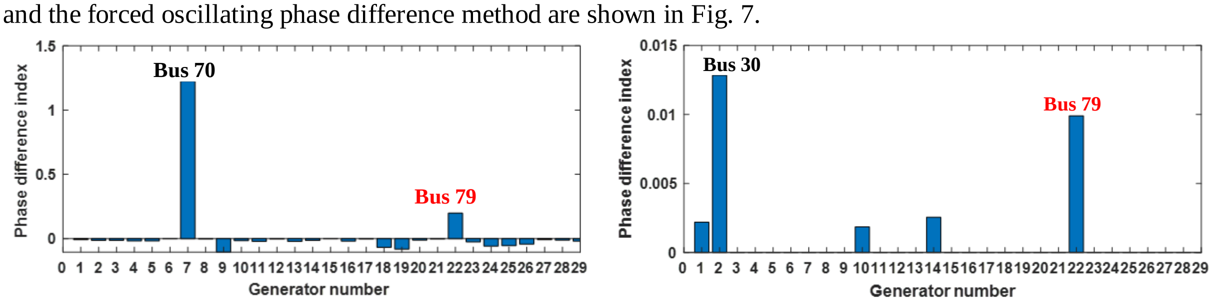
(a) Mass functions of three methods for 29 bus in case 2F (b) Synthesis decision values of 29 bus in case 2F

Fig. 6 Evidence theory positioning results in forced power oscillation case 2F (The bus 79 marked in red is indicated as oscillation source)

Similarly, the first type of misjudgment problems (4F1, 4F2) in the oscillatory energy flow method, (3F) in the oscillatory phase difference method, and (5F3, 6F1, 6F2) in the forced oscillatory phase difference method are determined by evidence theory. After the model, the real oscillation source has been effectively found.

2) *The Solution to The Second Type of Misjudgment*

Taking the forced oscillation 4F2 as an example, the oscillation source is caused by the sinusoidal signal of the excitation system injected into the generator bus 79. The phase difference indexes of each bus obtained by using the oscillating phase difference method and the forced oscillating phase difference method are shown in Fig. 7.

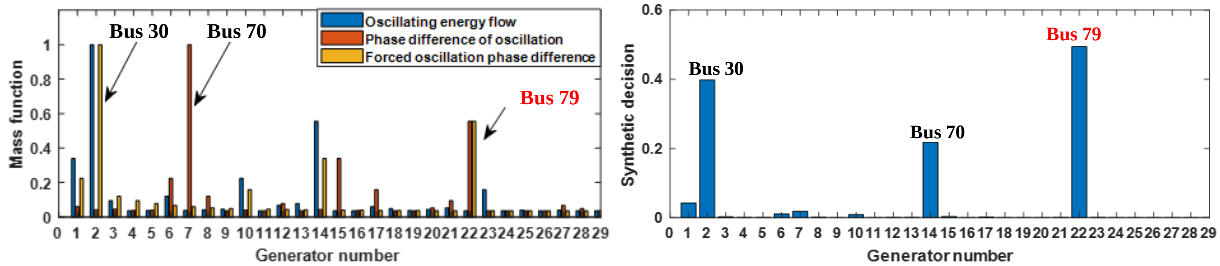


(a) Oscillation phase difference judgment result of case 4F2 (b) Forced power phase difference judgment results of case 4F2

Fig. 7 Two Misjudgments of Forced Power Oscillation Case 4F2 (bus 79 marked in red is the oscillation source)

It can be seen from Fig. 7 that the probability of bus 79 in the oscillating phase difference method is much lower than that of bus 70. Although bus 79 is located as the correct bus, it can still cause the second type of misjudgment problem easily; similarly, the probability of bus 79 in the forced oscillation phase difference method is also smaller than that of bus 30, so it will also cause the second type of misjudgment problem.

The results of the mass function and the composition rule calculated by the evidence theory model are shown in Fig 8.



(a) Mass functions of three methods for 29 bus in case 4F2 (b) Synthesis decision values of 29 bus in case 4F2

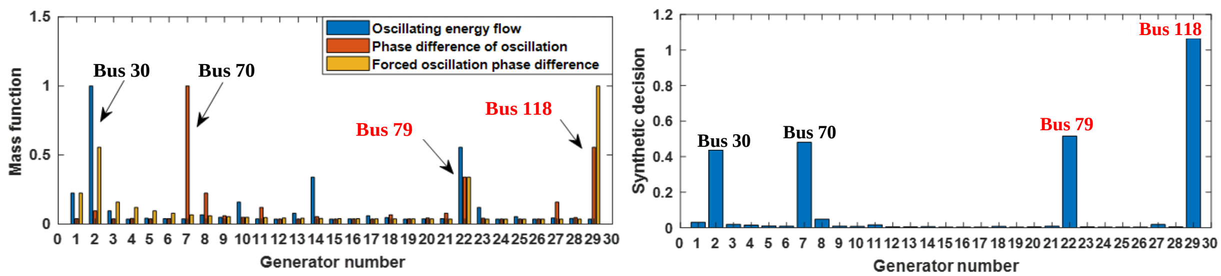
Fig. 8 Evidence theory positioning results in forced power oscillation case 4F2(The bus 79 marked in red is indicated as oscillation source)

It can be seen from the results obtained in Fig. 8 that after the optimization of the evidence theory, bus 79 has the highest synthesis decision value, which is preferentially considered as the oscillation source. The comparison with the information of the oscillation source proves that the judgment is correct.

3) The Solution to The Misjudgment of Complex Oscillation Sources

Taking complex case 7F1 as an example, all three methods of locating oscillation sources have been misjudged or under judged to some extent. Applying the theory of evidence method to this problem, the results of the obtained mass function and synthesis rules are shown in Fig 9.

From the synthesis rule, it can be concluded that bus 118, 79, 70, and 30 are potential sources of oscillation. Bus 118 and 79 are the two bus with the largest synthesis decision value, and the oscillations are inhibited in order according to the probability value. By analyzing data of the oscillation source, we found that the bus 118 and 79 are oscillation sources. This discovery can thus prove the method is effective.



(a) Mass functions of three methods for 29 bus in complex case 7F1 (b) Synthesis decision values of 29 bus in complex case 7F1

Fig. 9 Evidence theory positioning results in forced power oscillation complex case 4F2(The bus 79 and 118 marked in red is indicated as two oscillation sources)

4) Comparison of Overall Effects of Low Frequency Oscillation

It can be found from Table III that different oscillation source positioning algorithms have different effects on forced power oscillations and negative damping oscillations, and there is no method with high judgment accuracy and wide adaptability at the same time. Therefore, under the premise that the type of oscillation is unknown, the accuracy of the localization of the oscillation source becomes lower. Table IV compares the judgment results of the evidence theory and the other three judgment methods for all 27 low-frequency oscillation cases including forced power oscillation, negatively damped oscillation, and complex oscillation.

TABLE IV
Comparison of Oscillation Source Determination Results of Low Frequency Oscillation

Positioning method	judgement result (%)
Oscillatory energy flow	59.3
Oscillating phase difference	40.7
Forced oscillation phase difference	48.1
Evidence theory	70.4

It can be seen from Table IV that based on the evidence theory, the effect of judging the source of low-frequency oscillations is significantly improved. The accuracy of the fusion algorithm is 70.4%, which is higher than other single oscillation source location methods. The positioning of the oscillation source usually needs to first identify the type of oscillation, and then select the appropriate method to locate the oscillation source. The method in this paper has a good positioning effect for forced power oscillation and negative damped oscillation, so it can save the time of oscillation identification and increase the speed of oscillation suppression. At the same time, this method is also better for the complex oscillation of dual oscillation sources.

IV. CONCLUSION

This paper proposes a method for location of oscillation sources based on D-S evidence theory. The results of three different oscillating source localization method are synthesized and generate mass functions based on the measured data of the PMU. The results of the new method are applied to WECC 179-bus power system for verification, and the following conclusions can be drawn from the simulation results. Compared with the traditional three algorithms of low-frequency oscillation source localization, the data fusion evidence theory algorithm can (1) reduce the oscillation source misjudgment, (2) find out all the oscillation source accurately, and gives a reasonable order of the oscillation possibility via the mass function. The novel algorithm can achieve the on-line location of oscillating sources and improve the accuracy of judgment.

V. ACKNOWLEDGMENTS

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