1 Introduction

With the rapid increment in the number of phasor measurement units (PMUs) in the modern power system, many aspects of network dynamic behaviour manifesting as oscillation events have become more observable [1]. These oscillations may be poorly damped natural oscillations or forced due to repetitive network activity commonly termed as sustained oscillation which may pose a threat to the overall power system security [2].

In general, sustained oscillation can persist in the system because of (i) high gain-exciters or heavily loaded transmission lines [3, 4], (ii) emergence of supercritical Hopf bifurcation such as limit cycles in the system [5, 6], and (iii) external periodic disturbance such as modulated automatic voltage regulator (AVR) and turbine reference [7–9]. Natural sustained oscillation may be removed by increasing damping in the system, whereas to remove forced oscillation (FO), it is necessary to locate and remove the source of disturbance [10]. Methods have been proposed to detect the presence of FO in the system [11–13]. However, locating the source is more complicated and is the subject of this current work.

Different methods reported in the literature to locate the source of FO are based on the traveling waves [14], mode shape analysis [15], identifying transfer function [16], quantifying the magnitude of induced torque [17] energy-based technique [3] etc. The abovementioned techniques have some limitations as reported in [18]. For example, the traveling wave-based method usually requires expensive measurement and computational infrastructure, and also assume constant wave propagation speeds throughout the network. Location of the source of disturbance using mode shape analysis may not always yield accurate results for large systems with complicated dynamic behaviour [18]. Locating the source of disturbance using damping torque method involves measurement of generator electromagnetic torque, speed, and rotor-angle, which remains a challenge [19]. Energy-based techniques locate the source of disturbance is located by tracing the flow of the oscillating energy for the branch connecting a generator to the system. This method, however, indicates only the largest negative damping torque technique to locate the source of FO is discussed in Section 4. In Section 5, the proposed technique is shown in [22] for simple cases and some detailed and complicated cases with different load models are considered in this paper to show the efficiency of the proposed technique.

The rest of the paper is organised as follows. In Section 2, the preliminary concepts to locate the source of FO are discussed, whereas in Section 3, the proposed algorithm is presented and benchmarked against other methods reported in the literature. The effect of available system damping on the response of the system to FO is discussed in Section 4. In Section 5, the proposed technique is tested for different scenarios and Section 6 concludes the paper. A symbol ‘M’ is used in the figures throughout the paper to indicate the machine number.

2 Forced oscillation source location in power systems – preliminary concepts

It is stated and proved in [3] that dissipating energy gives a consistent result with damping torque technique to locate the source of oscillation. It is proposed in the current work that the dissipating energy injecting by a machine into the system can be calculated using the network and the load information and to prove a simplified two machine test system is taken as shown in Fig. 1. The total energy stored in the system is mainly distributed among generators, network components and loads. Mathematically
\[ E_i = E_G + E_N + E_L = K. \]  

(1)

where \( E_i \), \( E_G \), \( E_N \), \( E_L \) are total energy of the system, energy stored in the generators, network and the loads, respectively. Total energy of an undisturbed system is constant. Energy, \( E_{\text{Dis}} \), can be assumed to enter in the system during an external disturbance written as

\[ E_i = E_G + E_{Nw} + E_L = K + E_{\text{Dis}}. \]  

(2)

In terms of the deviation from the initial steady-state value, (2) becomes

\[ \Delta E_i = \Delta E_G + \Delta E_{Nw} + \Delta E_L = E_{\text{Dis}}. \]  

(3)

When the disturbance is removed then deviation in energy subsides with time (i.e. \( \Delta E_i \to 0 \)) if the network structure is unchanged and enough damping is present in the system. However, in the case of a periodic forced disturbance, the system keeps oscillating with the frequency same as that of the disturbance. It means in the presence of forced disturbance at a machine (say machine 1 of Fig. 1) (3) can be written as

\[ \Delta E_{G1} + \Delta E_{G2} + \Delta E_{Nw_{1-2}} + \Delta E_{L1} + \Delta E_{L2} = E_{\text{Dis}}. \]  

(4)

Incorporating load information in the reduced bus matrix, (4) can be written as

\[ \Delta E_{G1} + \Delta E_{Nw_{1-2}} + \Delta E_{G2} = E_{\text{Dis}}. \]  

(5)

Rearranging the terms of (5), it can be written as

\[ \Delta E_{Nw_{1-2}} = E_{\text{Dis}} - \Delta E_{G1} - \Delta E_{G2}. \]  

(6)

Since energy is a scalar quantity, hence for \( 0 \leq \alpha \leq 1 \)

\[ -\alpha \Delta E_{G1} = E_{\text{Dis}} - \Delta E_{G1} = \alpha \Delta E_{Nw_{1-2}} \]  

and

\[ -\Delta E_{G2} = (1-\alpha)\Delta E_{Nw_{1-2}}. \]  

(7)

The energy of a generator can be written as

\[ \Delta E_{G,i} = \Delta E_{G,\text{ax}} + \Delta E_{G,\text{ay}}, \]  

(8)

where \( E_{G,\text{ax}} \), \( E_{G,\text{ay}} \) are the kinetic energy and potential energy stored in generator, respectively [23, 24]. Hence (7) can be written as

\[ \alpha \Delta E_{Nw_{1-2}} = - (\Delta E_{G,\text{ax}} + \Delta E_{G,\text{ay}}), \]  

(9a)

\[ (1-\alpha)\Delta E_{Nw_{1-2}} = - (\Delta E_{G,\text{ax}} + \Delta E_{G,\text{ay}}). \]  

(9b)

The left-hand side of (9) may be considered as the contribution of the individual generator to a disturbance. If the calculated value of dissipating energy at a generator bus decreases monotonically with time, it implies the energy contribution from that generator to the system is positive and hence the machine is the source of the disturbance. Since the calculation of the dissipation energy contribution, (9), includes the network and load information, changes in the network structure during a disturbance does not affect the accuracy of the technique.

3 Forced oscillation source location in power systems – algorithm development

3.1 Algorithm development

As explained in Section 2 that energy contribution from a generator can be used to locate the source of disturbance and that may be computed as follows. Kirchoff’s current law for ‘n’ bus power system network can be written as

\[ YV_b - I_G + I_L = 0, \]  

(10)

where \( V_b \), \( Y \), \( I_G \) and \( I_L \) are bus voltages, admittance matrix, current injection from generators and currents drawn by loads, respectively, in phasor form. Kirchoff’s current law is valid at any point of time on the system trajectory, and thus taking a complex integral of (10)

\[ \int_{t=0}^{t=T} [(YV_b - I_G + I_L)^T] dV_b = 0, \]  

(11)

where ‘*’ represents the complex conjugate. Equation (11) may be written in summation form as (12), where \( Y_{pq}, V_{Bq} \), \( I_{Gp} \), \( I_{Lp} \) are complex variables with \( Y_{pq} = G_{pq} + jB_{pq} \) are \( Y_{pq} = Y_{pq} e^{j\phi_{pq}}, V_{Bq} = V_{Bq} e^{j\theta_{Bq}} \) and \( I_{Gp} = I_{Gp} e^{j\theta_{Gp}} \).

Here, ‘p’ and ‘q’ are bus numbers. The complex integral (12) can be divided in two types of energy functions: one consists of a real part [25] and another consist of an imaginary part [26]

\[ \int_{t=0}^{t=T} \sum_{p=1}^{n_b} \sum_{q=1}^{n_b} Y_{pq}^* V_{Bq}^* dV_b = \sum_{p=1}^{n_b} I_{Gp}^* dV_b + \sum_{p=1}^{n_b} I_{Lp}^* dV_b = 0. \]  

(12)

\[ \int_{t=0}^{t=T} \sum_{p=1}^{n_b} \sum_{q=1}^{n_b} Y_{pq}^* V_{Bq}^* dV_b = \sum_{p=1}^{n_b} I_{Gp}^* dV_b + \sum_{p=1}^{n_b} I_{Lp}^* dV_b = 0. \]  

(13)

The imaginary part (13) is used in the paper to derive the expression to locate the source of oscillation. Examining (13) it can be said that the total energy of the power system is distributed among three terms as in (14)

\[ TE = E_{NT} + E_{LT} + E_{GT} = K\left(\eta_{b}, \delta_{b}, \theta_{b}, V_{Bb}\right). \]  

(14)

where \( TE \) is the system total energy, \( E_{NT}, E_{LT} \) and \( E_{GT} \) is the energy contribution of network components, loads and generators, respectively, and \( K \) is the initial energy at the operating point of the power system. These are further elaborated in (15)–(17) [25]. Here \( \eta_{b}, \delta_{b}, \theta_{b}, V_{Bb} \) is the number of total buses, generator buses and load buses, respectively. As discussed in Section 2, energy contribution of a generator during a disturbance, (18), can be analysed by combining energy due to network (15) and load components (16).

It is assumed in this paper that the source of disturbance is a generator. Therefore, after converting all loads to impedances and applying Kron reduction to preserve only the generator buses (18) is written as (19). Here, \( Y_{pq,\text{ad}} = B_{pq,\text{ad}} + B_{pq,\text{ad}}^{\text{ad},\text{ad}} \) is the admittance matrix for the reduced network.

In (19), there are both path-dependent (within integral) and path-independent (outside integrals) terms. Path-dependent terms are responsible for dissipation/production of energy in the system, whereas path-independent terms are oscillating in nature. As stated in [3] that locating the source of disturbance using dissipating part of the energy flow is consistent with the damping torque method. Hence, dissipating energy of the total energy, (19), (path-dependent terms-(20)) is analysed further to locate the source of disturbance. Taking deviation from the steady state of each variable in (20),
individual generator damping may be calculated from (21). As discussed in Section 2, it can be said that the generators with negative dissipating energy are the sources of the disturbance. Derivative of \( E_{d_{\alpha\beta}} \) gives the power of the injecting energy at the generator terminal and that can be given as (22).

Generator providing damping to a disturbance depends on damping providing by the machine itself and damping due to its interaction with the rest of the network as shown in [27] where damping provided by a machine is reduced due to the network effect. Hence, network and load information need to be considered while calculating dissipating energy injecting by a machine into the system. Most of the techniques reported in the literature to locate the source of disturbance considers only the energy provided by the generator without incorporating the network or the load information. In the proposed technique dissipating energy provided by the generator is calculated by including the network and the load dynamics which are updated at regular interval. The dissipating energy calculated at the generator terminal using (21) consists of two terms \(-\sum_{p=1}^{n_q} E_{\alpha\beta}(\Delta q_p, \Delta V_p) \Delta \alpha_i + \sum_{q=1}^{n_q} E_{\alpha\beta}(\Delta q_p, \Delta V_p) \Delta \alpha_i\). The first and second terms refer to the dissipating energy due to self-conductance of the machine and the mutual conductance between the machine and the network, respectively. Thus, the interaction between a machine and network is taken into account to locate the source of disturbance, which results in locating all the sources successfully.

### 3.2 Impact of load model on the algorithm

During the formation of the reduced admittance matrix, the load is considered as CI, as per established practice due to its simplicity in application with little error in the result. As reported in the literature, transfer conductance present in an energy function is omitted to make the function

\[
E_{\alpha\beta} = \sum_{p=1}^{n_q} \left[ -a_i - \sum_{q=1}^{n_q} B_{pq} \bar{b}_i \right] + \sum_{q=1}^{n_q} c_{i\alpha\beta} \bar{d}_\beta_i \Delta \alpha_i \
+ \frac{1}{2} \sum_{q=1}^{n_q} G_{pq} \int_{0}^{\alpha_q} V_{q\beta} \Delta \alpha_i, \tag{15}
\]

\[
E_{\alpha\beta} = \sum_{p=1}^{n_q} P_{i\alpha\beta} \Delta \alpha_i \Delta \beta_i + \frac{1}{2} \sum_{q=1}^{n_q} \sum_{r=1}^{n_q} G_{pq} \int_{0}^{\alpha_q} V_{q\alpha_i} \Delta \alpha_i \Delta \beta_i \
+ \sum_{q=1}^{n_q} \int_{0}^{\alpha_q} \int_{0}^{\alpha_q} V_{q\alpha_i} \Delta \alpha_i \Delta \beta_i, \tag{16}
\]

\[
E_{\alpha\beta} = \sum_{p=1}^{n_q} P_{i\alpha\beta} \Delta \alpha_i \Delta \beta_i + \frac{1}{2} \sum_{q=1}^{n_q} \sum_{r=1}^{n_q} G_{pq} \int_{0}^{\alpha_q} V_{q\alpha_i} \Delta \alpha_i \Delta \beta_i \
+ \sum_{q=1}^{n_q} \int_{0}^{\alpha_q} \int_{0}^{\alpha_q} V_{q\alpha_i} \Delta \alpha_i \Delta \beta_i, \tag{17}
\]

(see (18)) where

\[
\frac{\partial E_{\alpha\beta}}{\partial \alpha_i} = \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\alpha_i} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\alpha_i} \Delta \alpha_i \
+ \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i,
\]

\[
\frac{\partial E_{\alpha\beta}}{\partial \beta_i} = b_i \Delta \alpha_i \Delta \beta_i + \frac{1}{2} B_{pq} V_{q\alpha_i} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i,
\]

\[
\frac{\partial E_{\alpha\beta}}{\partial \alpha_i} = \frac{1}{2} B_{pq} V_{q\alpha_i} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i,
\]

\[
\frac{\partial E_{\alpha\beta}}{\partial \beta_i} = b_i \Delta \alpha_i \Delta \beta_i + \frac{1}{2} B_{pq} V_{q\alpha_i} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i + \frac{1}{2} B_{pq} V_{q\beta} \Delta \alpha_i.
\]
disturbance. In the current work, the dissipating energy for each generator is computed using (21). This formulation of dissipating energy allows the accounting of the interaction between various generators in a multi-machine network to determine individual generator damping, as stressed in [27].

In order to demonstrate the effect of considering dissipating energy from the network, the test system of Fig. 1 is used (details in Appendix). An external disturbance was applied to the system at 2 s by modulating the generator 1 AVR reference input with a periodic disturbance of magnitude 0.01 pu and frequency 0.4 Hz. The dissipating energy flowing into the generator calculated as per (21) is shown in Fig. 2a, while that calculated per (21) is shown in Fig. 2b. It can be seen that the successive minima increases in the negative direction for machine 1 but increases in positive direction for machine 2, suggesting that machine 1 is the source of the disturbance [3]. Hence the proposed method is able to locate the source of disturbance accurately. These two methods are compared for a complicated situation as explained in Section 5.6.

4 Impact of system damping and forced oscillation frequency

The response of a power system in the presence of FO also depends on the available damping in the system in addition to the frequency of the FO [9]. The test system of Fig. 1 was used to investigate the effectiveness of the proposed technique in the presence of different system damping. The system exhibits simple dynamics, i.e. only one electromechanical mode exists apart from the mode due to the FO with magnitude 0.01 pu and frequency 0.2 Hz applied on machine 1. Systems considered are Case 1: well damped [individually tuned power system stabilisers (PSS) were deployed on both machines to obtain an interarea mode of 0.786 Hz with damping 13.04% [30]. All natural modes decay quickly and only the forced component remains]. Case 2: weakly damped (for this case, the gain of both PSS were readjusted to change the interarea mode frequency of the system to 0.729 Hz with damping 1.6%).

In both cases (Fig. 3), the disturbance locator method is able to clearly identify the source of the oscillations. However, the distinction is amplified by the absence of adequate damping (as in Case 2).

Locating the source of disturbance when the frequency of the FO equal to one of the system natural modes remains a challenge. The reason is that when the frequency of the external disturbance comes close to the natural mode (especially interarea mode), the system response is dominated by the natural mode itself and the machine which has highest participation factor for that mode, and thus the significance of the FO is lost.

5 Results and discussion

The proposed method to locate the source of the disturbance was tested for different cases different test systems – Kundur test system [30] and New England (NEW) test system [23] and measurements from IEEE Task Force on Oscillation Source Location.

5.1 Single source of disturbance

The AVR reference of generator number 2 of the Kundur test system [30] was modulated as \( V_{avr} = V_{ref} + 0.01 \sin(0.4\pi t) \) from 2–5 s. The speed of all machines for this disturbance is shown in Fig. 4a. The dissipating energy was computed for every generator as shown in Fig. 4a. Generator 2 was clearly identified as the source as its dissipating energy is in the negative direction (Section 2). It is stressed here that from inspection of Fig. 4a, it may be possible to identify the source but not the duration of the disturbance. Further, if measurements are not available at the time of the initiation of the disturbance, this inspection may fail to identify the source. From this technique, the time duration of the applied disturbance (2–5 s) is also identifiable from the monotonic dip in the dissipating energy. It can be stressed from Fig. 4b that longer the duration of the disturbance, dip in the negative direction and hence if dissipating energy is approximated with the straight line then higher will be the slope in the negative direction [31]. The initial rise in the curves of Fig. 4b is because of the temporary emergence of the other natural modes which subsequently die out quickly and the response evolves with characteristics that of the FO [9].

Similar disturbances were applied on the other machines, and the resultant slope of the dissipating energy for different machines are tabulated in Table 1. The slope was calculated for 2 s corresponding to the typical refresh rate of SCADA measurements. It can be seen from Table 1 that the proposed method is able to locate the disturbance creating generators. It can be seen from Table 1 that slope is highest (negatively) for machine 2 followed by machine 4. This is expected since these machines are connected to the system with long transmission lines and hence disturbance at these machines has more impact on the system.

Periodic FO was also applied on the NEW test system [23] wherein the turbine power reference of generator number 3 was modulated with a 0.3 Hz periodic disturbance of amplitude 0.01 for 2.5–5.5 s. Fig. 5a shows the resultant machine speeds. The dissipating energy is shown for all the machines in Fig. 5b wherein generator 3 exhibits negative dissipation energy indicating that it is the source of the disturbance. The approximate duration of the application of disturbance is also clear from the monotonic dip of the dissipation energy. Table 2 summarises the effectiveness of the proposed technique to locate the source of disturbance (in the form of modulation of AVR reference) from the negative slope for machine causing a disturbance in the system. It can be seen from Table 2 that slope for machine 10 is highest (negatively) followed by 9 which means the impact of disturbance is highest at machine 10 and is expected since machine 10 is equivalent machine.
followed by machine 9 which is connected to the system through a long transmission line. Hence disturbance at these generators create severe impacts in the system.

5.2 Multiple and simultaneous sources of disturbance

As indicated in [20], methods reported in the literature may fail to locate all source of disturbance in a system. The task to locate all source of disturbance in presence of multiple disturbing element is tested for NEW test system. A periodic disturbance was applied to AVR reference of machines 4 and 6 of NEW test system in sinusoidal form as $0.01 \sin(0.4 \pi t)$ and $0.02 \sin(0.5 \pi t)$, respectively, for 1–3 s. It can be seen from Fig. 6b that dissipating energy for machine 2 and 6 is going in the negative direction at 1 s for the time duration of 1–3 s implicating them as the source of disturbance. The accurate indication of the exact time duration of the presence of FO depends on the relative magnitude of the applied disturbances. Improving this accuracy remains an open problem.

5.3 Multiple sources – different time of application

A complicated scenario where multiple sources of disturbances exists with different time interval is tested. The scenario is created by modulating AVR reference of machine 4 and 6 of NEW test system with $0.01 \sin(0.6 \pi t)$ and $0.02 \sin(0.8 \pi t)$, respectively, for 2–5 s, whereas of machine 1 and 3 with $0.01 \sin(0.5 \pi t)$ and $0.01 \sin(0.8 \pi t)$, respectively, for 6–10 s. Each machine's speed for the case is shown in Fig. 7a, and the calculated dissipating energy for the same is shown in Fig. 7b. It is difficult to tell the time interval and the source of FO from the machine speed, Fig. 7a. The dissipation energy is calculated for the scenario and it can be seen from Fig. 7b that dissipating energy starts to dip in the negative direction for machines 2 and 6 at 2 s for duration 2–5 s indicating them as the disturbing element and for 6–10 s machines 1 and 3 starts to go in the negative direction implicating them as the source of disturbance for that duration. Dissipating energy for the rest of the machine is in the rising direction. It means that the proposed method locates all source of disturbance with the specified time interval effectively.

The technique discussed in [3] is tested for this complicated scenario and it can be seen from Fig. 8 that only for third and sixth machine successive minima is increasing in the positive direction indicating them as the source of oscillation for the time duration of 2–5 and 6–10 s, respectively, whereas for the rest of the machine, this increment is in the negative direction including the first and the fourth machine for which dissipating energy is rising initially in the positive direction. It can be said that the technique reported in the [3] sometimes may not locate all source of disturbance in a complicated scenario as also mentioned in [18, 20].

5.4 Test case reported by IEEE PES task force on oscillation source location

The proposed method was tested and verified on different test cases reported by IEEE PES Task Force on Oscillation Source Location [21]. These cases were simulated on PSS/E platform with CP loads [32]. A typical case (F_1) is discussed here, which involves modulating the AVR reference of generator 4 with a frequency of 0.86 Hz. The gain of the periodic disturbance was kept such that it created an oscillation in active power output of all generators of 157 MW peak to peak. The dissipating energy of all generators was calculated using (21) were reduced admittance matrix was approximated to a linear curve for visual impact, shown in Fig. 9, [31]. It can be seen from Fig. 8 that for the fourth generator dissipating energy is in the negative direction and for rest of the machines it is in the positive direction indicating the source of disturbance is fourth generator only. Point to be noted in this case is that time domain simulation was done considering CP load whereas dissipating energy is calculated considering CI load and this does not affect the accuracy to locate the source.
5.5 Impact of load uncertainty

Load model: As discussed in Section 3.2, the error in the identification of the source of disturbance due to inaccurate load modeling. Specifically, the load model (CI, CP, CC or ZIP) used in the time domain simulation to produce the PMU measurements may not match the load model considered while calculating the dissipating energy of each generator (always CI) and even then the error introduced to locate the source is mild. To verify this assertion, the test system of [30] was simulated on the RTDS with all loads modelled as CC, CI CP, or ZIP. The composition of the ZIP load model was considered as CI (20%), CC (40%) and CP (40%). The AVR reference of machine 1 was modulated with a 0.5 Hz periodic disturbance of amplitude 0.01. As shown in Table 3, a negative sign of the slope for the linearly approximated generator dissipating energy curve indicates it to be the source of the disturbance. It can be seen from Table 3 the source is clearly identified without any ambiguity for all cases.

Further, it has already been established in the literature that the stability margin for CP loads are usually the least, followed by CC and CI type loads for any particular operating condition and disturbance. This is corroborated by the results of Table 3, where the magnitude of the negative slopes for the dissipating energy of generator 1, show a similar pattern. The greater the slope in the negative direction, the more disturbed is the system due to the source.

Random variation in load: A challenge to the successful application of the proposed technique lies in the continuous and unpredictable load variations during the period of observation. The efficiency of the proposed method to locate the source of the disturbance was tested for a scenario when the loads (on buses 7 and 9) of Kundur test system [30] was varied with a Gaussian distribution of different standard deviations. Loads were modelled as CP (50%) and CC (50%), while the dissipating energy of each generator calculated considering CI loads. The same disturbance of

**Table 2** Slopes of individual machine dissipating energy for disturbances applied to different machines – NEW

| Disturbed machine | Slope @1 and 2 | Slope @3 and 4 | Slope @5 and 6 | Slope @7 and 8 | Slope @9 and 10 |
|-------------------|----------------|----------------|----------------|----------------|----------------|
| 1                 | -0.0310.003    | 0.0030.003     | 0.0030.003     | 0.0030.003     | 0.0030.003     |
| 2                 | 0.0010.016     | 0.0010.001     | 0.0020.001     | 0.0020.001     | 0.0010.001     |
| 3                 | 0.0030.002     | -0.0310.003    | 0.0030.003     | 0.0030.003     | 0.0030.003     |
| 4                 | 0.0120.012     | 0.0120.102     | 0.0040.009     | 0.120.012      | 0.0120.103     |
| 5                 | 0.0020.002     | 0.0020.002     | -0.0130.001    | 0.0100.002     | 0.0010.002     |
| 6                 | 0.0320.032     | 0.0320.029     | 0.0310.276     | 0.0230.032     | 0.0310.003     |
| 7                 | 0.0180.018     | 0.0180.016     | 0.0170.001     | -0.1430.018    | 0.0170.018     |
| 8                 | 0.0080.010     | 0.0100.011     | 0.0110.001     | 0.0100.010     | 0.0090.001     |
| 9                 | 0.1180.120     | 0.1200.118     | 0.1190.118     | 0.1190.115     | -1.0680.118    |
| 10                | 0.1320.133     | 0.1340.136     | 0.1370.136     | 0.1370.135     | 0.137-1.221    |

Bold values represents source of forced oscillation.
Table 3  Slopes of individual machine dissipating energy for disturbances applied at generator 1 considering different load models – Kundur test system

| All loads modelled | Slope @1 Slope @2 Slope @3 Slope @4 |
|-------------------|--------------------------------------|
| CI                | -1.94 0.66 0.64 0.64 |
| CC                | -7.45 2.54 2.45 2.09 |
| CP                | -9.15 3.10 3.02 3.02 |
| ZIP               | -6.21 2.03 2.09 2.45 |

Bold values represent source of forced oscillation.

Fig. 9  Dissipating energy curve for all machines for the test case F_1 reported by IEEE PES task force on oscillation source location

Fig. 10  Dissipating energy curve for all machines of Kundur test system with a random variation of standard deviation
(a) 0.5, (b) 2.8 with Case 1 – without network information updating and Case 2 – with network information updating

6 Conclusion

In this paper, the source of an external periodic disturbance leading to FOs in the connected power system is located using the measured energy dissipated at individual generator terminals. The proposed method shows promising results, which have been further related to the available modal damping of the power system due to the application of the disturbance. The proposed technique has been tested and verified for various scenarios such as the presence of multiple sources of oscillation, random variation in loads as well as in system with varying modal damping. The formulation allows incorporating changing load and/or network information as soon as they are available from SCADA.

7 References

[1] Ghorbaniparvar, M.: ‘Survey on forced oscillations in power system’, J. Mod. Power Syst. Clean Energy, 2017, 5, pp. 671–682.
[2] Zhang, Q.F., Luo, X., Litvinov, E., et al.: ‘Advanced grid event analysis at ISO New Eng land using PhasorPoint’. 2014 IEEE PES General Meeting | Conf. & Exposition’, 2014, pp. 1–5.
[3] Chen, L., Min, Y., Hu, W.: ‘An energy-based method for location of power system oscillation source’, IEEE Trans. Power Syst., 2013, 28, (2), pp. 828–836.
[4] Ma, J., Zhang, P., Fu, H., et al.: ‘Application of phasor measurement unit on locating disturbance source for low-frequency oscillation’, IEEE Trans. Smart Grid, 2010, 1, (3), pp. 340–346.
[5] Ajarapu, V., Lee, B.: ‘Bifurcation theory and its application to nonlinear dynamical phenomena in an electrical power system’, IEEE Trans. Power Syst., 1992, 7, (1), pp. 424–431.
[6] Alberto, L.F.C., Chiang, H.D.: ‘Characterization of stability region for general autonomous nonlinear dynamical systems’, IEEE Trans. Autom. Control, 2012, 57, (6), pp. 1564–1569.
[7] Magdy, M.A., Coowar, F.: ‘Frequency domain analysis of power system forced oscillations’, IEE Proc. C Gener. Transm. Distrib., 1990, 137, (4), pp. 261–268.
[8] Rostamkolai, N., Pwko, R.J., Matsuk, A.S.: ‘Evaluation of the impact of a large cyclic load on the LILCO power system using time simulation and frequency domain techniques’, IEEE Trans. Power Syst., 1994, 9, (3), pp. 1411–1416.
[9] Ye, H., Liu, Y., Zhang, P., et al.: ‘Analysis and detection of forced oscillation in power system’, IEEE Trans. Power Syst., 2017, 32, (2), pp. 1149-1160.
[10] Li, Y., Huang, Y., Liu, J., et al.: ‘Power system oscillation source location based on damping torque analysis’, Power Syst. Prot. Control, 2015, 43, (14), pp. 84–91.
[11] Ghorbaniparvar, M., Zhou, N., Li, X., et al.: ‘A forecasting-residual spectrum analysis method for distinguishing forced and natural oscillations’, IEEE Trans. Smart Grid, 2015, 6, (1), pp. 1–1.
[12] Zhou, N., Dagle, J.: ‘Initial results in using a self-coherence method for detecting sustained oscillations’, IEEE Trans. Power Syst., 2015, 30, (1), pp. 522–530.
[13] Wang, X., Turitsyn, K.: ‘Data-driven diagnostics of mechanism and source of sustained oscillations’, IEEE Trans. Power Syst., 2016, 31, (5), pp. 4036–4046.
[14] Geng Zhang, T., Xiang, Z., Bao, L., et al.: ‘A locating and splitting scheme for disturbance source of forced power oscillation based on the propagation characteristic’, Power Syst. Prot. Control, 2015, 43, pp. 98–103.
[15] Myers, R.B., Trudnowski, D.J.: ‘Effects of forced oscillations on spectral-based mode-shape estimation’. IEEE Power and Energy Society General Meeting’, 2013.
[16] Zhou, N., Ghorbaniparvar, M., Akhlaghi, S.: ‘Locating sources of forced oscillations using transfer functions’. 2017 IEEE Power and Energy Conf. at Illinois (PECI) IEEE, 2017, pp. 1–8.
[17] Xie, R., Trudnowski, D.: ‘Comparison of methods for locating and quantifying turbine-induced forced-oscillations’. 2017 IEEE Power & Energy Society General Meeting IEEE, 2017, pp. 1–5.
[18] Wang, B., Sun, K.: ‘Location methods of oscillation sources in power systems: a survey’, J. Mod. Power Syst. Clean Energy, 2017, 5, pp. 151–159.
[19] Sarmadi, S.A.N., Venkatasubramanian, V.: ‘Inter-area resonance in power systems from forced oscillations’, IEEE Trans. Power Syst., 2016, 31, (1), pp. 378–388

[20] Maslennikov, S., Wang, B., Zhang, Q., et al.: ‘A test cases library for methods locating the sources of sustained oscillations’. IEEE Power and Energy Society General Meeting, 2016

[21] ‘IEEE PES TF on Oscillation Source Location’, http://web.eecs.utk.edu/~kaisun/TF/index.html, accessed July 2018

[22] Jha, R.: ‘Locating the source of forced oscillation in power systems using system oscillating energy’. 2018 8th IEEE India Int. Conf. Power Electron., 2018, (1), pp. 1–6

[23] Pai, M.A.: ‘Energy function analysis for power system stability’ (Kluwer Academic Publishers, New York City, 1989)

[24] Bhui, P., Senroy, N.: ‘Real-time prediction and control of transient stability using transient energy function’, IEEE Trans. Power Syst., 2017, 32, (2), pp. 923–934

[25] Moon, Y.-H., Cho, B.-H., Lee, Y.-H., et al.: ‘Second-kind energy function of power system and its applications’. 2001 Power Eng. Soc. Summer Meet. Conf. Proceeding, 2001

[26] Moon, Y.-H., Ryu, H.-S., Cho, B.-H., et al.: ‘Energy conservation law and its application for the direct energy method of power system stability’. IEEE Power Engineering Society General Meeting, 1999, pp. 695–700

[27] Kettner, A.M., Paolone, M.: ‘On the properties of the power systems nodal admittance matrix’, IEEE Trans. Power Syst., 2018, 33, (1), pp. 1130–1131

[28] Al-Ashwal, N., Wilson, D.H., Parashar, M.: ‘Identifying sources of oscillations using wide area measurements’. Grid of the Future Symp., 2014

[29] Chevalier, S.C., Vorobev, P., Turitsyn, K.: ‘Using effective generator impedance for forced oscillation source location’, IEEE Trans. Power Syst., 2018, 33, (6), pp. 6264–6277

7 Appendix

Machine parameter for two machine test system:

\[
X_d = 1.8, X_q = 1.7, X_I = 0.2, \\
X'_d = 0.3, X'_q = 0.55, X''_d = 0.25 \\
X''_q = 0.25, R_I = 0.0025, T'_d0 = 8.0, \\
T'_q0 = 0.4, T''_d0 = 0.03 \\
T''_q0 = 0.05, H_I = 6.5s, H_d = 24.5s, R \\
+ j X of each line = 0.0001 \\
+ 0.001 pu/km, R, of each line = 0.000175 pu/km.
\]

\[
X_{Tr1} = X_{Tr2} = 0.15 \text{ on 900 MVA with 20/230 kV base and off nominal tap ratio = 1}
\]