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A model-based decoupling observer to locate forced oscillation sources in mechanical power

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ABSTRACT

In this paper, a method is proposed to locate the forced oscillation source, which is often resulted from a continuous disturbance on unit's mechanical power. By judiciously designing a Luenberger observer using an eigenstructure assignment, the relationship between outputs of observer and disturbance in mechanical power of a unit is decoupled. The introduced observer cannot only locate the forced oscillation source in mechanical power, but also estimates the amplitude of the oscillation source. Simulation results of the 19-machine 118-bus test system demonstrate the effectiveness of the proposed method.

1. Introduction

Low frequency oscillation is a long-standing problem threatening the stable operation of power systems. Often there are two kinds of low frequency oscillations, i.e., free oscillation and forced oscillation. Due to lack of damping, a free oscillation can be excited by load fluctuations and sudden network switches [1]. In the literature, different solutions have been presented to suppress free oscillations, such as those using power system stabilizer (PSS) [2–4], supplemental control in flexible AC transmission system [5], DC transmission modulation [6], etc. A comprehensive review on the study of free oscillations is available in the recent monographs [7,8] and references cited therein.

The forced oscillation is a relatively new form of low frequency oscillation and is receiving more and more attention in recent years [9–11]. Unlike free oscillations, a forced oscillation is often introduced by a sustained disturbance in mechanical power of a unit [12]. Thus, a forced oscillation may occur even if the system is well damped. Such forced oscillation events have occurred in Southern Power Grid of China [13] and Western America power grid [14].

The causes for a forced oscillation can be rather complex. Ref. [9] points out that the forced oscillation of western America power grid in summer 2013 is caused by hydro plants with Francis blades undergoing a vortex related mechanical turbine oscillation. A forced oscillation can also be triggered by other causes such as unsteady combustion of boiler [15], undesirable steam turbine value discharge characteristic [16], or turbo pressure pulsations [17]. The complex natures of the forced oscillation make it difficult to locate the oscillation's source.

Recently, various approaches are presented to locate forced oscillation sources. In [9], subspace method is applied to locating forced oscillation source by comparing the amplitudes of eigenvectors obtained using subspace identification. In [13], a hybrid dynamic simulation method is proposed to locate source off-line. In [10], a transient energy flow based method is proposed to allow, on-line location of oscillation sources. In [11], a method based on uniqueness of component properties and envelope shapes of forced oscillation is proposed. Besides, a cross-coherence method was proposed in [18] to detect oscillations in a power system using PMU data. However, these methods cannot estimate the amplitude of the forced oscillation source and most of them are executed off-line. The frequency-domain approach in [30,31] utilizes some fundamental magnitude and phase relationships between system input and output to diagnoses oscillation sources. The approach, while developing, opens up a promising avenue to the state-of-the-art. For an excellent survey on the subject, the readers are referred to [32].

In this paper, a method is proposed for locating the forced oscillation source and estimating its amplitude by designing a Luenberger observer that can execute on-line. The number of the observer outputs is the same as the number of generators in a power system and the Luenberger observer can decouple relationship between outputs of observer and disturbance in mechanical power of a unit, which simplifies the analysis of the interactions between forced oscillations and increases the observability using PMUs. The efficacy of the proposed method is demonstrated on a 19 machines, 118 bus system.

The rest of this paper is organized as follows. In Section 2, the model of the forced oscillation in mechanical power is introduced. In Section 3, the structure of a Luenberger observer is discussed, and an

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eigenstructure assignment approach is then introduced to design the observer parameters. In Section 4, the Luenberger observer is tested on a 19 machines 118 bus system. In Section 5, the conclusions are drawn.

2. Problem description

The forced oscillation problem of a power system can be described by the following state space model:

$$\begin{aligned}\dot{x}(t) &= Ax(t) + Rf(t)\\ y(t) &= Cx(t)\end{aligned} \tag{1}$$

where $x = [\Delta\delta^T \;\; \Delta\omega^T \;\; \Delta E_q'^T \;\; \Delta E_{fd}^T]^T$ is the $4ng \times 1$ state variable vector. Here ng is the number of units in system. Vector $\Delta\delta = [\Delta\delta_1 \;\; \Delta\delta_2 \;\; \cdots \;\; \Delta\delta_{ng}]^T \in ng \times 1$ consists of rotor angles; vector $\Delta\omega = [\Delta\omega_1 \;\; \Delta\omega_2 \;\; \cdots \;\; \Delta\omega_{ng}]^T \in ng \times 1$ consists of rotor speeds; $\Delta E'_q = [\Delta E'_{q1} \;\; \Delta E'_{q2} \;\; \cdots \;\; \Delta E'_{qng}]^T \in ng \times 1$ consists of transient EMFs in the q-axis, and $\Delta E_{fd} = [\Delta E_{fd1} \;\; \Delta E_{fd2} \;\; \cdots \;\; \Delta E_{fdng}]^T \in ng \times 1$ consists of excitation voltages. Thus, it is easy to conclude the dimension of matrix A is $4ng \times 4ng$. In modern power systems, the matrix A can be obtained on-line from Energy Management System (EMS). Details on how to derive A can be found in [1].

Suppose the mechanical power of units is subjected to a periodic disturbance $f(t) \in ng \times 1$. In (2), the disturbance matrix $R \in 4ng \times ng$ can be represented:

$$R = \begin{bmatrix} 0 \\ 1/M \\ 00 \end{bmatrix} \tag{2}$$

where $0 \in ng \times ng$ denotes a zero matrix, and $M \in ng \times ng$ is a diagonal matrix with machine inertia constants being the diagonal elements. In reality, machine inertia constants can be measured using field tests. Thus, R is known for system operators.

State vectors $\Delta\delta$, $\Delta\omega$, ΔE_{fd} are either measured or estimated using wide-area PMUs [21], thus, $y = [\Delta\delta^T \;\; \Delta\omega^T \;\; \Delta E_{fd}^T]^T$. Then, measurement matrix $C \in 3ng \times 4ng$ is determined as follows:

$$C = \begin{bmatrix} I & 0 & 0 & 0 \\ 0 & I & 0 & 0 \\ 0 & 0 & 0 & I \end{bmatrix} \tag{3}$$

where I is the unit matrix of dimension of ng and 0 denotes a zero matrix of dimension of ng.

The time-domain solution of forced oscillation problem described in (5) can be represented [22]:

$$y(t) = C[e^{At}x(0) + \int_0^t e^{A(t-\tau)}Rf(\tau)d\tau] \tag{4}$$

Eq. (4) indicates when mechanical power is disturbed by a periodical input $f_i(t) \neq 0$, all outputs of system will vary periodically. To locate the source of forced oscillation and estimate its amplitude, the crucial problem is to find a method to decouple system outputs $y(t)$ from mechanical power input $f(t)$.

A judiciously designed Luenberger observer [19] can serve this purpose. When the potential periodic disturbance occurs on generator mechanical power, the number of potential periodic disturbance is ng. The designed Luenberger observer establishes ng outputs, which can be decoupled from the potential periodic disturbance. For example, if a forced oscillation occurs due to a disturbance in mechanical power of ith unit, only ith output of the observer shows periodical variation and other outputs of the observer are identically zero. Thus, the mechanical power of ith unit can be identified as the forced oscillation source, and the amplitude of oscillation source can be estimated through the amplitude of the ith output. Thus, based on the suggested observer, it will be easy to locate forced oscillation source and estimate its amplitude.

3. Design of Luenberger observer based on eigenstructure assignment method

3.1. Structure of Luenberger observer

From model (1), it is easily shown that:

$$\begin{aligned}\dot{\hat{x}}(t) &= (A-KC)\hat{x}(t) + Rf(t) + Ky(t)\\ \hat{y}(t) &= C\hat{x}(t)\\ r_1(t) &= Q_1C[x(t)-\hat{x}(t)] = Q_1[y(t)-\hat{y}(t)]\\ r_2(t) &= Q_2r_1(t)\end{aligned} \tag{5}$$

where $\hat{x}(t) \in 4ng$ denotes estimated states of system provided by the observer; $\hat{y}(t) \in 3ng$ denotes estimated outputs of system provided by the observer; $K \in 3ng \times 4ng$ is observer gain matrix; $Q_1 \in ng \times 3ng$ and $Q_2 \in ng \times ng$ are scale matrices; $r_1(t)$ denotes intermediate variables of observer. The function of intermediate variable $r_1(t)$ is to decouple forced oscillation sources $f(t)$ from mechanical power. The dimension of $r_1(t)$ is ng. However, the amplitude of elements in $r_1(t)$ is not equal to the amplitude of elements in forced oscillation sources $f(t)$ in model (1). After re-scaling by matrix Q_2, the amplitude of elements in $r_2(t)$ equals to the amplitude of elements in $f(t)$. $r_2(t)$ denotes outputs of the observer and the dimension of $r_2(t)$ is ng too. If the i^{th} elements in $r_2(t)$ is zero, it can be concluded that the mechanical power of the i^{th} unit is not the forced oscillation source. If the i^{th} elements in $r_2(t)$ varies periodically, it can be concluded that the mechanical power of i^{th} unit is the forced oscillation source and the amplitude of oscillation source is estimated through the amplitude of the i^{th} elements in $r_2(t)$. Thus, it is easy to locate and estimate the amplitude of forced oscillation source through $r_2(t)$.

3.2. Design of Luenberger observer

To obtain $r_1(t)$ and $r_2(t)$ in (9), we represnt them in the frequency domain:

$$r_1(s) = Q_1C(sI-A+KC)^{-1}Rf(s) \tag{6}$$

Let:

$$H = Q_1C \tag{7}$$

It follows:

$$r_1(s) = H(sI-A+KC)^{-1}Rf(s) \tag{8}$$

Determination of Q_1 can be transformed into determination of H through (7). If $H(sI-A+KC)^{-1}R$ is a diagonal matrix, observer outputs $r_1(s)$ and disturbance source $f(s)$ is decoupled. The function of scale matrix Q_2 is to re-scale the elements in $r_1(s)$ to reveal the amplitude of the oscillation source:

$$r_2(s) = Q_2r_1(s) \tag{9}$$

Let $U = [u_1 \;\; u_2 \;\; \cdots \;\; u_{4ng}] \in 4ng \times 4ng$, $u_1,u_2,\ldots u_{4ng} \in 4ng \times 1$ are right eigenvectors of $A-KC$. $V = [v_1 \;\; v_2 \;\; \cdots \;\; v_{4ng}]^T \in 4ng \times 4ng, v_1^T, v_2^T, \ldots, v_{4ng}^T \in 1 \times 4ng$ are left eigenvectors of $A-KC$, and $\Lambda \in 4ng \times 4ng$ is a diagonal matrix and each diagonal element of the matrix is equal to an eigenvalue of matrix $A-KC$. Notice that the closed-loop matrix has an eigenvalue decomposition:

$$A-KC = U\Lambda V^{-1}$$

Eq. (8) is re-arranged as:

$$r_1(s) = H(U(sI-\Lambda)V)^{-1}Rf(s) \tag{10}$$

Using the properties of matrix inverse, (10) is further re-written as the following form:

$$r_1(s) = HU(sI-\Lambda)^{-1}VRf(s) \tag{11}$$

Choose K and H such that: