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Optimal placement of rotor angle transducers for power system stability

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Abstract

An optimal placement method of rotor angle transducers for power system stability is presented in this paper. For angle stability, information content of generator rotor angle responses to disturbances is an appropriate performance criterion of placement sites. To maximize information content, the method consists of three steps: clustering, grouping and selecting. After distinct dynamic scenarios are extracted by a hierarchical agglomerative clustering technique, a coherency identification step is implemented to form candidates and then placement sites are determined using Gram determinant as the information content measure. The proposed method is applied to a transient stability emergency control scheme in a practical power system. Simulation results demonstrate its rationality.

Keywords: Power system stability; Rotor angle; Optimal placement; Information content

1. Introduction

Under economic and environmental pressures, power systems are operated closer to their stability limits. To maintain stability, reliable and robust controls will be required when power systems are subjected to disturbances, even for many single contingences [1]. As to transient stability controls, a global view of wide-area generator rotor angles is generally required [2–5]. A power system often involves two kinds of small-signal stability phenomena: local modes and inter-area modes. Although local modes can be stabilized using local measurements, it suggests that the best control signals for damping of inter-area oscillations are to be derived from angle measurements got from remote generator terminals [6,7]. The rotor angle of a generator can be measured by installing an optical or magnetic sensor around the rotor shaft to capture the rotor angle position from pulses generated by tooth wheels or painted stripes on the shaft [8]. Rotor angle transducers with Global Positioning System (GPS) capability can provide wide-area information for angle stability controls because remote angle measurements are time-stamped and coordinated in a common reference frame by using GPS timing signals.

The number of rotor angle transducers available for installing is often constrained by the investment budget and communication capacity. There emerges the optimal placement issue that aims to minimize the number of rotor angle transducers while representing angle dynamics of a power system correctly. Previous researchers were likely to use the phrase “generator rotor angles” interchangeably with “generator voltage angles” and “phasor measurements” where Phasor Measurement Units (PMUs) were considered to contain the function of rotor angle transducers [4,5]. It is reasonable to generalize principles guiding the optimal placement of PMUs to rotor angle transducers. There are mainly two kinds of PMU placement methods. One is to place PMUs so that the system measurement model is observable [9,10], which is from the steady-state estimation point of view and requires a relatively large number of PMUs, e.g. 20–30% of the number of system buses [10]. The other is based on coherency analysis to partition a power system into several coherent groups

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for each of which only one PMU is required in principle [11,12]. A prominent problem in implementing such kind of methods is whether a fixed placement set can represent all possible dynamics correctly. Recently, PMU placement algorithms aimed at maximizing the amount of information about disturbances while minimizing cross correlation of bus measurements have been proposed [13,14]. Gram determinant of time-response signal matrix is used as the information content measure. Sequential placement algorithms based on greedy optimization are presented. Limitations of such algorithms fall into two aspects. Firstly, greedy optimization algorithms adopted cannot guarantee to find the global optimal solution. Secondly, candidate buses from which to select PMU placement sites are predefined; however, a process to form candidates is necessary in many cases.

Combining the coherency analysis based method and information content based method while incorporating a hierarchical agglomerative clustering technique, a placement method for rotor angle transducers is proposed. It is a “clustering–grouping–selecting” process. Clustering aims to compact dynamic scenarios and extract distinct scenarios for consideration. Grouping refers to coherency identification of generators and is the process to form candidates. And selecting is to select the final placement sites from the candidates using Gram determinant as the information content measure.

2. Problem formulation

Optimal placement of rotor angle transducers is by nature a constrained optimization problem, which aims to minimize the number of transducers to be installed while representing angle dynamics correctly. In general, for an n_G-generator power system (with N_G representing the set of generators), the problem can be formulated as:

$$\text{Minimize} \ \ \mu(N_T) \tag{1}$$

$$\text{Subject to} \ \ C_1(N_T) = 0 \tag{2}$$

$$C_2(N_T) \leq 0 \tag{3}$$

where $N_T \subseteq N_G$ represents a subset of generators at which transducers are installed; $\mu(N_T)$ is the number of transducers; C_1 and C_2 are equality and inequality constraints, respectively.

Time-series matrices of generator rotor angles can be taken as the basic data to represent angle dynamics of a power system. A generator rotor angle matrix is as:

$$R = \begin{bmatrix} \delta_1(1) & \delta_2(1) & \cdots & \delta_{n_G}(1) \\ \delta_1(2) & \delta_2(2) & \cdots & \delta_{n_G}(2) \\ \vdots & \vdots & & \vdots \\ \delta_1(m) & \delta_2(m) & \cdots & \delta_{n_G}(m) \end{bmatrix} \tag{4}$$

where each column δ_i is a rotor angle series, m the number of samples in a time span following a disturbance, and n_G the number of generators. In this paper, δ_i denotes specifically the ith generator’s rotor angle deviation from the pre-disturbance steady-state value.

Taking information content as the performance criterion of a placement set, optimization problem formulated in Eqs. (1)–(3) is specified as:

$$\text{Minimize} \ \ \mu(N_T) \tag{5}$$

$$\text{Subject to} \ \ I(R(N_T)) = I(R(N_G)) \tag{6}$$

where $R(N_G)$ and $R(N_T)$ are rotor angle matrices of the whole generator set and its subset, respectively, and I is a measure of the information content.

The equality constraint provides the principle for guiding the minimization of rotor angle transducers. In practice, information loss is inevitable in representing the whole generator set by its subset, so $I(R(N_T)) \approx I(R(N_G))$ is the practical version of the ideal one in Eq. (6).

Another form of Eqs. (5) and (6) is that given a fixed number of transducers, a placement set N_T maximizes the information content. It is expressed as:

$$\text{Maximize} \ \ I(R(N_T)) \tag{7}$$

$$\text{Subject to} \ \ \mu(N_T) = n_T \tag{8}$$

where n_T is the given number.

In Eqs. (5)–(8), inequality constraints are not given. In fact, inequality constraints accounting for various economic and technical considerations can be added readily without changing the framework of the placement method [14].

3. Placement method

Dynamic behavior of a power system varies according to operating conditions and disturbances where operating conditions consider network topologies, generator outputs and load levels whereas disturbances involve different line and bus faults, load and generation variations, etc. As for angle stability, transient stability depends on both the initial operating condition and disturbance while small-signal stability is influenced significantly by the operating condition but has little to do with the disturbance. Define an ordered 2-tuple $S = (O, \ D)$ to depict dynamic scenarios, where O represents pre-disturbance operating conditions and D disturbances imposed on the system.

To reveal system dynamics, numerical simulations are performed to cover numerous dynamic scenarios. To each scenario $s \in S$, there corresponds a rotor angle matrix R as Eq. (4). Taking R as the basic data, coherency analysis combined with the information content-based method leads a way in solving the optimization problem defined in Eqs. (5)–(8). However, it is obviously difficult to execute on such significantly