Electrical Power and Energy Systems 83 (2016) 470–484

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

A new approach for online coherency identification in power systems based on correlation characteristics of generators rotor oscillations

M.R. Aghamohammadi *, S.M. Tabandeh

Faculty of Engineering, Electrical Eng. Dept., Shahid Beheshti University, AC, Iran

ARTICLE INFO

Article history:
Received 21 February 2015
Accepted 4 April 2016
Available online 29 April 2016

Keywords:
Coherency
Rotor angle/speed oscillation
Correlation coefficient
Clustering
Inter-area oscillation

ABSTRACT

In this paper, a new approach for identifying coherent groups of generators in power systems based on the correlation coefficients between rotor angle/speed oscillations of generators is presented. The method uses a newly proposed clustering index based on the correlation coefficients of generators oscillations which is able to classify any number of generators into coherent groups. The proposed approach uses real time data of generators oscillations via VAMS/PMUs, so it is able to easily take into account the effect of system detailed modeling, generators and system controllers and type of events. The proposed correlation index evaluated from the real time behavior of generators in time-domain following disturbances are used to evaluate the degree of coherency between any pair of generators. The generators' rotor angles and speeds can be obtained from synchronized measurements of system quantities using PMUs. Hence, the proposed method could be integrated into a wide-area measurement system enabling fast identification of coherent groups of generators. It is shown that by using COI of the aggregated in-phase coherent groups, the frequency of the inter-area mode can be evaluated. The proposed method is tested on the IEEE 39-bus with 10 generators and realistic power system of Iran with 405 generators.

Introduction

Today's power systems are very complex for performing on-line security assessment with the detailed system modeling, so, the dynamic security assessment of large interconnected power systems requires new techniques which mainly rely on the on-line data provided by the wide area measurements system (WAMS). When a stressed power system encounters a disturbance or a change in operation condition, it experiences electromechanical oscillations between interconnected synchronous generators in the form of local or inter area oscillations. In the case of inter area oscillation, system generators tend to separate into coherent groups oscillating against each other. Clustering generators oscillations into coherent groups following a disturbance is an inherent dynamic characteristic of electric power systems. Slow coherency has originally been used in the development of dynamic equivalents for simplifying transient stability studies [1]. The identification of such groups is vital for dynamic security assessment and designing the appropriate countermeasures for maintaining system stability. The methods for transient stability analysis of large interconnected power systems via simplified dynamic equivalents are attracting which is received increasing attention by researchers [2–4]. Previously, several methods such as electrical distance method; time domain approach; and frequency domain approaches utilizing Fourier transform and Laplace transform techniques have been used to identify the coherent groups of generators [5]. Controlled islanding of a power system is an efficient corrective measure for limiting system blackouts after a large disturbance [5–7]. An islanding solution must satisfy a large number of constraints, such as load-generation balance, voltage stability and generator coherency for preserving transient stability. Therefore, besides system dynamic equivalency, controlled islanding is another field of interest for application of slow coherency. Identification of coherent group of generators is a relatively old research problem. Over the past decades, various notable methods have been developed for constructing the dynamic equivalent of large power systems [8]. In recent decades, several dynamic reduction techniques have been developed, including coherency-based equivalence techniques, modal equivalence techniques and slow coherency techniques which combine the merits of both of the preceding types. Of these, the coherency-based techniques are most widely used in practical applications for nonlinear dynamic simulation because of their simplicity [1,2,8–16]. A dynamic reduction procedure consists of three steps, 1 – identification of coherency with respect to the dynamic behavior of generators during

* Corresponding author.
E-mail address: M_Aghamohammadi@sbu.ac.ir (M.R. Aghamohammadi).

http://dx.doi.org/10.1016/j.ijepes.2016.04.019
0142-0615/

disturbances, 2 – clustering generators into groups according to coherency characteristics and 3 – finally aggregates coherent generators in the same group as an equivalent generator [13,14,17,18].

In the previous studies, power system is divided into two subsystems, denoted as the "study system" and the "external system" which are identified and established based on the location and magnitude of the disturbance [1,8,19]. The algorithm of dynamic reduction based on the "study system" and the "external system" is also used in [20] which explains Partitioning Around Medoids (PAM) algorithm and compares it with the algorithms proposed by [21] and K-means [22]. The K-means algorithm has some drawbacks, such that the groups are determined differently depending on the calculation procedure and initial group [8]. In [23], clustering techniques based on the data similarity matrix have been used for large network to identify coherent generators. The data can be gathered from different location and can have different values. In the clustering methods such as hierarchical clustering [23,24] and neural clustering [25], the power system is divided into several groups and the coherent generators lie in each group. The problem of coherency identification can be regarded as the problem of pattern recognition. ANN technique shows superiority in processing nonlinear pattern recognition. Kohonen self-organizing neural network and adaptive resonance theory network (ART net) were applied in [25,26] respectively for identifying the coherency in power system. In [27], a two-step spectral clustering algorithm is used for controlled islanding. In [28], a simple criterion for coherency as $\max|\Delta\delta i(t) - \Delta\delta j\ (t)| < \varepsilon$ with $5° < \varepsilon < 10°$ denoted as Max–Min criterion is applied for identifying coherent generators. In [29], a new threshold for identifying coherent groups of generators through their rotor angle curves measured by GPS is specified.

In [30], by applying random load changes as a distributed disturbance on the system and using spectrum analysis of the generators velocity variations, coherent generators and their related non-generator buses to form areas in inter-connected power systems are detected. In [31-A29], modal analysis of short-term swing dynamics is performed. The analysis is based on Koopman operator, a linear, infinite-dimensional operator that is defined for any nonlinear dynamical system. Koopman modes provide a nonlinear extension of linear oscillatory modes which can extract single-frequency, spatial modes embedded in non-stationary data of short-term, nonlinear swing dynamics. In [32], by examining the instantaneous phase differences among inter area oscillations and swing curves in disturbed multi area power systems, coherency between generators is tracked. Huang's empirical mode decomposition is applied to extract dominant oscillatory modes from inter area oscillations/swing curves. Hilbert transform on these modes yields their instantaneous phase. In [33], the continuation method has been applied to track generator coherency under different operating conditions. However, implementing this technique requires complete knowledge of the system in detail, which may not always be possible. Evaluation of generator coherency from power system measurements has been implemented using fast Fourier transform (FFT)-based spectral techniques [34–36] and principal components analysis technique [37]. All these techniques assume stationary and linear data being analyzed, an assumption which is not always justified. In [38], by introducing rotor trajectory index and based on the coherency obtained using time domain simulations, for improving transient stability a generation rescheduling based preventive control is proposed. In this method, selection of participating generators has been introduced using generator coherency for given contingency. On the other hand, the evolving technology of wide-area measurement systems (WAMS) and the use of the synchronized phasor measurement unit (PMU) have made the monitoring of the dynamics of power systems in real-time a promising aspect to enhance and maintain power systems stability. In [39], techniques from graph theory are applied to identify coherent generators without carry out a transient stability study. In [40], an integrated algorithm to identify a cutset for a large power system for the application of a slow coherency based controlled islanding scheme is proposed in which large scale power system is represented as a graph. In [41], by proposing a connection between the Krylov subspace model reduction and coherency in power systems, the use of Krylov subspace method for the model reduction of power systems is described.

In [15], in order to improve the accuracy of dynamic equivalents, by incorporating rotor and voltage dynamics a technique for coherency identification is proposed in which a new method to match the power flow conditions for generator aggregation is presented. In [42], based on the PAM algorithm and minimizing the change in the dynamic response of the reduced equivalent system a new method for identification of coherency in power systems is presented. In [43], by applying independent component analysis (ICA) to the generator speed and bus angle data, a new approach for coherency identification in interconnected power system is presented.

In [44], a new technique based on Support Vector Clustering (SVC) for direct identification of coherent generators in a large Power Systems from the time domain responses of the generators following system disturbances, is presented. In [16], a systematic approach for predicting the effect of operating conditions and topology changes on the patterns of generator slow coherency is presented and it is shown that system topology changes have more influences on generator slow coherency behavior than load or generation changes.

In [2], a new alternative and much more justified approach without any need to measurement data from the external area is proposed for aggregation of coherent generators. In [3], an efficient method for estimating transient stability indices of electric power systems based on the equivalent network reduction techniques by considering clusters of coherent generators is presented. In [45], identification of the dynamic equivalent of a power system from on-line measurements by using coherent generators based on graph model of a power system without the necessity of dynamic parameters is investigated in [45].

The importance of fast identification of coherent groups of generators based on the wide-area measurements lies in its contribution to the design of wide-area based stability control schemes that aim to enhance the overall performance of power systems.

In this paper, a new approach for identifying coherent groups of generators in power systems based on the correlation coefficients between rotor angle/speed oscillations of generators is presented. The method uses a newly proposed clustering algorithm [46] to classify any number of synchronous generators into coherent groups based on the correlation coefficients between them. The proposed approach can easily take into account the effect of system detailed modeling, generators and system controllers and the type of events. The method is based on the indices of correlation coefficients evaluated from the real time behavior of generators in time-domain following system disturbances. These indices are used to evaluate the degree of coherency between any pair of generators. The generators rotor angles and speeds can be obtained from synchronized measurements of system quantities using phasor measurement units (PMUs). The proposed method could be easily integrated into a wide-area measurement system that enables fast identification of coherent groups of generators.

Generators correlation coefficients as coherency index

Correlation is a measure of the strength of linear association between two variables. The degree of coherency between two generators can be evaluated by the correlation coefficient of their