Electric Power Systems Research 122 (2015) 86–95

Contents lists available at ScienceDirect

Electric Power Systems Research

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

Design and implementation of an identifier system for inter-area power oscillations

Tevhid Atalik [a,b,*], Mustafa Dogan [b], Turan Demirci [a]

[a] TUBITAK MRC, Energy Institute, Ankara Branch, Ankara, Turkey
[b] Baskent University, Department of Electrical and Electronics Engineering, Ankara, Turkey

ARTICLE INFO

Article history:
Received 13 June 2014
Received in revised form
31 December 2014
Accepted 2 January 2015
Available online 22 January 2015

Keywords:
Inter-area oscillations
STATCOM
Hilbert-Huang transform (HHT)
Empirical mode decomposition (EMD)
FFT
Target-based refinement

ABSTRACT

Identifying inter-area oscillations can be a challenge for interconnected grids. Two identifier algorithms (FBMSWA and TBR-EMD) proposed to detect these oscillations are comparatively tested in this research. FBMSWA is implemented with T-STATCOM to damp out 0.15 Hz low-frequency inter-area oscillation after interconnection Turkey with ENTSO-E. Developed TBR-EMD algorithm has certain achievements, e.g. admissible for real time, handling intermittency problem of EMD, proved by real data.

1. Introduction

Geographic growth of power transmission systems, and increased interconnected network activities between countries cause occasional system stability problems, e.g. frequently observed local oscillations between neighbour generator facilities, and inter-area oscillations. Both are classified as two main problems for power systems in literature [1]. These oscillations have low frequency and create usually small changes on the grid frequency. The period of frequency variation for local oscillations is about 1–5 s. Besides, this value for inter-area oscillations is about 5–10 s. In some cases, oscillations can be mitigated by the dynamics of the power system, or in the worst case, they can grow steadily, and may result in brownout or blackout.

Turkish power grid has been connected to European Network of Transmission System Operators for Electricity (ENTSO-E) over three transmission lines (2 × 380 kV through Bulgaria and 1 × 380 kV through Greece) on September 18, 2010 for an amount of 1200 MW bidirectional power exchange. The preparation phase for this interconnection was implemented at several stages for problem-free integration [2,3]. One of the important stages was the identification and mitigation of expected inter-area power oscillations resulting in frequency oscillations in time.

After interconnection of Turkey with ENTSO-E, dynamic analysis showed that a new dominant mode of oscillation was expected with a frequency around 0.15 Hz [2,3] instead of 0.22–0.26 Hz prior to interconnection. It should be noted that power system stabilizers (PSSs) are not quite effective in 0.1–0.2 Hz range of oscillation frequencies [4]. Therefore, FACTS devices already installed at the transmission system have been planned to damp out the inter-area oscillations. Originally designed and implemented 154 kV, ±50 MVAr Transmission STATCOM (T-STATCOM) [5] and four static VAr compensator (SVC) systems with a reactive power of 300 MVAr for each are deliberately employed to be able to mitigate the inter-area oscillations. Since the grid is strong, the measurements taken by wide area monitoring systems (WAMS), from all over Turkey showed that the frequency is almost the same in the Turkish grid. Furthermore, the simulation studies in [2] showed that the locations of FACTS devices would not alter the inter-area damping performance, significantly. Therefore, the already installed T-STATCOM and four SVCs mentioned in this work are utilized with the inter-area oscillation identifier, while the frequency measurements are taken from their own point of common couplings.

Inter-area power oscillations can be detected as frequency oscillations in time for quick and easy intervention. While higher frequency corresponds to more supplied active power, lower frequency corresponds to more consumed active power. In the

* Corresponding author at: TUBITAK MRC, Energy Institute, Ankara Branch, METU Campus, Ankara, Turkey. Tel.: +90 312 210 18 30/1262; fax: +90 312 210 10 33.
E-mail address: tevhid.atalik@tubitak.gov.tr (T. Atalik).

http://dx.doi.org/10.1016/j.epsr.2015.01.004
0378-7796/

positive cycle of the oscillations, T-STATCOM and SVCs are supposed to produce capacitive reactive power to increase the voltage and hence local active power consumption. On the contrary, in the negative cycle of the oscillations, T-STATCOM and SVCs should consume inductive reactive power, to be able to decrease the voltage and local active power consumption in their neighbourhood. The proposed damping method has been simulated to show that inter-area oscillations can be damped effectively [2,3]. A detection system and an identifier algorithm should be developed to activate the mentioned FACTS devices. Since power oscillations result in frequency oscillations, the inter-area modes can be identified by measurements of the frequency at connection points of each FACTS device to the grid. Therefore, these devices can be controlled independently to damp the oscillations.

In the literature, it is seen that identification of inter-area oscillations is usually based on active power or frequency measurements [6–8]. However, low-frequency oscillations on power and frequency cannot be easily identified due to the non-linear, non-stationary, aperiodic and stochastic characteristics of the electric power systems [9–11]. Structural challenges as mentioned above make identification process difficult for many signal processing methods [12–14].

Hilbert-Huang Transform (HHT) is a sophisticated analysis method for non-linear systems and non-stationary signals. This method comprises of well-known Hilbert transform and empirical mode decomposition (EMD) proposed by Huang [15]. EMD is used to separate different frequencies in the signal. Thus, intrinsic mode functions (IMF) containing only mono frequency component are obtained. However, noisy and biased signals will deteriorate the performance of this iterative method. Therefore, substantial pre-filtering techniques should be developed beforehand. Also, stopping criterion, border effects, intermittency, and two modes within an octave are challenging problems in this research area [8,10,16–25].

In this work, two new algorithms named FFT-based modified sliding window algorithm (FBMSWA) and target based refinement empirical mode decomposition (TBR-EMD) are proposed for detection of inter-area oscillations in power transmission systems. The previous works in literature cover mainly the modelling of transmission system and mitigation devices for inter-area oscillations, and also stability analysis of the grid [26–31]. Briefly, poles and zeroes of the system are altered by FACTS devices, to be able to keep the power system stable. However, in this work, the stability test of the system and linearization are not required, modulation of active power consumption by FACTS devices results in system stability indirectly.

2. Design criteria for inter-area oscillation identifier system

Turkish transmission system operator (TEIAS) has imposed some case-specific constraints for the identifier system as listed below:

a. Identifier system should detect and send the control commands to the FACTS devices in real time, only for 0.1–0.2 Hz sub-band frequency oscillations having adjustable amplitude of 7–20 mHz.
b. The phase of the frequency oscillations in 0.1–0.2 Hz sub-band can be identified with $\pm 30^{\circ}$ phase error at most. Frequency oscillation is a sinusoidal signal. This signal is processed through some methods explained in this work, which cause a phase difference (error) between the processed and original signal. Any significant error on detected phase may result in growing oscillation because the operation mode of FACTS device would be selected as inductive where the actual one should be capacitive mode, or vice versa.
c. It is expected that the identifier system should sense the periodic oscillations which have growing amplitude in a stationary or continuous way with at least two periods of oscillation frequency.

Grid frequency should be measured fast and accurate enough to identify inter-area oscillations. In this work, supply voltage waveform is sampled by precise GPS-based sampling system (16 bit, 25.6 kHz ± 0.1 ppm) and it is converted to digital signal [32]. Then, produced digital signal is band-pass filtered to eliminate other frequencies than the fundamental one and to be able to find zero-crossings properly. Since it is a digitized signal, zero-crossing can reside between two consecutive sampling points in time. Since sine waveform can be approximated as linear around zero, zero-crossing points on time axis can be calculated precisely by linear interpolation method. Consequently, frequency can be obtained by evaluation of time between two-consecutive zero-crossing points belonging to supply voltage waveform.

3. FFT-based modified sliding window algorithm (FBMSWA)

FFT method is developed for stationary signals in linear systems. However, the required signal to identify inter-area oscillations is non-stationary, naturally. Therefore, sliding window Fourier analysis has been used with the assumption that the windowed signal is stationary for an appropriate window length. FBMSWA (Fig. 1) is based on Fourier spectral analysis for two-different-length sliding windows. Hence, phasor-frequency representation of the signal is obtained. Oscillations are detected in relevant frequency band by examining FFT components within.

FFT method produces an average value for given magnitudes of the signal components in the active window by its characteristics. However, high frequency resolution analysis of components requires many samples of the signal or longer window sizes. If the identifier system cannot detect the signal within 0.1–0.2 Hz band correctly, then the reaction of the identifier system will not be at the right time. For high frequency resolution, window size should be long, however in that case unwanted delays occur. Therefore, two-different-length windows are chosen to make FFT analysis. While quick detection of the amplitude is done with short-window in this method, the proper phase identification is done with long-window for inter-area frequency oscillations.

3.1. Identification of amplitude for inter-area oscillations

Grid frequency signal used for detection of inter-area oscillations has higher amplitude dc component (50 Hz) and the other oscillation modes with relatively lower amplitudes. The identifier system is trying to catch the frequency deviations within 0.1–0.2 Hz band. Since these lower amplitude signals are close to dc, the highest amplitude component (dc) will suppress seriously the other components in the relevant frequency band due to smearing effect. Therefore, grid frequency should be pruned from main dc component as much as possible, prior to applying Fourier analysis. A wash-out filter which is simply a high-pass filter is used for this purpose. Transfer function of this wash-out filter, $G(s)$, is given below [33]:

$$G(s) = \frac{Y(s)}{X(s)} = \frac{s}{s+d} \tag{1}$$

where $X(s)$ is the input, $Y(s)$ is the output and d is a constant. The filter is stable for positive values of d which can be chosen in $0 < d < 2$, regarding damping ratio.

Window length is proportional to sampling frequency. Since frequency calculation is done every 10 ms, if window length is set to 1000, then step frequency interval will be 0.1 Hz by Fourier analysis.