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Inter-Area Oscillation Detection by Modern Digital Relay

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1 INTRODUCTION

The inter-area oscillation phenomenon of large synchronously interconnected power systems consists on rotor angle/frequency/power/voltage/current swings between the synchronous generators of a subsystem (or of large power plant) against the synchronous generators of another subsystem (or other subsystems) that are electrically far from each other. Oscillations modes may be global, involving the whole interconnected system, or regional. Oscillations may be excited by a large disturbance (loss of a generator or load; a line short circuit) or in weak systems may also be excited by very small disturbances (just in normal operation)

It is known from the angular transmission stability theory that the frequency of inter-area oscillations is very low when the MW capacity of the interconnected systems (i.e. the kinetic energy of rotating masses) is large and the impedance of the interconnection lines is high. Recent extensions of continental synchronous interconnections spanning over some thousands of km have determined situations with very low frequency of the inter-area oscillations, in the range of 0.1 to 0.25 Hz. Governors of hydroelectric power plants with high transient gain performing primary frequency control, may contribute to the excitation or amplification of these very low frequency inter-area oscillations, thus increasing the negative damping caused by the fast response excitation systems of synchronous generators. On the other hand, the damping action of PSSs may be markedly reduced for these very low frequencies.

As an example, the dynamic simulation performed for the synchronous connection of the national power system of Turkey (2010 peak load of ~ 34,500MW) with the Western Europe system (peak load of ~ 400,000MW) via the power systems of the Balkan countries, which have a relatively high transfer impedance, has shown that the frequency of the inter-area oscillations at peak load operation is ~ 0.13Hz (period of ~ 7.5 sec) [1]. Actually the ENTSO-E Continental Europe system extended to Turkey spans over ~ 4500km between Portugal at one end, and Eastern Turkey at the other end.

Small signal stability is generally studied in frequency domain with the eigenvalue (modal) analysis. The damping ratio of inter-area oscillations is defined as follows:

$$\xi = \frac{-\sigma}{\sqrt{\sigma^2 + \omega^2}}$$

Equation 1

where σ and ω are the real part and -the imaginary part of the eigenvalues $[\sigma + j\omega]$ (sec⁻¹). Damping is usually considered satisfactory if all the electromechanical oscillation modes have a ratio $\xi \geq 5\%$. If $\xi = 5\%$, the amplitude of oscillations is reduced to 33% after 3 full periods.

Calculation of the inter-area oscillation frequencies is accurate because they depend from accurately known system parameters. On the other hand, prediction of damping ratios may be far from accurate, because they depend from the simulation of many control functions and components, some of which have an uncertain damping effect (e.g. the loads). The changes of values and direction of inter-area active power flows usually markedly affect damping. A good tool for system operation is therefore the function developed in this paper, that is capable to detect the inter-area frequency (and power) oscillations, for alerting operators and, in case of persistence or amplification, for initiating automatic corrective actions. The latter may be the control, driven by the oscillation frequency, of a static var compensator (SVC) or of a STATCON, or of a braking resistor, or of a HVDC link. As the last line of defense, the function can initiate system separation by opening the interconnection lines in selected transmission sections, where the detected oscillations foreshow an impending start of cascade network trips.

2. LIGHT OVERVIEW OF METHODS AND LIMITATIONS FOR SMALL STABILITY ANALYSIS

Modern power systems are becoming increasingly interconnected to each other for the benefits of increased reliability, reduced operation cost, improved power quality and reduced necessary spinning reserve. However, the interconnected power systems also bring some technical challenges. Of them, inter-area low frequency oscillations have become one of the major threats to reliable operations of large-scale power systems. Inter-area oscillations not only limit the amount of power transfer, but also threaten the system security, because it may lead to system instability and as a result in cascading outages in the system. Therefore, it is essential to identify the characteristics of the inter-area oscillations, including oscillation frequency and damping ratio, so that proper actions can be taken based on the identification results to improve system damping and maintain system stability.

Basically, there are two approaches for low frequency oscillation analysis and parameters identification. One is dynamic model-based approach and the other is measurement-based approach.

With the dynamic model-based approach, the nonlinear differential equations are linearized around an operating point, and the power system oscillation modes are estimated through eigenvalue analysis. Based on eigenvalues, eigenvectors and participation factors, the system dynamic behaviors can be clearly predicted. Generally, a detailed representation of the entire interconnected system is required to study inter-area oscillation issues with this approach [2].

With the measurement-based approach, the low frequency oscillation mode estimation is done through direct measurements [3]. With the deployment of GPS-based PMUs in the system and the rapid advancements of WAMS (Wide Area Measurement System) technology in recent years, this approach is becoming more prevailing. Several algorithms have been developed to perform low frequency oscillation parameters estimation with WAMS.

3 INTER-AREA OSCILLATION DETECTION ALGORITHM

An inter-area oscillation detection algorithm, hereinafter referred to as SSOD (Small Signal Oscillation Detector), has been implemented on a modern digital relay to estimate the oscillation frequency and the oscillation magnitude on the tie line. Unlike the eigenvalue analysis and the Prony method that estimate the damping and frequency of all possible modes, the SSOD is intent to estimate the most dominant mode on the tie line so as to provide alert to system operators, or as the last defense step to separate the interconnected system when a persistent or an unstable oscillation occurs. The SSOD is based on the real time measured analogue quantities, for example frequency or real power on the tie lines between different power systems.

As shown in Fig. 1, the SSOD algorithm structure consists of 5 parts: data alignment and consolidation, data validation and filtering, oscillation frequency estimation, oscillation magnitude estimation, alarm and trip decision. They are described below respectively.

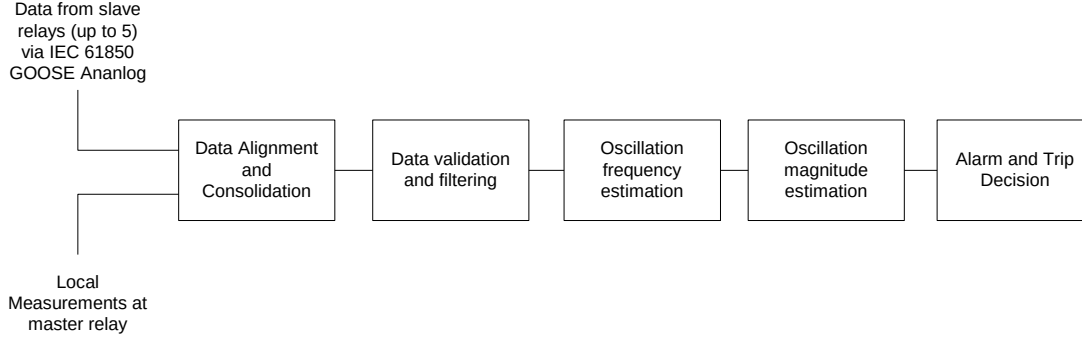


Fig. 1: SSOD Algorithm Structure

4. LOW PASS FILTERING

A low pass FIR filter, with cutoff frequency at 2 Hz, is applied to the signal $y_{ac}(n)$ to eliminate high frequency noises. The frequency response of the low pass filter is shown below. The signal after low pass filter is denoted as $u(n)$.



Fig. 3: Low Pass Filter

4.1 Oscillation Frequency Estimation

After the validation check is passed, frequency estimation will be started. A time domain estimation method of wide range frequency changes with sinusoidal signal [4] has been used in this implementation. The fundamental concept of this method is described below.

A time domain sinusoidal signal can be expressed as: $x(n) = X \cos(n\omega T + \phi)$, where T is the sampling period, and X is the amplitude of the signal. Consider the following function,

$$\begin{aligned} h_{k,m}(\omega) &= x(n-k)x(n-m) - x(n)x(n-k-m) \\ &= X^2 \sin(m\omega T) \sin(k\omega T) \end{aligned}$$

$$\frac{h_{2k,m}(\omega)}{h_{k,m}(\omega)} = \frac{X^2 \sin(m\omega T) \sin(2k\omega T)}{X^2 \sin(m\omega T) \sin(k\omega T)} = \frac{\sin(2k\omega T)}{\sin(k\omega T)} = 2 \cos(k\omega T)$$

$$\cos(k\omega T) = \frac{1}{2} \frac{h_{2k,m}(\omega)}{h_{k,m}(\omega)} = \frac{1}{2} \frac{x(n-2k)x(n-m) - x(n)x(n-2k-m)}{x(n-k)x(n-m) - x(n)x(n-k-m)} \quad \text{Equation 2}$$

With the above equation and let $m=k$, the raw frequency can be estimated from the time domain signal $u(n)$, and also the average frequency can be calculated accordingly, note that $u(n)$ is the signal after DC removal and low pass filtering as defined in 4.

$$f(n) = \frac{1}{2\pi k T_s} \arccos \left\{ \frac{1}{2} \frac{u(n-2k)u(n-k) - u(n)u(n-3k)}{u(n-k)u(n-k) - u(n)u(n-2k)} \right\} \quad \text{Equation 3}$$

$$f_{avg}(n) = \frac{1}{N} \sum_{i=0}^{N-1} f(n-i)$$

$$N_m = \frac{f_s}{f_{avg}(n)} \quad \text{Equation 4}$$

Where N_m is the number of samples in a full oscillation period, and k is a number of delay samples. Both of them vary during program running. In each loop of program running, if $N < N_m$, increase N by 1 and if $N > N_m$, decrease N by 1. In this way, Number N will gradually rather than abruptly approach to N_m , so as to keep the estimation more smooth and stable. K is set to the maximum value between $N/12$ and 3.

4.2 Oscillation Magnitude Estimation

Once the oscillation frequency is estimated, the number of N (i.e. the total number of samples in one oscillation period) is known accordingly. The oscillation magnitude is calculated by using the adaptive window length full cycle Fourier, i.e. the Fourier window length will follow the change of number N . The full cycle N points Fourier calculation is defined below:

$$C_p = \cos\left(\frac{2\pi}{N} p\right) \quad p = 0, 1, \dots, N-1$$

$$S_p = -\sin\left(\frac{2\pi}{N} p\right) \quad p = 0, 1, \dots, N-1$$

$$UC(n) = \frac{2}{N} \sum_{p=0}^{N-1} u(n+p-N+1) \cdot C_p$$

$$US(n) = \frac{2}{N} \sum_{p=0}^{N-1} u(n+p-N+1) \cdot S_p$$

$$Umag(n) = \sqrt{UC(n)^2 + US(n)^2}$$

Equation 5

In this way, the estimated oscillation magnitude will be accurate as long as the frequency is estimated accurately. The input signal (red trace) and the estimated oscillation magnitude (black trace), by using the adaptive window length Fourier, are plotted in the following figure. It can be seen that the estimated magnitude follows the input signal magnitude very well under varying frequency and varying magnitude condition.

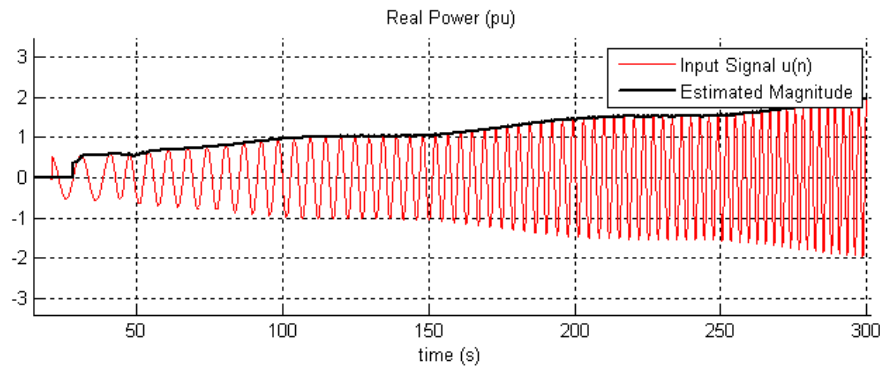


Fig. 4: Magnitude Estimation by Adaptive Window length Fourier

4.3 Alarm and Trip Decision

The SSOD element logic is shown in the following figure. It can be seen that the pickup level and the time delay for alarm and trip can be set independently to accommodate different application requirement, for example, the alarm can be set more sensitive and with shorter delay than the trip. Besides, the SSOD element is also supervised by the measured oscillation frequency, i.e. in order for SSOD to pickup, the estimated oscillation frequency must be within the frequency range of interest as specified by the Low Frequency and the High Frequency setting. Alarm and trip output are asserted when the pickup conditions are satisfied and the associated pickup timers are expired.

5 TEST RESULT ANALYSIS

Various tests have been carried out to validate the described algorithm and to check the performance of the SSOD function in the relay. Basic functional tests are performed using math function driven signals under various conditions, including different number of slave relays, using frequency or real power as inputs to the SSOD, different levels of oscillation magnitude and oscillation frequency, different dead band settings and noises, step change and a ramping signal applications, etc. Real time power system simulation tests are also carried out to test the performance of the SSOD element under various power system operating conditions using RTDS (Real Time Digital Simulator). Besides, the IEC 61850 communication link, data alignment and aggregation, data loss and error handling are also tested thoroughly.

5.1 Basic Functional Test by Math Function Driven Signal Injection

Case 1: Sensitivity Test with a fixed oscillation frequency

This test is to check the sensitivity of the SSOD function. In this test, the input signal was applied with a low oscillation magnitude (0.07 pu of oscillation peak value at 0.15Hz of oscillation frequency). The trip and alarm pickup level were both set to 0.03 pu and without delay. It can be seen that both trip and alarm picked up at the same time as expected. The oscillation magnitude was estimated accurately by the SSOD element, and plotted in the following figure.

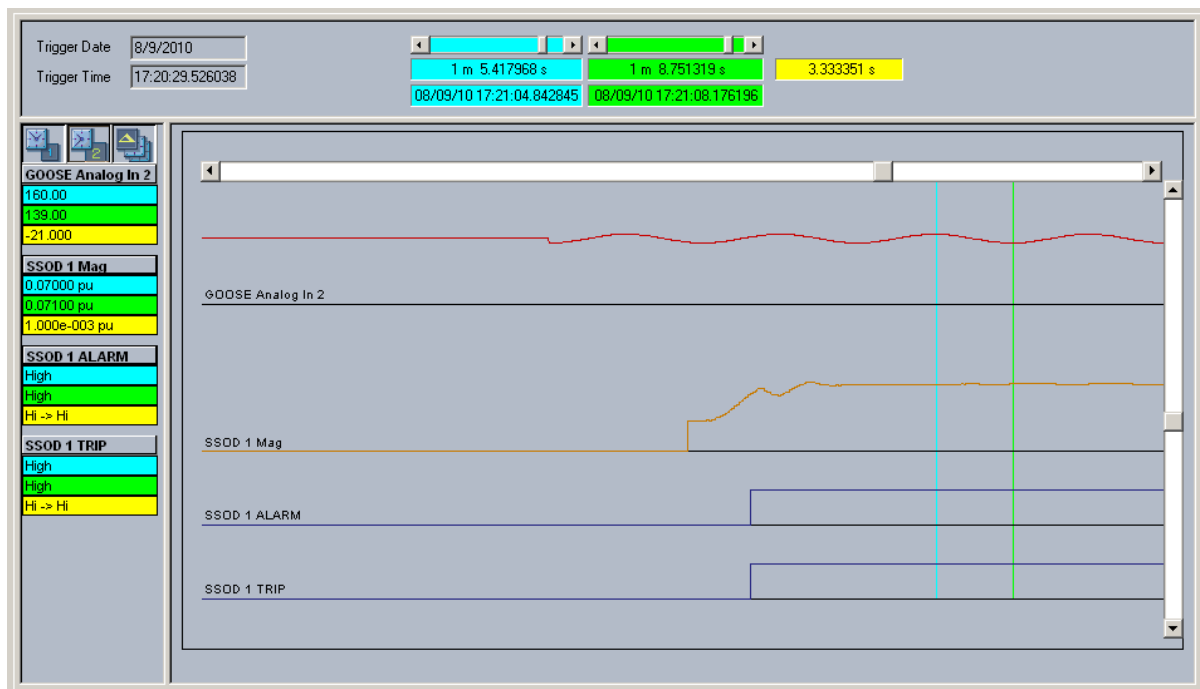


Fig. 5: Sensitivity Testing

5.2 RTDS Dynamic Simulation Test

The 2-area 4-machine system that was specified in [5] has been used for the RTDS dynamic simulation test of the SSOD function. The single line diagram and the associated RTDS model of the said system are shown in the following figures, where GEN 1 and GEN 2 are in area 1, and GEN 3 and GEN 4 are in area 2. The 4 machines are identical and each of them is rated at 900MVA, and connected to the system via a Delta/Wye 900MVA transformer (20kV/230kV). The line impedance listed in the single line diagram is in per unit with a 100 MVA base.

Many researchers have used this 2-area 4-machine model in their small signal low frequency oscillation studies. Though the system is simple, the dynamic characteristic of the inter-area oscillations and general conclusions drawn from this model are valid [5], and can be applied to large systems.

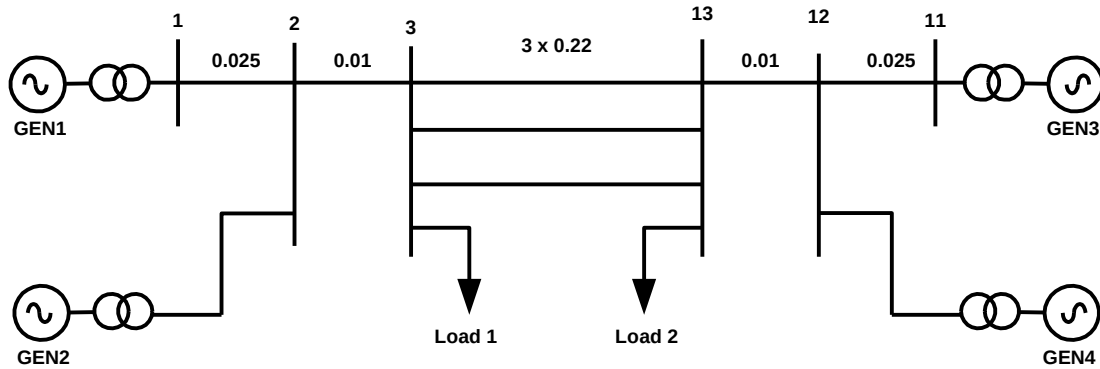


Fig. 6: Single Line Diagram of the 4-Machine System

1. Case 1

Case Description:

- Number of tie line in service: 3
- PSS installation: GEN1 only
- Area 1 and area 2 have the same generation and load: 1400 MW generation and 1367 MW load.
- Power flow on the tie lines: 0 MW

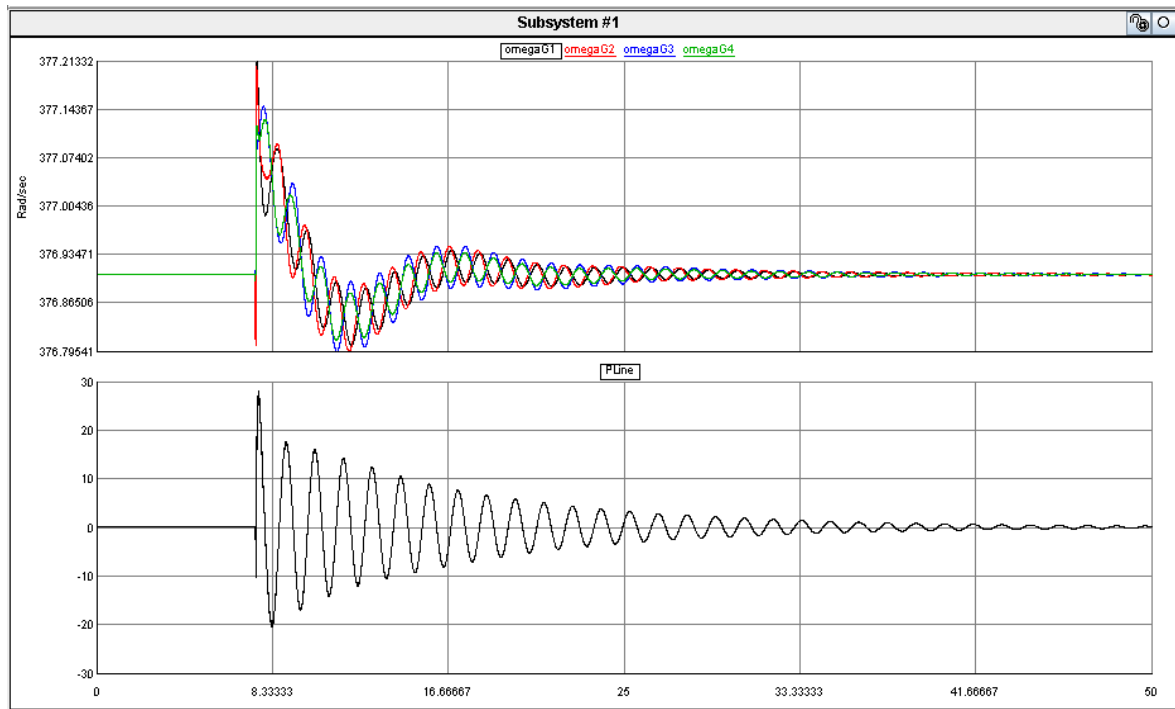


Fig. 7: RTDS Simulation Runtime Plot

It can be seen that this is a stable oscillation, but with insufficient damping. The damp ratio is much less than 5% (magnitude reduced to 33% after 3 periods). This oscillation took about 10 cycles to drop to 33%, which was equivalent to a damp ratio of approximately 1.8%.

The estimated oscillation magnitude and oscillation frequency from the real power measurement signal on the tie line by SSOD are plotted below. The oscillation frequency is 0.734 Hz. Both the damping ratio and the oscillation frequency agreed with reference [5]. The SSOD element alarm has been asserted (indicating the oscillation magnitude has exceeded 0.1 pu for at least 5 seconds), but no trip output is asserted.

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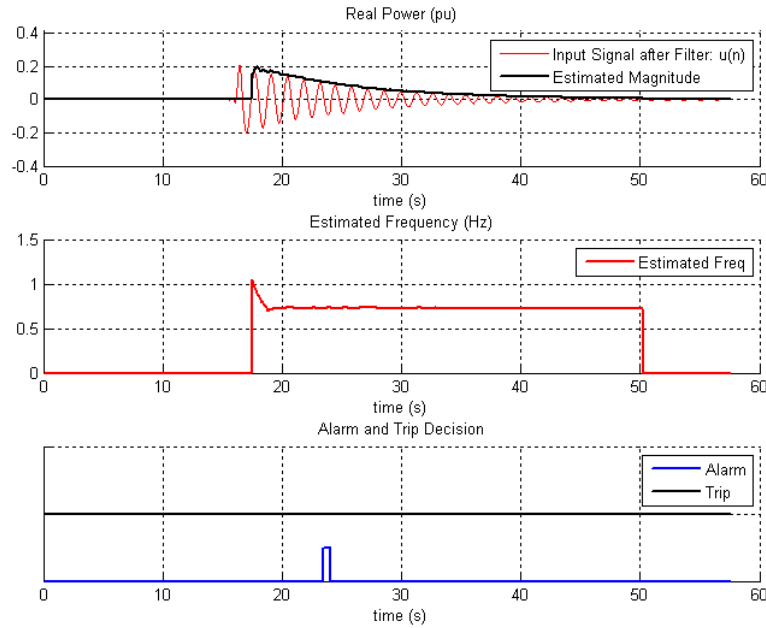


Fig. 8: SSOD Measurement and Action

2. Case 2

Case Description:

- Number of tie line in service: 1
- PSS installation: GEN1 only
- Area 1: 1670 MW generation and 1367 MW load.
- Area 2: 1140 MW generation and 1367 MW load.
- Power flow on the tie lines: 300 MW

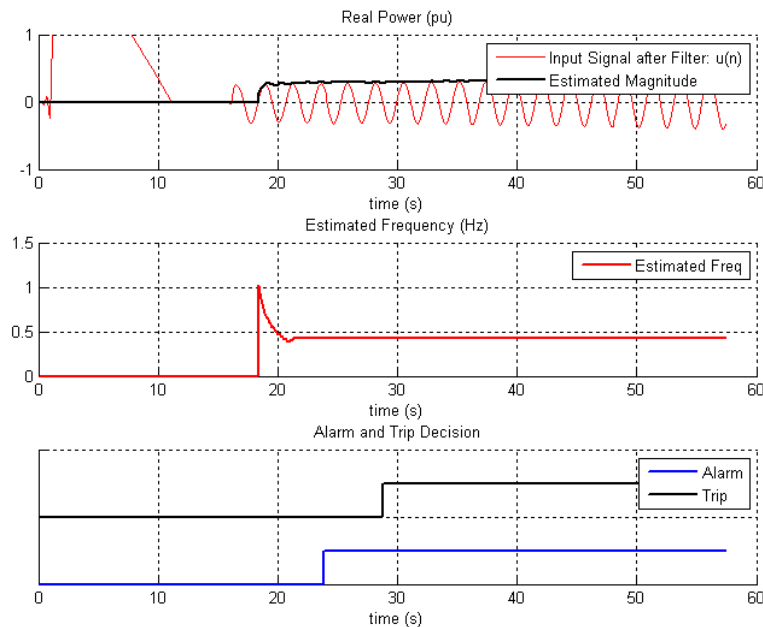


Fig. 9: Case 2 PSS-2 On

It can be clearly seen from the above figure that this is an unstable oscillation. Compare to case 2, the oscillation frequency further dropped (to 0.433Hz) because of the increase of the power flow on the tie line. Both alarm and trip were asserted correctly for this unstable oscillation test case.

As shown in the above figure, alarm was asserted in 7.7 seconds after the disturbance occurrence, and trip command was asserted in 12.7 seconds after the disturbance.

6 CONCLUSION

This paper describes an algorithm for small signal oscillation detection (SSOD) based on the direct measurement data, which identifies the most dominant oscillation mode on the tie lines using the adaptive window length Fourier and the time domain frequency estimation method. When poorly damped or unstable inter-area oscillation is detected, an alarm or a trip command will be initiated to alert the system operators, or as a last defense step to separate the interconnection lines to avoid further cascaded network trips.

Various validation-checking conditions have been applied to prevent the SSOD algorithm from responding to noise, or other non-oscillatory variations of the input signal, such as step change, ramping. The SSOD algorithm has been implemented on a modern digital relay, and has been extensively tested for consistency and accuracy in the lab, both with math function driven signals and with real power system simulation signals using RTDS.

The type of relay presented in this paper, with SSOD function, has been installed in Turkey system, to detect low frequency (0.1–0.2Hz) inter-area oscillations on the 3 x 400kV lines connecting the Turkish system to the Continental Europe Synchronous Area System via Greece and Bulgaria. The initial settings of the SSOD relay are 30mHz-10s for alarm and 60mHz-50s for system separation.

To further damp the inter-area oscillations, it is planned to add in Turkey a special control scheme to N°4 static var compensators (SVCs) each rated at about ± 300 MVAR, that are in service in arc furnace steel factories. In case of build-up of inter-area oscillations in the frequency range of 0.1 to 0.2 Hz exceeding a set amplitude, detectors will modulate the SVCs MVAR output in phase with the frequency of oscillation, thus modulating by a few percent the supply voltage of the arc furnaces. The resulting proportional modulation of real power absorbed by the arc furnaces is expected to compensate the power flow oscillations on the interconnection lines and to damp the inter-area oscillations.

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