LOW FREQUENCY OSCILLATIONS IN POWER SYSTEMS: A REVIEW

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Abstract:

Low frequency oscillations (LFO) are a frequent harmful phenomenon which increases the risk of instability for the power system. They limit the steady-state power transfer and change the operational system economics and security. The identification of LFO and solution to LFO problems with reference to power system stabilizer is carried out in this literature survey.

I. INTRODUCTION

In 1969, F.P. Demello **[1]** analyzed the low frequency oscillations in OMIB by use of damping torque conception and indicated that the basic reason of low frequency oscillations is negative damping action. Low frequency oscillations can cause over current in tie lines and loss of synchronism between systems and generator sets and destroy the stability of power systems **[2-3].** Damping of LFO and its effect in Central China power grid and Sichuan-Chongqing power Network are studied in **[4].** Low frequency oscillations in the power grid can be classified into three types associated with power system events, non-obvious disturbances, and normal power system operations and statistical analysis of oscillations occurring between 2009 and 2010 was conducted to determine the numbers and percentages of each type based on the oscillation data captured by FNET **[5].**

Now a days, many power systems face the problem of troublesome power oscillations in the range of 0.1 to 2.5 Hz due to heavy load condition or system interconnection **[6-10].** LFO cases have been studied in **[11].** The use of high-gain, low time constant automatic voltage regulator, or efforts to transmit bulk power over long distances may create LFOs with negative damping **[12].** The damping of these Oscillations is commonly performed with power system stabilizers **[13].** LFO occur with electric fields that are in the range of 0.5 kv/cm to about 2.5kv/cm which is well below the field required for inter valley transfer [**14].** Low-frequency oscillations in various GaAs FET structures have also recently been reported **[15-17]**. Low-frequency oscillations in GaAs MESFET's were observed under back-gating conditions where FET oscillations are directly related to oscillations in leakage currents in the semi-insulating GaAs substrate [**18].** The effect of prime moves and governors on LFOs is analyzed by using eigenvalue, relativity method and show that the prime mover and governors make inhibition for the LFOs to some extent **[19]** Low frequency oscillation have occurred many times in actual power grid. Some experts and scholars conduct a lot of useful studies **[19-24],** and give forced resonance mechanism of low frequency oscillation. The interactions between thermal system and power system are considered and the sources of resonance mechanism low frequency oscillations in power system are explored in theory in **[24-25].** Increasing active load power at various buses in the power system lead to the development of many oscillations at low frequency in the power system and found that it was easier to identify unstable modes of oscillation using the constant current and constant impedance load model than using constant current model **[26].**

The structure of this paper is outlined as follow: overview issues of LFO in Section II. Identification of LFO in Section III. PSS as solution to LFO problems in Section IV. Finally, Section V summarizes the study.

II. AN OVERVIEW ISSUES OF LFO

Oscillations in power systems are classified by the system components that they affect. Some of the major system collapses attributed to oscillations are described [**27].** Electromechanical oscillations are of the following types: interplant mode oscillations, local plant mode oscillations, inter area mode oscillations, control mode oscillations, tensional modes between rotating plant **[28].** There are two types of such oscillations referred to as local mode and inter-area mode, corresponding to a single machine- to-infinite-bus structure and those occurs in interconnected power systems respectively **[29-31].** Low-frequency oscillations have happened several times in Central China power grid [**32].** Strong LFOs in the 100-MHz range can interfere with the diagnostic and control system of the gyrotron as was observed in General Atomics **[33]** and coaxial gyrotron **[34].**

The power system low frequency oscillations of resonance mechanism might be caused by the pulsation of turbine's main steam pressure, when its pulsating frequency is consistent with or close to power system natural oscillations frequency. In thermal system, the introduction of a large number of control strategies is one of the reasons that caused the turbine pressure pulsation **[35].**

III. IDENTIFICATION OF LFO

On LFO identification, there are Fourier method, Prony method **[36-38.],** HHT **[39]** and signal energy method **[40].** Fourier method can't show damping and instantaneous frequency of oscillations. Although Prony method can quickly analyze the dominant mode, it is more sensitive to noise, and it is difficult that which mode is chosen when several signals are identified **[41].** Wavelet can analyze time-varying characteristics, but the selection of wavelet bases is still difficult. HHT method is used in fields of atmosphere, medicine and structural engineering**.** Yang **[42-43]** made use of HHT to identify structural dynamic parameters and proposed a method to identify vibration modes, frequency and damping.

Prony analysis is a technique of analyzing signals to determine model, damping, phase, frequency and magnitude information contain within the signal where each exponential component with a different frequency is viewed as a unique mode of the original signal [**44].** Besides, Ref. **[45-46]** has compared Prony algorithm with Fourier analysis and eigenvalue analysis and shows that the Prony algorithm has advantages to obtain the oscillation information, but the results usually contain more than one mode **[47].** The standard Prony method can be sensitive to the noise. Hence, the improved Prony method **[48]** has been developed, which is similar to the Kumaresan and Tufts (KT) **[49]** algorithm. This method uses the order of the signal subspace i.e. it discards the noise from the noise subspace, while in KT method, the singular values corresponding to the noise are set to zero. However, the method has some sensitivity towards the noise. In Ref **[50],** a method based on noise space decomposition (NSD) for the identification of low frequency oscillations in power systems which uses a median filter to reduce the variance of the estimated modes has been proposed**.** A comparative analysis of the existing improved Prony method with the proposed method has been presented on a test signal having different noise levels. It is observed that the proposed method performs much better than the improved Prony method in terms of reducing the standard deviations in frequency and damping of the estimated modes.

The Wavelet transform is a mathematical tool, like the Fourier transform for signal analysis. A wavelet is an oscillatory waveform of effectively limited duration that as average value of zero [**51-52].** It is a relatively new signal processing tool and is applied recently by many researchers in power systems due to its strong capability of time and frequency domain analysis **[53-54].** Application of wavelet analysis is presented in **[55-57].**

Eigenvalue analysis technique is based on the linearization of the nonlinear equations that represent the power system around an operating point which is the result of electromechanical modal characteristics: frequency, damping and shape **[28].** Different eigenvalue methodologies have been discussed in **[58].**

Prony analysis and eigenanalysis are complementary methods **[45].** A new technique for low frequency oscillation analysis of bulk interconnected power system by combining sparse eigenvalue analysis with Prony method. This technology not only grantee the reliability and convergence of the sparse eigenvalue calculation, but also has no limitation to the size of the system scale [**59].** An Improved Prony based method with median filter employing PMU measurements for identifying small signal oscillations in power system has been proposed and a comparative analysis of the standard Prony with the improved Prony method shows that, the improved Prony method performs much better than the standard Prony method in terms of the standard deviations in frequency and damping of the estimated modes **[60].**

Another improved Prony method which uses dynamic variation ratio (DVR) and signal to noise ratio (SNR) to prescribe the standard parameter choice has been proposed and it perform more efficient identification than common Prony method **[61].** A noise space decomposition (NSD) based method along with median filter, employing PMU measurements, for identifying the small signal oscillations in power systems and a comparative analysis of the existing improved Prony method with the proposed method shows that the proposed method performs much better than the improved Prony method in terms of reducing the standard deviations in frequency and damping of the estimated modes **[50].**

An energy-sorted Prony method can reliably identify the dominant modes by sorting the energy of each mode and this method outperforms the basic Prony method when the trivial modes with low damping modes are exist in the system **[62].**

The popular index used to identify the source of LFO is the node contribution factor (NCF), which reflect the contribution of the node in the corresponding LFO. Currently, there are two approaches to calculate the NCF. One is based on the eigenvalue analysis **[63],** and the other is based on the measured data. Currently, the popular measured data based approaches for NCF are the Fourier algorithm, Prony algorithm **[45]**, wavelet algorithm **[64]** and Hilbert-Huang transform (HHT) **[65-66]**. On the other hand, with the rapid development of Wide Area Measurement System (WAMS) which is based on synchronized phasor measurement unit (PMU), it is possible to quickly acquire the voltage, current and other information, and furthermore, extract the information of LFO and calculate the NCF. In ref **[67]**, the proposed algorithm is based on the measured data and the HHT approach which is more effective method to calculate the NCF for LFO of power system. Unusual vertical and meridional heat distribution oscillation that may need further study and may help reveal new dynamics of the ocean have been found in **[68-69]** presents a Newton-type current injection model of the UPFC for studying low-frequency oscillations of a power system installed with a UPFC. The main contribution of this paper is the derivation of the Newton-type iteration formulation based on the current balance equations. There are several approaches in the current injection model **[70-72**]. A practical analysis method of low frequency oscillations is proposed, which combines the QR eigenvalue algorithm and Prony method which is suitable for analyzing low frequency oscillations of large power systems **[73]**. Analysis is made that the low frequency oscillation modes of power systems with hydropower plants do have relationship with the parameters and operating points of hydro-turbines and governors is performed using eigenvalue, relativity and sensitivity methods **[74].** An online determination of the low frequency oscillation modes based on PSS/E in large interconnected power system and the result indicate that different modes correspond to different phase angle combinations, and vice versa **[75].**

A principal component analysis subspace tracking algorithm for parameter identification of low-frequency oscillation has been presented **[76]** which has the advantage of prony algorithm, high resolving power, and it's very suitable for parameter identification of low-frequency oscillation.

To solve mode mixing, Improve HHT is put forward to identify parameters of LFO and beginning and end moment of disturbance, high-frequency oscillations, and nonlinear oscillations **[77].** Inter-area oscillation in interconnected power system is analyzed and showed that the frequency and damping of the inter-area oscillation are in close relations with inertia constant, tie-line power flow and excitation characteristic **[78].**

IV. PSS A SOLUTION TO LFO PROBLEMS

A PSS is an additional control block used to enhance the system stability. This block is added to the AVR, and uses stabilizing feedback signals such as shaft speed, terminal frequency and/or power to change the input signal of the AVR. The three basic blocks of a typical PSS model are stabilizer Gain block, which determines the amount of damping. The second is the Washout block, which serves as a high-pass filter, with a time constant that allows the signal associated with oscillations in rotor speed to pass unchanged, but does not allow the steady state changes to modify the terminal voltages. The last one is the phase compensation block, which provides the desired phase-lead characteristic to compensate for the phase lag between the AVR input and the generator electrical (air-gap) torque **[79].**

Since the early 1960s, power system stabilizers have been considered as integral components of the excitation systems installed on all large generators on the Ontario Hydro system. The use of these PSS units continues to produce millions of dollars of annual benefits **[80-82].**

CHARACTERISTICS OF ALTERNATIVE INPUT SIGNALS

The general frequency response characteristics of stabilizers utilizing alternative input signals **[83-86]** are designed over the last 30 plus years. The various inputs are speed, frequency and power **[13, 87-89].**

PSS DESIGN CONCEPTS

The developments in the area of PSS in the power systems have been discussed through the various PSS system designs methods. Most of the PSS designs are based on the application of techniques developed in the area of control system designs. Different designing methods from late 1980s to till 2014 have been discussed in this section.

The application of WEIGHTING FUNCTION in designing PSS is explained in **[90].** Some investigations on applying $H\infty$ methods to the PSS design are also presented in **[91-92].** A simple and effective way of selecting weighting functions is discussed in **[1].** The design method presented in **[93]** for single-machine power systems are extended to multi machine systems in **[94].** The design is based on the use of Pseudo Global System Models (PGSM).

Same $H\infty$ Optimization Method **[95-96]** is used and to test the robustness of the designed PSS, experiment was conducted over various operating points. A new robust design of PSS applying $H\infty$ mixed sensitivity technique is proposed to mitigate low frequency oscillations **[97].** The motivation to apply this control strategy is the simplicity and flexibility of synthesis procedure. The reduction in the controller complexity is averted by reducing system size keeping in view suitability for practical installation. Zames originally formulated the $H\infty$ optimal control theory **[98].** Demonstrations of $H\infty$ based design techniques for controllers applicable to power system have been reported in literature **[99]**

Application of an Eigen solution Free Method **[100]** make use of the **[101].** The major contributions of this paper are the presentation of a new method of reduced-order modal analysis, which is completely independent of the eigensolution. It is difficult to obtain accurate physics model of power system **[102].** Prony analysis describes the mathematical model of equal space sampling data by a linear combination of exponential functions The results of small disturbance analysis show that the method improves system eigenvalue and enhance system damping after PSS whose parameters are optimized by above method is set into system. Therefore, according to the result based on iterative Prony analysis, to adopt residue method to configure PSS parameter optimally is viable **[103].**

In the last few years, application of Genetic Algorithms (GAs) to design power system controllers has attracted considerable attention. But the drawback of GA is that, the performance depends on the optimal selection of its operators. To cope with the GA limitations, Population-Based Incremental Learning (PBIL) was originally proposed by Baluja **[104-105**]. The issue of tuning the parameters of the PSSs has been converted into an optimization problem which is solved via PBIL and GAs. Comparison between PBIL-PSSs and GA-PSSs in **[106]** shows that PBIL-PSSs perform better than GA-PSSs and gives adequate and consistent damping.

The PSS designed using conventional method performs well around the nominal operating condition. However, its performance degrades as the system becomes more loaded **[107].** BGA-PSS performs slightly better than the GA-PSS. GA however has some limitations such as premature convergence, difficulties in selecting optimal genetic operators as well as the high computational capacity required in solving complex optimization problems. In order to deal with some of the limitations, Breeder Genetic Algorithm (BGA) was proposed by John Greene **[108].** This paper uses a slightly different version of BGA known as adaptive mutation BGA.

The Bacteria Foraging Algorithm has been reported by Mishra, Tripathy, and Nanda **[109]**. A new procedure for improving BFA called Smart BFA is a modification of the classical BFA and is applied for tuning the PSS coefficients in a multi machine power system. Due to having the bacteria conduction at a smart direction, the cost function decrease is better than the classical BFA and the speed convergence is also increased **[110**]. Large order models are reduced by PSO technique developed by Eberhart and Kennedy **[111]** which was inspired by the Social behavior of Bird flocking and fish schooling.

A new method based on the big bang-big crunch theory is introduced **[112]**. BB-BC algorithm has already been applied to different areas such as airport gate assignment problem **[113],** fuzzy model inversion **[114],** non-linear controller design **[115]** and target motion analysis **[116].**

Artificial Bee Colony proposed by Karaboga **[117-119]** is a new technique proposed to optimize the parameters settings of CPSS. Another version of ABC is Interactive ABC, Investigations reveal the performance of IABC based multiband power system stabilizers in a multi machine infinite bus system is better in terms of settling time and peak overshoot under fault conditions and provide good damping characteristics during small disturbance and large disturbances for local as well as inter area modes of oscillations **[120]**

S Paul and K RO proposed Oppositional gravitation search algorithm **[121].** The computed results obtained are compared with other population based optimization techniques like GSA, DE and the proposed algorithm show more potential than other population based optimization algorithms.

The coordinated design of the UPFC-PSS **[122-123]** and PSS-TCSC **[124-125]** and PSS-SVC **[126]** stabilizers are significantly more efficient in damping oscillations and improving stability compared to an individual design of these stabilizers.

V. CONCLUSSION

From the critical review, a general potential research direction with strong feasibility in practical applications is introduced to stabilize damping low frequency oscillations in power systems. The work brings various interesting research issues in LFO and various identification techniques followed by discussion about different power system stabilizer design methods. Hopefully it will be a useful reference for the interested researcher.

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