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Low frequency oscillation in power system: a survey

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***Abstract*: Low frequency oscillations are commonly experienced on the moder transmission system. Their frequency ranges are between 0.1-2.5 2.5 Hz and is related to the dynamic power transfer between areas. These oscillations can severely restrict system operations by requiring the curtailment of electric power transfers as an operational measure. These oscillations can also lead to widespread system disturbances if cascading outages of transmission lines occur due to oscillatory swings. Previously power system stabilisers are used to suppress these oscillations and many researchers have worked on it. This paper provides a survey of many of these work done.**

Keywords: LFO, power system;

I. INTRODUCTION

Power system operation is characterized by the random variation of the load condition, continuous change in generation schedule and network interconnection. Moreover, power systems are subject to different exogenous disturbances such as actions of different controllers, switching of lines or increasing such loads in the system. Such disturbances will initiate low frequency power system oscillations which should be consequently endangering the overall stability of the system. Ones the low frequency oscillations started, they would continue for a while and disappear, or continue to grow causing system separation. In modern power system operation, the low frequency power system oscillations initiated by disturbance have been one of the major concerns. The oscillations may sustain and grow to cause system separation if adequate damping is not available. Over last 25 years, the problems of low frequency power system oscillations have assumed importance. The frequency of oscillation is in the range of 0.2 to 2.0 Hz. The lower the frequency, the more widespread are the oscillations (also called inter – area oscillations). In the recent years many efforts have been dedicated to damp these low frequency oscillations, additional positive damping is required which can be provided by supplementary excitation control. In the late 1950's and early 1960's most of power systems used automatic voltage regulators (AVR) to provide useful damping to the power system to maintain the overall stability of the power system. Nowadays power system stabilizer (PSS) is one of the most important controllers in modern power systems for damping low frequency oscillations. Traditionally, the conventional power system stabilizer (CPSS) mostly used to obtain damping to the system using ($\Delta\omega r$) as a stabilizing signal. The conventional power system stabilizer (CPSS) will enhance the performance and the stability of the system. Optimal control theory has been utilized for the design of optimal power system stabilizers to obtain optimal performance. Recently, alternative control schemes that does not require model identification, and required less computational efforts than the self tuning controllers and easier to be implemented on a microcomputer. Fuzzy logic based power system stabilizers is an example of such scheme. In most of these studies the power system considered is a single machine infinite bus (SMIB) or multi-machine system with classical model for the synchronous machine. The block diagram of a synchronous excitation system is as shown in below figure.

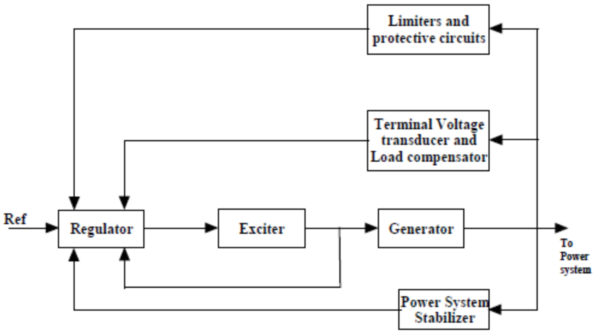

Figure: Block diagram of synchronous generator power system

Components in above system model are analog in nature. The main function of a power system stabilizer (PSS) is to introduce a component of electrical torque in the synchronous machine rotor that is proportional to the deviation of the actual speed from synchronous speed. When the rotor oscillates, this torque acts as a damping torque counter to the low frequency power system oscillations.

In this paper we have surveyed the work done by researchers previously, so that it can provide a milestone for the future developments.

II. LITERATURE REVIEW

Numerous works have been done and published on the damping of power system low frequency oscillations. This section will review some of the published work in this area. DeMello and Concordia [2] used a single-machine infinite bus system to analyze the nature of the low frequency electro-mechanical oscillations in power systems. They were the first to explain the phenomena of oscillation by the concepts of synchronous and damping torques, and stated that lack of adequate damping torque is the cause of oscillation or instability. They developed a linearized model of a synchronous generator and its excitation system connected to an infinite bus in the form of a block diagram. Based on this block diagram, the authors came up with expressions of torques and thus revealed the effect of excitation system on stability: normally, the AVR actions increases the synchronizing torque and decreases the damping torque inadvertently. Based on this understanding, the authors used frequency domain methods to develop a speed-based PSS to compensate this negative impact on damping torque caused by the excitation system and demonstrated the effectiveness through analog simulation.

Kundur et al. [3], provided the analytical work and systematic method to determine PSS parameters for large power generation in a practical power system. The basic PSS design idea in this paper is based on the stabilizer proposed in [2]. However, the phase characteristics were obtained using a multi-machine eigenvalue program instead of a single machine model. This work emphasized enhancement of overall system stability, and the authors considered simultaneous damping of inter-area and local modes and discussed the performance of the PSS under different system conditions. In addition to small signal stability performance, the authors also tested the transient stability performance of the PSS and the performance during system islanding. The authors also demonstrated the importance of appropriate choice of washout time constant, stabilizer output limits and other excitation system control parameters. The authors claimed that the frequency response method used to compensate the lag between the excitation input and the electrical torque was fairly robust.

Chow and Sanchez-Gasca [4], proposed four pole-placement techniques for the design of power system stabilizers, with the emphasis on frequency response characteristics of the controller. For controllers to exhibit desirable frequency response characteristics, a simple procedure was proposed to obtain controllers suitable for multiple operating conditions. The issue of robustness of state space designed controllers was investigated.

Hsu and Cheng [5] proposed a power system stabilizer (PSS) based on fuzzy set theory. Speed deviation Dw and acceleration (Dw&) were chosen as the input signals to the fuzzy stabilizer. A classical Mamdani type fuzzy system [70] was used to build a mapping relationship from inputs to control output. A seven-by-seven rule table was employed, and all the membership functions were determined based on the authors' experience and no optimization on these membership functions was considered in their paper. The proposed PSS was tested on a two-machine nine-bus system including an infinite bus. The results reported showed better damping as compared with a conventional lead-lag PSS. Hiyama published a series of papers on applying rule-based fuzzy logic controllers to stabilize power systems [6,7,8,9]. He used speed deviation and acceleration as two inputs and constructed a phase plane. The phase plane was divided into several sectors which represent different control regions and require different control actions. Most parameters used in this controller are represented in a linguistic form. For example, the gain levels high and low were used to implement "strong" and "slight" controls respectively. The gain of the controller is also dependent on how far the state is from the origin of the phase plane, which is the equilibrium point of the generator: it is proportional to the distance from the origin within a given threshold, and is a constant beyond that. To achieve optimal performance, an optimization routine is used to determine the optimal parameter setting. A time-domain summation of squared errors is used as the performance index, and the parameters are optimized sequentially. Simulations were performed on a single machine infinite bus system and a 3-machine 9-bus system. The results showed damping improvement over conventional stabilizers.

In [8] Hiyama presented a modified version of the rule-based stabilizers. Instead of using two gain levels and sign of the control signal to realize the control strategy as reported above, he introduced a fuzzy logic scheme to describe the transition of different controls. The same sequential optimization technique was again used to get a minimal oscillation. However, inferior performances or even instability associated with a condition was reported in [10] when the acceleration and speed deviation were close to zero while the phase was not at its steady-state value. A PID Type fuzzy logic stabilizer was introduced to solve this problem: the information of the integration of the speed deviation was also used as one input and the origin of the phase plane was moved leftward or rightward depending on the sign of the integral. Both simulations and experiments were performed to demonstrate the effectiveness of the modification. Hiyama's heuristic based approach showed some success in his series of research works. However, in his work, the fuzzy PSS parameters were not optimized in a global sense because he claimed the parameters are reasonably insensitive to external conditions. In reality, this approach is only considered robust in the cases considered in his design. Malik is another person who has done a lot of work in designing fuzzy logic based and neural network based PSS.

In [11], Hariri and Malik proposed a fuzzy logic based PSS; the parameters of their PSS were trained off-line so that it works like the self-optimizing pole shifting APSS proposed in [12]. The training was performed over a wide range of conditions for the generating unit and a wide spectrum of possible disturbances was used for the training. Malik and He presented a recurrent neural network based adaptive PSS in [13]. The basic architecture has two recurrent neural networks. One works as a tracker to learn the dynamic characteristics of the power plant and the other as a controller to damp the oscillations. The weights of the neural network are updated on-line using real time recurrent learning. Both of the proposed PSSs were tested only on a one machine infinite bus system and they both showed better damping results than a conventional PSS for that small system.

In [14], Shamsollahi and Malik also proposed a neural adaptive PSS with a similar architecture as the PSS proposed in [13]. However, the training process and training method are different than their former work. In this work, the adaptive neural identifier was first trained offline before being used in the final configuration. Further training of the adaptive neural controller and adaptive neural controller is carried out in every sampling period employing the on-line version of the back propagation method. They applied this neural adaptive PSS both in a SMIB system and a 5 machine system [15]. Also, they investigated the coordination of CPSS and proposed PSS and the self-coordination ability of the proposed PSSs by simulation. It was shown that the proposed PSS not only provides better damping than CPSS, but also coordinates itself with existing PSSs already installed in the system due to its on-line learning ability. The implementation and experimental test of this PSS was performed in the Power System Research Lab at the University of Calgary and the work was reported in [16]. The digital control system composed of a micro-alternator, a Programmable Logic Controller acting as AVR, a data acquisition system and a PC-based Man-Machine-Interface routine and a DSP board as the controller. The proposed PSS was tested for a variety of operating conditions and disturbances. The experimental results verified the simulation results and conclusion in [15].

Another research effort on this topic is the application of Genetic Algorithm, Fuzzy Logic, Neural network or other intelligent methods to adjust or select an optimal set of parameters for PSS. In [17], a neural network was used to tune the parameters of a conventional PI type PSS. Wen, Cheng and Malik [18] designed an optimal fuzzy logic excitation controller by applying GA in the design process to select all the parameters of the fuzzy controller. Abido [19] designed a hybrid rule based PSS by incorporating GA to search for optimal settings of his proposed PSS parameters. In [20], the simultaneous stabilization of a power system over a wide range of operating conditions via a single-setting conventional power system stabilizer using GA is investigated. The authors wanted to select a single set of power system stabilizer parameters which can make the PSS simultaneously stabilize the power system over a wide range of operating conditions. They treated the power system operating at various loadings as a finite set of plants. The problem was converted to a simple optimization problem which is solved by a genetic algorithm and an eigenvalue based objective function. Two objective functions were presented, allowing the selection of the stabilizer parameters to shift all or some of the system eigenvalues to the left-hand side of a vertical line and a wedge-shape sector in the complex s-plane. The authors proposed in [21] a similar idea to design a PSS. However, another optimization method, tabu search was used to select PSS parameters. Lu, Nehrir and Pierre [22] proposed a power system stabilizer with a fuzzy logic based parameter tuner. Reduced order linear models for the synchronous generator at a large number of operating points were obtained and the optimal PSS at each operating point were designed by the traditional frequency domain method. In addition, a fuzzy signal synthesizer is introduced to achieve adaptiveness based on the operating condition. They also applied a similar idea for Static Var Compensator (SVC) controller design [23].

Various approaches were also proposed to design damping controllers for different FACTS devices. Larsen, Sanchez-Gasca and Chow [24] tried to represent each electromechanical swing mode in terms of a synchronizing and a damping torque with control loops built around it. They proposed the idea of modal decomposition. In this paper, the impact of the synchronizing and damping components of torque on each electromechanical mode of oscillation in a multi-machine system is determined by decomposing the system variables into their modal components. For each power swing mode, the block diagram representation of modal synchronizing and damping torques similar to [2] is derived and a similar controller design method is used. This method was applied in a Thyristor-controlled Series Capacitor (TCSC) damping controller design in [25]. However, the authors used the multi-modal decomposition on an identified low-order system model rather than on the exact system model. Noroozian, et al, proposed a very interesting control strategy for SVC and TCSC in [26]. The author incorporated the model of SVC and TCSC in an energy function and then derived the control law by taking the derivative of the energy function and making this derivative be negative. The author also claimed that by using this method, each device can contribute to the damping of power swings without coordination with other power oscillation damping devices. In [27], Ghandhari, Andersson and Hiskens applied Lyapunov function theory to design a controller for controllable series devices. They derived the control strategy by making the derivative of the energy function be negative. However, the model used in the development of the control laws has a specific form. It is made convenient for obtaining a Lyapunov function, but it doesn't precisely describe actual power system behavior. Ramirez Arredondo represented the power system in the form of a Hamiltonian system and designed a passivity-based nonlinear controller for a TCSC to enhance power system stability in [28]. This control strategy was only tested on a one machine infinite bus system. Rosso, Canizares and Dona proposed a hierarchical control strategy for both dynamic and steady state stability enhancement [29]. Control Strategies to mitigate adverse interactions among the TCSC hierarchical controls are also presented. In this paper, the authors analyzed and compared various locally measurable input signals qualitatively using the equal area criterion. However, due to the limitation of the method, they only concentrated on comparing the use of active power and line current as input signals and did not make an effort to analyze the possibility of using bus voltage and bus frequency as input signals of the damping controller. Similar analysis of applying SVC to enhance the damping using the equal area criterion was proposed by Zhou in [30]. Zhou also proposed a discontinuous SVC control approach in which the change of SVC reactive power output at discrete points is determined by the power deviation on a transmission line. Optimal control and adaptive control strategies were also employed in the design of damping controllers for FACTS. In [31] & [32], Smith et al presented two enhanced LQ adaptive SVC controllers which only use local network information to damp oscillations. These control strategies have shown good performance on simulation of a 3-machine 9-bus system. Son and Park [33] applied the Linear Quadratic Gaussian technique to the design of TCSC damping controller. The optimal Hankel norm approximation technique was used for obtaining a low-order power system model, and a controller was designed based on the reduced-order model. The authors also discussed the application of the Loop Transfer Recovery technique to reserve the robustness of the designed damping controller. The 3-machine 9-bus system was again used here to verify the performance of the control strategy. Even though those methods showed good results on a 3-machine 9-bus system, due to the matrix size problem, they were not applied to higher order systems. Field test results for TCSC in commercial operation were reported in [34], [35]. In [34], Gama presented the project which supported the task of locating and designing a TCSC to damp the North-South low frequency inter-area mode. In [35], the authors presented the result of a joint research project which aims at investigating the feasibility of installing a combination of conventional series capacitors and TCSC at a main transmission line connecting northern area of Taiwan and Central area of Taiwan. The damping controller design was based on a conventional root locus method. Intelligent control strategies have also been applied to damping controller design for FACTS devices. Hsu and Luor [36] designed a PI controller for TCSC with the gain of the PI controller tuned online by a neural network. The proposed controller was tested on a one machine infinite bus system and it demonstrated by simulation better damping performance over fixed parameter PI controller over a wide range of operating conditions.

Mok, Ni and Wu [37] proposed a fuzzy damping controller for UPFC. The scaling factors of the fuzzy controller were optimized by GA. Simulation results for a two area system showed that the fuzzy damping controller performs better than a conventional transfer function based damping controller. In [38], Dash, Mishra and Panda presented a hybrid fuzzy logic proportional plus conventional integral controller for FACTS devices in a 3-machine power system. The controller used an incremental fuzzy logic controller in place of the proportional term in a conventional PI controller and provides a wide variation of controller gains in a nonlinear manner. Simulation results of the 3 machine system validate the effectiveness of the new control strategy in enhancing the damping of oscillations. Research on the possible damping effect of UPFC, the most versatile FACTS device, has also been conducted during the recent years. Besides the works in [37, 38], Dong, Zhang, and Crow [39] proposed a PI based approach for the dynamic control of UPFC. With this new control strategy, the active and reactive power flow control was achieved as well as the damping of system oscillations. In [40], the authors tested two damping schemes for the UPFC: one is voltage modulation in voltage control of the shunt element and the other is power modulation in constant power control of the series element. A cascade lead-lag transfer function was used for the supplementary control. In [41], a fuzzy logic based damping controller for UPFC was developed, and the effectiveness of this fuzzy controller was demonstrated in the simulation results of a two area four machine system. The authors expanded their work in [42], where two fuzzy logic schemes were used to design a UPFC damping controller. One is based on Mamdani inference engine and the other uses the Takagi-Sugeno engine to compute the controller output. Simulation was also performed on a two-area-four-machine system and the results for the system with two different fuzzy logic damping controllers were compared. However, so far, the proper modeling of UPFC for both steady-state power flow and dynamic behavior analysis is not readily available. Unlike the SVC and TCSC, which are simply considered as variable reactance from a power system viewpoint, the UPFC is like an ideal synchronous machine that can exchange both real power and reactive power with the power system to achieve simultaneous control of load flow and bus voltage. Therefore, the UPFC brought many new issues on steady state power flow calculation, the dynamic modeling of UPFC control, and transient simulation. Studies on these topics have been conducted for better understanding the impact of UPFC on the behaviour of power systems. In [44], a comprehensive load flow model is proposed, which can be incorporated into an existing Newton-Raphson load flow model. In [48], a detailed modeling of UPFC based on power electronics switching functions is proposed and simulated with EMTP. But the modeling did not include the most important part of the UPFC which is the converter control. In [49], a decoupled control strategy based on [45] is proposed and the UPFC behavior is simulated within a short-time frame. The study mainly concerns the internal control and dynamics of UPFC. The interface of UPFC with the power system, however, is not considered in this paper. In [50], a detailed power flow and transient stability model is proposed. While the model is validated by comparing the results with the results for EMTP models, it is very complicated and not easy to apply in a transient simulation program. In [44], a power frequency model for UPFC is suggested and four control strategies for UPFC are discussed. A method to include the UPFC into the power system transient simulation is also proposed. But the iteration schemes for the transient simulation only guarantee linear convergence. In [51], a Newton-type current injection model of UPFC is proposed mainly to improve the iteration convergence for the transient simulation process. The Jacobian matrix used at each time step is of very large dimension, however. Industry planning and operation experience about UPFC were also presented in [43, 46, 47, 52, 53].

III. CONCLUSION

We have studied many papers on low frequency oscillations in transmission system. It has been noticed that two kundur area is used by maximum of authors as a standard test system and power system stabilisers are used to suppress those. It has been notices that the fluctuation in the system can be compensated due to maintaining the change in power or change in angular velocity. So in our future work we will keep our focus on these.

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