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Power System Dynamic Stability Using Static VAR Compensator Powered With Fuzzy Logic Controller

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Abstract: Sub-Synchronous Resonance (SSR) is an adverse oscillation that may happen when steam turbine-generator is connected to a long transmission line system which compensated with series capacitor. If this oscillation is not damped completely, the operation of the turbine-generator shaft will be deteriorated, that causes serious shaft failure. The main scope of this paper is to design a Fuzzy Logic Damping Controller (FLDC) for Static VAR Compensator (SVC) to suppress the SSR. It is widely accepted that, the main duty of SVC in power system is to regulate the bus voltage. The novel FLDC is designed and granted to conventional controller of SVC in order to alleviate the SSR. For analyzing the designed controller, a summarized prony analysis associated with time domain simulation is also clarified. Simulation results are carried out with MATLAB/SIMULINK in order to prove the capability of proposed controller in power system stability. Also, a comparison between suggested controller and conventional damping controller (CDC) is performed that demonstrates the superior operation of FLDC toward its counterpart, CDC.

1. INTRODUCTION

It is a well-known fact that, series capacitor compensation is employed in electrical power system to increase power transfer capability, especially, where the large amount of power must be transmitted through long transmission lines. However, when this technique is implemented together with a steam-turbine generator, it may cause to SSR phenomenon [1]. Generally, SSR may occur when an electrical resonance frequency is close to the complement of one of the torsional mode frequencies of the turbine-generator shaft system [2].

Until now, many scientists and investigators havededicated comprehensive probes to this unfavorable kind of oscillations. Furthermore, many methods are implemented to eliminate the hazardous conditions that may be yielded from the SSR [3]. It is widely accepted that, Flexible AC Transmission System (FACTS) can provide constructive solution in alleviating the SSR [4]. Series FACTS devices can operate as a controllable series compensation and decrease or even remove the effects of the SSR [5]. Thyristor- Controlled Series Capacitor (TCSC) is one of the FACTS devices that has been utilized to alleviative the SSR [6]. One of the other FACTS devices that can mitigate the SSR is the Unified Power Flow Controller (UPFC) [7], but it is more expensive than the other devices. In addition, Jowder and Ooi have demonstrated that, the Static Synchronous Series Compensator (SSSC) is also effective to damp the SSR [8]. In addition, due to some merits of SVC toward other FACTS devices such as: quick voltage regulation of power systems, reactive power compensation, power oscillation damping and steady state stability [9] and [10], it may be installed in the power systems broadly. Many papers have investigated the implementation of SVC for additional purposes such as: SSR damping or dynamic stability with esigning supplementary controllers. For example, in [11], R.K. Varma and S. Auddy have demonstrated the performance of SVC for damping the SSR at the wind farm terminal beside of its main function.

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Many techniques have been utilized in the scheme of auxiliary damping controllers for SVC in the recent papers, for example: self-tuning adaptive control algorithm [12]. The major obstacle with these methods which are mentioned above is that, the control rule is based on a linearized model and control variables are adjusted to some nominal performance positions. As regards of large disturbances, the system situation will change in a highly nonlinear behavior and controllers completely are not able to damp the oscillations, evencontrollers can make the system condition unstable by for example inserting negative damping. To overcome these problems, the control design method should consider nonlinear dynamics of power system. In this base, some stabilizing control techniques for power system have been proposed [13]. Recently, fuzzy logic controllers have generated a great deal of interest in various applications and have introduced in power-electronic field [14]. The benefits of performing fuzzy control in power systems are apparent. Modern power systems are huge, complicated, geographically widely dispersed and highly nonlinear systems. So, it is not feasible to derive detailed global system model. Furthermore, power system operation conditions and topologies are time varying and the disturbances are not predictable. These uncertainties make it very difficult to effectively take care of power system stability problems through CDCs that are based on linearized model and single operation condition. Therefore, the fuzzy logic control approach, as one aspect of an artificial intelligence, has been emerging in recent years as a complement to the conventional approaches [15].

This paper presents a FLDC strategy for SVC to alleviate the SSR and improve the power system stability. The FLDC is varied widely by a suitable choice of membership functions and parameters in the rule base. $\Delta\omega$ [p.u] (generator speed deviation) and, $\frac{d\Delta\omega}{dt} = \Delta\alpha$ [p.u] (the derivative of speed deviation) are two supplemental signals that exhibit the sub-synchronous information, will be inserted as the FLDC input signals, then output signal of supplementary FLDC is used to modulate the reference voltage regulator of SVC controller for effective sub-synchronous oscillation damping.

The paper is organized as follows: In section II, sub-synchronous resonance phenomenon is explained briefly. Power system structure for SSR study is clarified in section III, Furthermore, the Fast Fourier Transform (FFT) analysis on the generator rotor speed, is demonstrated in this section. The main configuration of SVC is explored in section IV. Section V covers the control system design of the SVC and damping ratio analysis for exactly investigation of SSR. Simulation results with detailed comparison between two proposed controllers (FLDC and CDC) in various conditions are included in section VI. Finally, in section VII, the results obtained from previous sections are concluded.

2. SUBSYNCHRONOUS RESONANCE

Generally, SSR occurs in series compensated transmission lines [2]. Series compensation of transmission line can be resulted the excitation of oscillatory modes of the rotor shaft in sub-synchronous frequency. A series capacitor-compensated power system has a sub-synchronous natural frequency (f_e) which is given by:

$$f_e = f_o\sqrt{\frac{X_c}{X_l}} \tag{1}$$

Where, X_c is the reactance of series capacitor, X_t is the leakage reactance of compensated line and f_o is the synchronous frequency of the power system in HZ. At this sub-synchronous natural frequency, these oscillatory modes result in rotor torques and currents at the complementary frequency, f_r as: $f_r = f_o - f_e$. So, if f_r is close to one of the torsional frequencies of the rotor shaft, the torsional oscillations will be excited and this condition will be resulted unfavorable phenomena namely SSR [2]. Generally, SSR is divided into two major parts: self-excitation which is named by steady-state SSR and the second one is named as transient torque or transient SSR. Self-excitation is separated into two major parts: the first one is Induction Generator Effect (IGE), and the second one is torsional interaction (TI). The IGE is improbable in series compensated power system. However, the TI and transient SSR are mostly occur in series compensated power systems [16]. Because the main aim of this paper is to suppress the SSR in series compensated transmission line, the proposed controller is designed to solve major SSR problems.

3. STUDY MODEL

The structure of the power system that has been utilized for SSR study purpose is shown in Fig. 1. This figure shows the IEEE Second Benchmark Model combined with SVC in bus 1 which is mainly used for SSR studies [18]. The system composed of a synchronous generator supplying power to an infinite bus via two parallel transmission lines, it is a Single Machine Infinite Bus (SMIB) power network that has two transmission lines, and one of them is compensated by a series capacitor. A 600 MVA turbine-generator is connected to an infinite bus, and the rated line voltage is 500KV, while the rated frequency is 60Hz. The shaft system consists of four masses: a high pressure turbine (HP), and low pressure turbine (LP), the generator (G) and rotating Exciter (EX). All masses are mechanically connected to each other by elastic shaft. The complete mechanical and electrical information for the study system are demonstrated in [18]. It should be noted that, Z_{L1}, Z_{L2} are defined as:

$$Z_{L1} = R_{L1} + jX_{L1}, \; Z_{L2} = R_{L2} + jX_{L2} \tag{2}$$

Fig. 2 describes the FFT plot of generator rotor speed in time interval of 1 to 2.5 sec. percentage of compensation which means the proportion of series capacitive reactance to line reactance $\left(\frac{X_c}{X_{L1}} \times 100\right)$, is set to 55% to excite the oscillatory mode of the generator rotor shaft. It is founded by FFT analysis with MATLAB that, three modes exist in the rotor speed in this study. As shown Fig.2, it can be deduced that,

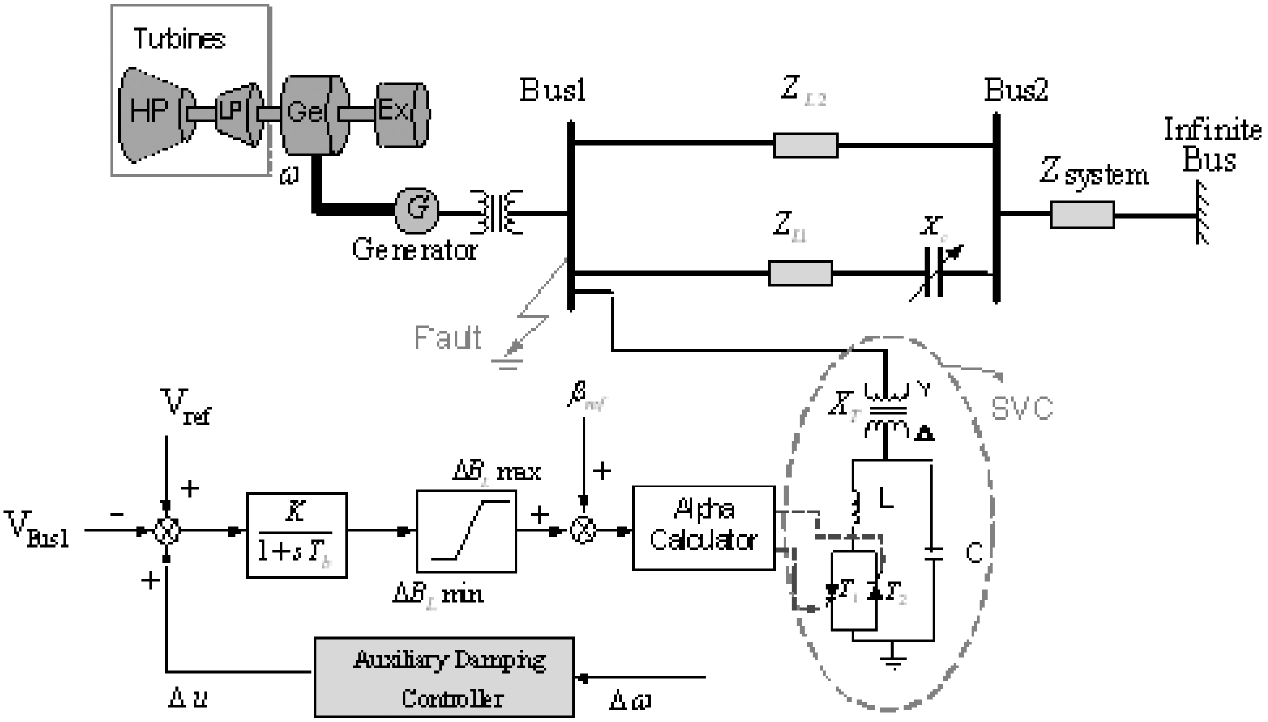

Figure 1: The IEEE Second Benchmark Model combined with SVC for SSR analysis

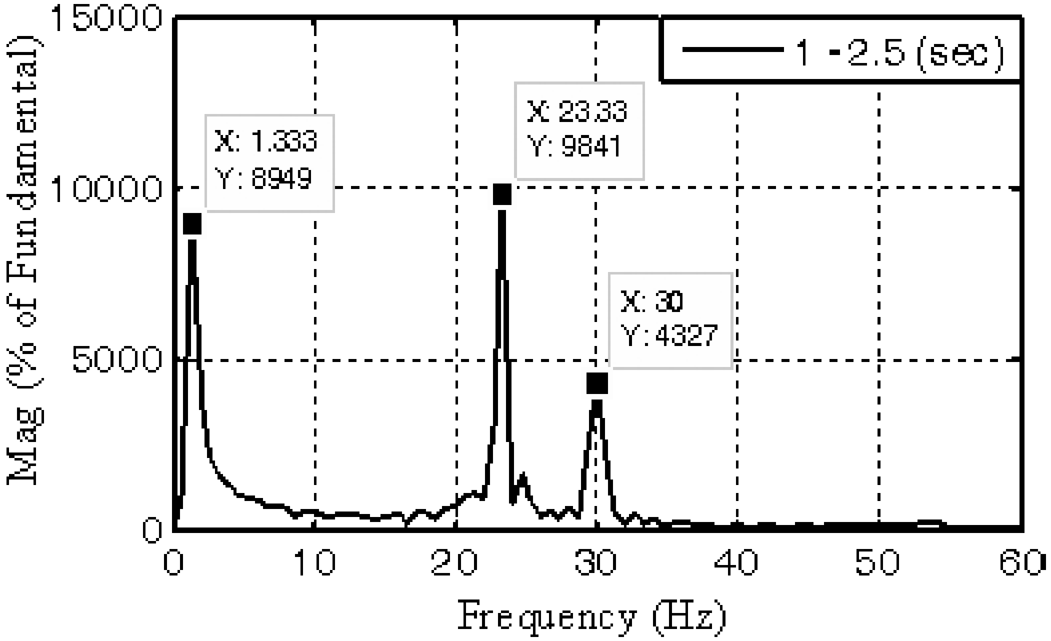

Figure 2: FFT analysis on generator rotor shaft in order to confirm the dominant mode

due to the chosen level of series compensation, the electrical resonance happens at 23.33 Hz. From FFT analysis of the mechanical system, the oscillatory modes of the generator shaft are 23.33, 30 Hz and 1.333 Hz is the low frequencyoscillation. Furthermore, maximum destabilization is for 23.33 Hz mode, or in other way, the dominant mode which has sub-synchronous frequency is 23.33 Hz.

4. SVC STRUCTURE

A typical structure of SVC with Thyristor Controlled Reactor (TCR) and fixed capacitor which is connected to a Bus 1 through a step-down transformer is shown in Fig. 1. Where, X_T is the transformer reactance, C and L are the capacitance and inductance of SVC respectively. The main scope of SVC controller is to create pulses for Thyristor valves in order to fix the AC bus voltage of SVC. For achieving this goal, first, the reference value of AC bus voltage is compared with measured bus voltage and the error signal passes over a PI controller in order to create the pulses.

The TCR is composed of a fixed reactor with inductance L, and a bidirectional Thyristor switch. The amplitude $I_{LF}(\alpha)$ of the fundamental reactor current $i_{LF}(\alpha)$ can be explained as a function of angle :

$$I_{LF}(\alpha)=\frac{V}{\omega L}\left(a-\frac{2}{\pi}\alpha-\frac{1}{\pi}\sin\left(2\alpha\right)\right) \tag{3}$$

Where, V is the magnitude of the AC voltage, L is the inductance of the TCR, ω is the angular frequency of the AC voltage in *rad/s*. The fundamental current can be controlled continuously from zero (switch open) to maximum (switch close) by TCR, as if it was a changeable reactive admittance. Efficient reactive admittance, $\beta_L(\alpha)$ for the TCR as function of angle α, can be obtained from equation (3). Obviously, the admittance $\beta_L(\alpha)$ changes with α in the same as the fundamental current $I_{LF}(\alpha)$[19]:

$$\beta_L(\alpha)=\frac{1}{\omega L}\left(1-\frac{2}{\pi}\alpha-\frac{1}{\pi}\sin\left(2\alpha\right)\right) \tag{4}$$

Among the existing FACTS devices, the SVCs have been used extensively to provide voltage support at strategic locations of the system [20].

5. CONTROL SYSTEM DESIGN OF THE SVC AND DAMPING RATIO ANALYSIS

Presentation of SVC as a changeable reactance that acts in two inductive and capacitive modes has acquired great deal of attention as its time constant is able to be compared with the time constant of other FACTS devices. As the conventional controller of SVC is not capable of performing additional functions such as LFO damping or SSR damping, many papers investigated and planned an additional controller to enhance the damping property of SVC [10]. A supplementary controller can be connected to the summing junction of the SVC voltage regulator as shown in Fig.1, with feedback signal derived from the generator rotor speed. The output of supplementary controller causes alternation in reference value of SVC bus voltage and hence, the damping of oscillations will be achieved. In this paper, a novel FLDC is designed and supplemented to SVC traditional controller in order to improve the dynamic stability of power system and specially SSR damping. In order to prove the superior performance of proposed controller than other controllers that designed before, a CDC is also planned and utilized in the proposed system for SSR alleviation. With comparison of these two designed controller both in time domain simulation and damping ratio analysis, the superior performance of FLDC controller will be clarified in the next sections. In the following, each controller will be described separately:

5.1. CDC design for SVC

CDCs have been widely used in industry because of their simple structure, easy to design, robust performance in the linear system and low cost [21]. In general, the inputs of typical CDC are: line real power flow, bus frequency, bus voltage magnitude, line current amplitude, etc. [22]. In this investigation, because the aim is to mitigate the SSR, the speed deviation of generator rotor has been utilized as input signal of CDC. As shown in Fig. 3, $\Delta\omega$ [p.u] has been implemented as an additional signal to mitigate the unstable modes. The auxiliary CDC for SSR consists of four blocks: a washout filter, a phase compensator block, limiter block, and a gain block. As shown in Fig. 4, the output of the CDC is therefore send to the SVC voltage regulator. The parameters of the CDC which are obtained through trial and error method, are: $K = 100$, $Tw = 20$, $T1 = 0.1$, $T2 = 0.01$.

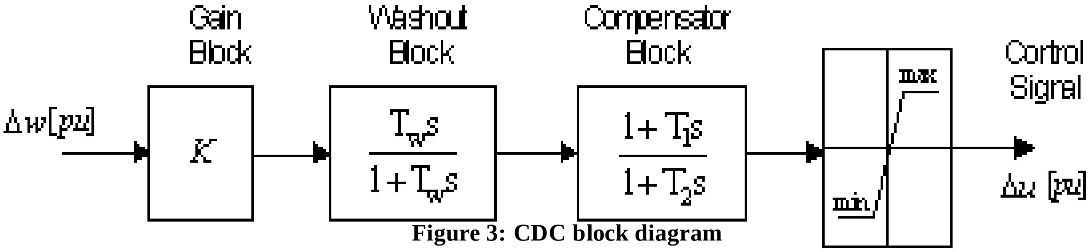

Figure 3: CDC block diagram

5.2. FLDC DESIGN FOR SVC

It is widely accepted that, CDC with fixed parameters can play significant role in stability of the dynamic power system and particularly for mitigation of SSR phenomenon and LFO. In contrast, the best operation of the CDC and correspondingly the performance of the SVC depend on an appropriate choice of the CDC gains. Consequently, tuning the CDC gains to yield the optimum response is complicated task, specially, when the procedure is nonlinear and it seems to change throughout the work. Also, the CDC cannot guarantee effective control over a wide performing range when there is disturbance in the power system, or when the system is varying nonlinearly. Recently, Fuzzy Logic Controllers (FLCs) have emerged as an effective tool to stabilize the power network with different devices such as FACTS devices or other power electronic apparatuses [23], [24]. The main significant advantage of FLCs over the CDCs can be cited as: FLCs do not require an exact mathematical model; they can act with inaccurate inputs, control nonlinearity, and are more robust and effective than the CDCs in the power system [25]. Fuzzy Logic Controller (FLC) presents methodical approach to control a nonlinear strategy based on human experience that can be regarded as a heuristic technique to enhance the operation of closed loop system. The FLC performance is based on its capability to simulate many functions at its same time process and output results of FLC is considerably thorough. Fig.4 shows schematic of the auxiliary FLDC which is used for enhancing the SVC with damping controller. In this part, rotor speed deviation and its derivative $\left(\Delta\omega \text{ and } \frac{d\Delta\omega}{dt} = \Delta\alpha\right)$, are used as inputs for suggested FLDC that is schemed based on Mamadani inference engine [26].

The basic structure of FLDC is classified in four sections: Fuzzification Block, Fuzzy Knowledge-based Block, a Fuzzy Inference Engine and a Defuzzification Block.

The frame and number of the membership functions explaining the fuzzy value of controller (for the inputs and output) are described off-line. Zmf and Smf (*Z* and *S* shape Membership Function) membership's functions are employed for the inputs and output fuzzy sets of the FLDC. The designed membership functions for:,as inputs and as output are shown in Fig. 5.

The control rules of the fuzzy controllers are showed by set of heuristically selected fuzzy rules. The fuzzy sets have been determined as: *N*: negative, *Z*: zero, *P*: Positive, respectively. The rule base with two proposed input is shown as:

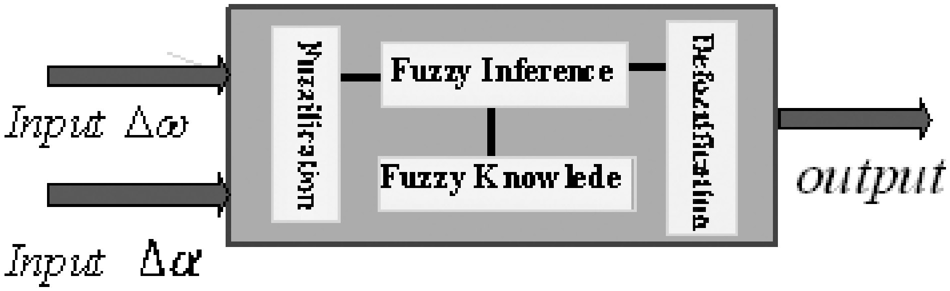

Figure 4: Generalized SVC auxiliary fuzzy controller and Structure of SVC sub-synchronous resonance damping controller

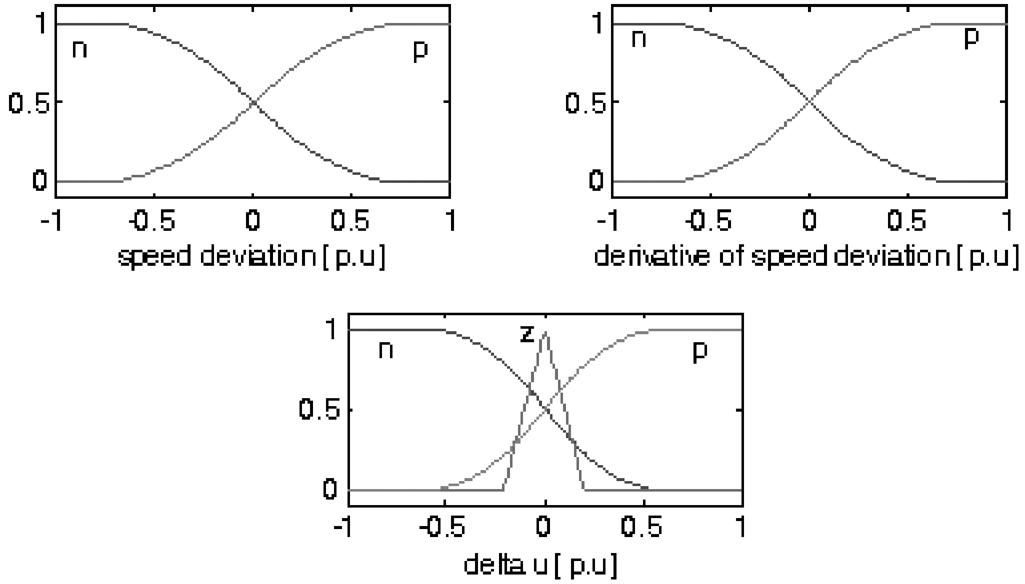

Figure 5: Membership functions for inputs and output fuzzy sets of the FLDC

1. If ($\Delta\omega$ is P) and ($\Delta\alpha$ is P) then (Δu is P)
2. If ($\Delta\omega$ is P) and ($\Delta\alpha$ is N) then (Δu is Z)
3. If ($\Delta\omega$ is N) and ($\Delta\alpha$ is P) then (Δu is Z)
4. If ($\Delta\omega$ is N) and ($\Delta\alpha$ is N) then (Δu is N)

5.3. Damping Ratio Analysis of SSR

It is widely accepted that, application of the fuzzy logic controller limits the validity of mathematical functions. So, it is not feasible to acquire the state space model and apply small signal analysis on a basis of eigenvalue analysis. In order to solve this problem, in this study, time domain simulations are extracted to analyze the performance of each controller. The main objective is to find weak modes and damping ratios from time domain data acquired from numerical integration of differential equations which is held on a basis of Prony Analysis. Some simulation data such as: frequency of oscillations (f_{oc}), un-dampednatural frequency (ω_n), and first prediction of damping ratio (ζ) are obtained firstly, then, the first attempt is held to shape the envelope of time domain simulation. This tracked envelope has specific damping ratio which precisely explains the damping ratio of the simulated figure. On the sequel, with comparison of damping ratios which are attained by various methods of control, the best approach is recognized. The procedure of finding of damping ratios from simulation results is summarized in the following steps:

1. Time domain data that have steady state values are added or subtracted with a dc component equal to the steady state value of simulated data.
2. Equation (6) is implemented to gain the frequency of oscillations namely f_{oc}. Where, T_{max}, T_{min} correspond to maximum and minimum points of simulated plot which is shown in Fig.6.

$$f_{oc} = \frac{1}{T_{oc}} = \frac{1}{\left|T_{\max} - T_{\min}\right| \times 2} \tag{6}$$

3. So, in order to gain the envelope equation, the un-damped natural frequency should be attained first. Equation (7) is utilized to calculate the un-damped natural frequency. Where, ω_n is un-damped natural frequency in rad/s; ω_d is the damped natural frequency in rad/s; f_{oc} is the frequency of oscillations which obtained in part 2, and ζ is damping ratio predicted.

$$\omega_n = \frac{\omega_d}{\sqrt{1-\zeta^2}} = \frac{2\pi f_{oc}}{\sqrt{1-\zeta^2}} \tag{7}$$

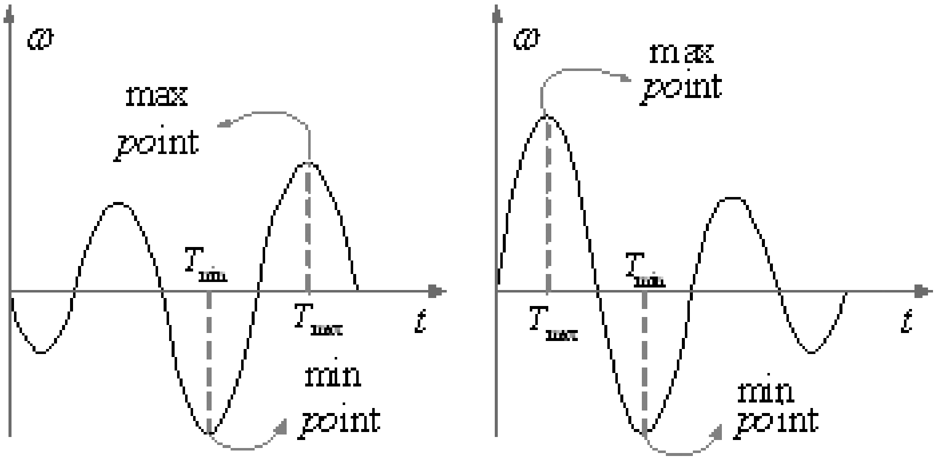

Figure 6: Definition of oscillation frequency

With parameters obtained in parts 2, 3 the envelope equation concluded from equation (8). Where *Y* is the envelope equation, *C* is the constant value which normally is the same as maximum or minimum of simulated response.

$$Y = \pm C e^{-\zeta \omega_n t} \tag{8}$$

The proposed novel method of analysis can be implemented for fuzzy logic based controllers to compare the performance of approaches precisely. In the following, simulation results are carried out based on time domain simulation and also proposed analysis in order to compare the results of FLDC with CDC and to clarify the best approach for SSR attenuation.

6. SIMULATION RESULTS AND DISCUSSION

To prove the effectiveness of the proposed FLDC in SSR attenuation, the IEEE SBM with SVC has been simulated. Two cases of study are considered. Firstly, the power system without any damping controllers is simulated. Simulation results for rotor speed, the torque between Generator and LP turbines are provided in Fig. 7 (a, b). Due to unstable mode, when the fault is cleared, large oscillations will be experienced between sections of the turbine generator shaft. For this state, the system is completely unstable and as depicted in Fig. 7. a, the rotor speed is oscillating with sub-synchronous frequency of 23.33 Hz.

The FFT analysis on the generator rotor speed for SVC enhanced with FLDC is depicted in Fig. 8. It is observed that the dominant torsional mode with frequency of 23.33 Hz is diminishing as the time is going

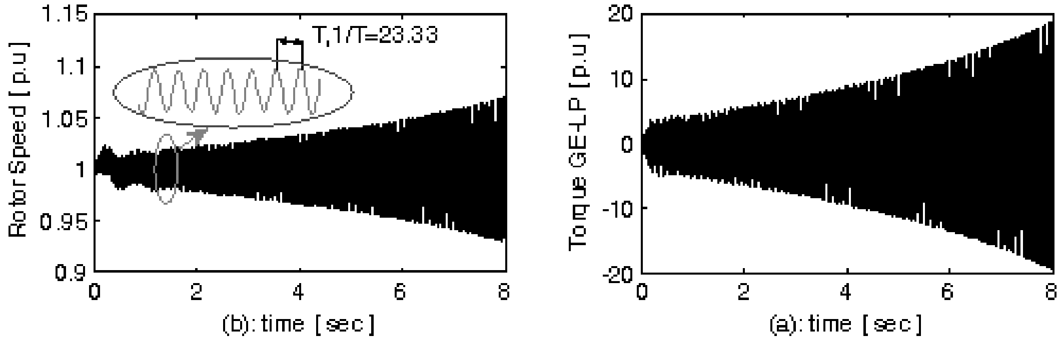

Figure 7: Simulation results for un-damped condition: (a): of generator, (b): torque between generator and Low pressure turbine

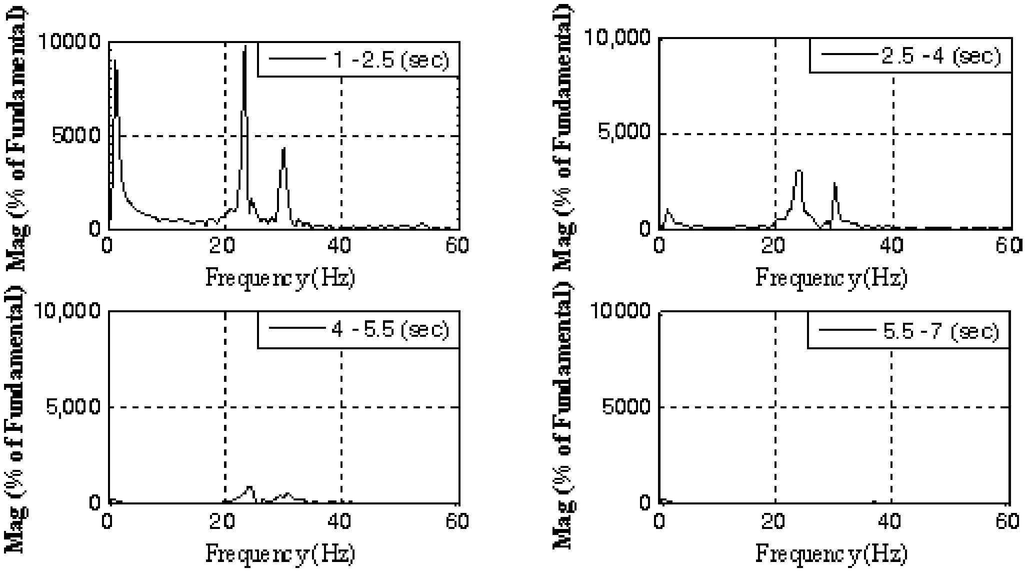

Figure 8: FFT analysis on generator rotor speed with FLDC on shunt converter

on. Also, this figure shows that, for 1-2.5 second, a low frequency power oscillation with frequency of 1.33 Hz can be found that is completely eliminated with this FLDC.

The second case of simulations includes the condition in which the SVC is enhanced with proposed FLDC and also CDC. To examine the effectiveness of each controller in mitigating SSR, a comparison between two controllers is also included in this part. The comparison is based on both time domain simulation and damping ratio analysis performed at previous sections. Fig. 9 (a, b) reveals the rotor speed of the generator, and the torque between generator and low pressure turbine with both proposed FLDC and designed CDC, where the dashed lines correspond to CDC and solid lines correspond to FLDC. From this figure, it is observed that, FLDC operates better than the CDC counterpart since the system with Fuzzy controller has less overshoot and less settling time, compared with the CDC. As shown in the plots, it is clear that, the damping controller is effective for damping the sub-synchronous oscillations with the frequency of 23.33Hz. It should be noted that, if the small changes occur in the system, the CDC performance would be remarkably weak that is due to nonlinear and coupling terms, so a new adjusting of the gains would be essential. On the other hand, the FLDC operates robustly, despite the reality that, membership functions and the rules were not carefully regulated as in the CDC scheme.

Fig.10 (a-c) illustrates the results obtained from damping ratio analysis for three cases of study. First, the results conducted for without any controller, and then the results of CDC and FLDC is also performed.

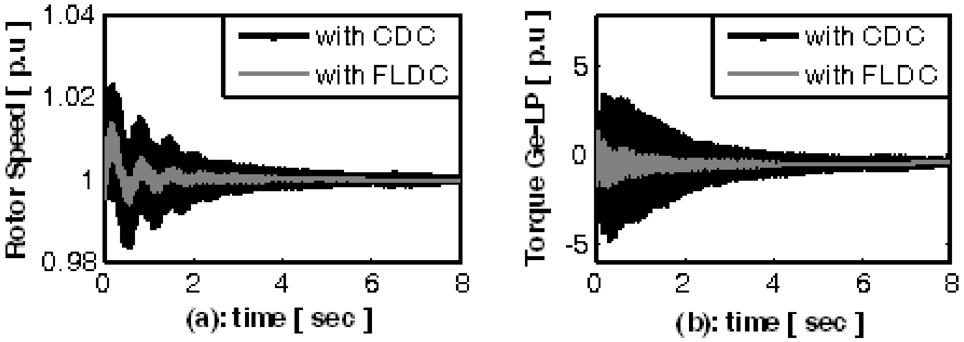

Figure 9: Simulated results for comparison between FLDC and CDC: (a): of generator (b): Torque between generator and low pressure turbines

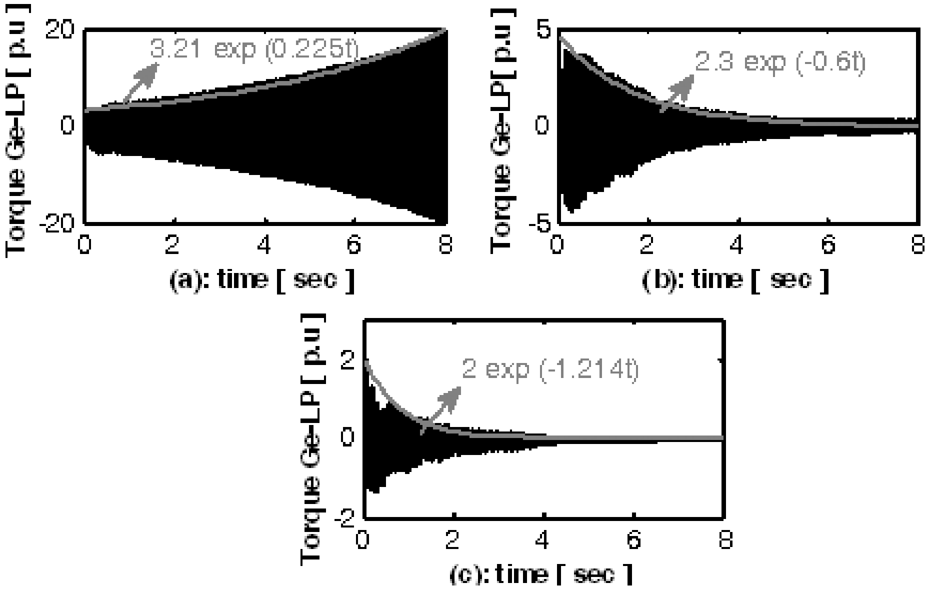

Figure 10: Results from damping ratio analysis: (a): without any controller (b): with CDC (c): with FLDC

The equation of each envelope is given in each figure. In order to summarize the results, just the torque between generator and low pressure turbine is included in the analysis. The envelopes are traced for the purpose of finding damping ratio on critical mode (23.33Hz) using the analysis described in last section. The obtained envelope equations are utilized to calculate the damping ratio from equation (8). It is clear that, the envelopes for both CDC and FLDC have negative damping ratio (ζ) due to equation (7) which means both controllers are capable of damping unfavorable oscillations. But, for precisely determining the performance of each controller, calculated damping ratios and maximum and minimum overshoots for each simulated result are included in Table.1.

Among the diverse cases, the power system response lacks in terms of maximum or minimum overshoot and damping ratio when there is no supplementary controller. Notice that, the system torque between generator and low pressure turbine has the maximum and minimum overshoot of 20p.u and 19p.u for positive and negative half cycles respectively after 8 sec. This case is the unstable mode of the power system. When the SVC is enhanced with CDC, the oscillations will be damped after short period of time, so the damping ratio is positive in this case. Also in this case the maximum and minimum overshoot is decreased significantly toward previous case. Furthermore, when SVC is enhanced with FLDC, the system response is the best. The maximum and minimum overshoot decreases significantly toward CDC, and damping ratio is positive and much more than CDC case. For example damping ratio for torque between HP and LP turbine sections is 0.0093 when FLDC is considered, but with CDC, damping ratio is 0.0047. Damping ratio for the case with FLDC is 6 times greater than CDC. This means that, the proposed FLDC has the superior performance toward its CDC as earlier verified in simulation results.

Table 1

Result from damping ratio analysis for three cases of Studies

Case	*Envelope equation*	ζ	*Overshoot [p.u]*	
			Max	*Min*
FLDC Torque Ge-LP	$2.08^{-1.241t}$	0.0084	2.08	–1.786
CDC Torque Ge-LP	$4.8^{-.6t}$	0.0041	4.78	–4.69
Without control Torque Ge-LP	$3.21e^{0.225t}$	Unstable	20	–19.062
			Until 9 sec	

7. CONCLUSION

This paper has shown the impact of SVC on the SSR and LFO damping in highly unstable power system. For achieving this goal, the novel FLDC is designed as an auxiliary controller for SVC conventional controller. Generally, designed fuzzy logic method has variety of advantages toward other proposed methods. In order to verify the their performance of proposed FLDC toward conventional methods, the CDC is also designed and implemented in control loop of SVC for alleviating the SSR. Two different approaches are implemented to compare the results of two controllers. Firstly, simulationsare carried out on IEEE Second Benchmark Model accumulated with SVC in two separate cases: one included FLDC based SVC and another included CDC based SVC. As it was illustrated, the FLDC performs more beneficial than CDC, because the CDC's better operation is required to reach the suitable range of gains that, is possible when the simulation is repeated more and more, while the proposed auxiliary fuzzy controller design were adjusted in just a few simulations. In the second approach, in order to complete the comparison, the modified Prony analysis which is derived from time domain simulation is used in order to obtain the damping ratio for each proposed controller. The results from damping ratio analysis also revealed the superior performance of FLDC toward CDC, because the damping ratio in each simulated result for FLDC is much greater than simulation results for CDC.

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