Fuzzy Logic Controller for Damping Sub-synchronous Oscillation in Power System

A. Shoulaie
Iran University of Science and Technology
Tehran, IRAN
Shoulaie@iust.ac.ir

M. Bayati poodeh
Islamic Azad University
Najafabad Branch
Isfahan, IRAN
Bayati@iaun.ac.ir

Gh. Shahgholian
Islamic Azad University
Najafabad Branch
Isfahan, IRAN
Shahgholian@iaun.ac.ir

A. H. Zaeri
Islamic Azad University
Majlesi Branch
Isfahan, IRAN
Amzaeri@gmail.com

***Abstract*-Sub-synchronous oscillation occurs in frequency less than synchronous frequency, in transmission systems compensated by series capacitor and in a state of equilibrium of the system, it imposes great disturbance which brings about tortional modes with varied frequencies in the shaft of the generator which ultimately can result in fatigue in the shaft of the turbine-generator and even might result in fracture in the shaft with irrecoverable damages. To damp and to control the sub-synchronous oscillations, exciter voltage controller was employed in this study. In line with the improvement of this controller, fuzzy control method was used. The results of simulation confirm the effect of fuzzy controller optimization in this system.**

I. Introduction

From the onset of the appearance of electricity production and distribution industry, there has always been an interesting and sensitive subject for power and control engineers. As this industry grows older, the power systems become more intertwined, more complex and more extended, demanding more precise control and dynamic studies and since, after any modification in the inlets or any disturbance in the power systems, some oscillations are created in frequency, active and reactive power. One of the most basic principles in dynamic studies, is stability, so the oscillations (the transient state) should be minimized as much as possible and the permanent error should not exist in the system. One of the methods of transient stability improvement in the power systems and increasing the system stability power is the use of series capacitor, in locations where the transfer line is long, but there are some complexities present. This capacitor forms an RLC circuit with the line inductance possessing the frequency resonance. The interference of this frequency resonance with rotor tortional oscillation frequencies results in the production of the phenomenon of sub-synchronous resonance (SSR) [1]. In a general state, the sub-synchronous oscillations are the electrical conditions in the power system in which the electrical network exchanges much energy in the generator-turbine unit and introduces a disturbance in the equilibrium state of the system in one or several natural frequencies of the multiple systems, in frequency less than the system synchronous frequency. In the generator-turbine shaft, tortional modes with varied frequencies are produced which ultimately can result in the production of fatigue in generator–turbine shaft and even might result in fracture in the shaft bringing about much damages.

Some papers explain the terms, definitions and symbols in pursuit of electric utility industry uniformity and common understanding in the analysis of subsynchronous resonance. These definitions are recommended, where applicable, in other unique areas encompassing subsynchronous oscillations [2].

In order to eliminate and dump the oscillations of sub-synchronous resonance and the prevention of the occurrence of this phenomenon, different controllers are employed in both power station and transmission lines [3]. The power station control loops consist of drum surface control or opening and closing inlet water valves, and the control of inlet vapour pressure into the turbine, rotor governor, exciter voltage control [4]–[6], and other controllers like FACTS devices are employed in the transfer lines.

A long last decade many controlled equipment under name of flexible AC transmission systems (FACTS) technology have been designed and completed. These devices placed in transmission lines as series, parallel and series-parallel, which control exploitation parameters of transmission systems in steady state and also dynamic conduct of system in transient flow, load divider between parallel corridors, voltage adjustment, increasing transient stability and also reducing of system oscillations [7].

One of the famous FACTS devices is Thyristor-Controlled Series Capacitor (TCSC), that substantially improves transmission capacity. TCSC, has been well known as a potential countermeasure against SSR since it was introduced [8]. In [9] is illustrated the capability of TCSC to mitigate SSR. With an appropriate angle of thyristor firing, electrical damping becomes almost zero, which is called SSR neutral. This quality comes from TCSC itself. [10].

Another kind of FACTS devices is static synchronous compensator (STATCOM). It is possible to damp subsynchronous resonance caused by series capacitors with the help of an auxiliary subsynchronous damping controller (SSDC) on STATCOM [11].

Recently, Jowder and Ooi [12] have shown that SSSC (Static Synchronous Series Compensator) can damp SSR. The SSSC is a more complete device in terms of flexibility than the others FACTS series devices, however, its cost and complexity is also much higher [13]. Other FACTS device that can mitigate SSR is the Unified Power Flow Controller (UPFC) [14]. However since it has a shunt and series converters it is more expensive and complex than the SSSC.

The capability of the Gate Controlled Series Capacitor (GCSC), as another device, to mitigate SSR. GCSC is a powerful device for controlled series compensation both for power flow control and SSR damping [15]. In some case, the GCSC can damp SSR even without a specific control.

In stabiliy analysis, it is well documented that inappropriate setting of HVDC controller could cause dynamic instability of an AC/DC system, but by use adaptable HVDC transmission system in the network, not only is not caused instability rather it is improved the subsynchronous oscillations as a FACTS device [16].

In some of the FACTS devices and instruments that are used to damping and mitigating the oscillation, several control methods are applied, such as fuzzy control method, sliding mode or other optimisation methods [17]-[18].

In this paper, in order to control the oscillation of subsynchronous generator, exciter voltage controller is used and in line with the improvement of the control response, modern fuzzy control is benefited from. The results of the system simulation, shows the improvement in the functioning of the exciter voltage controllers along with fuzzy logic controller.

This paper is organized as follows: Introduction, that contains the identification of SSR phenomenon, and several control methods to eliminate and mitigate the oscillations in power system. power system model is described in section 2. Then in section 3, excitation system in power station is explained. In section 4, the fuzzy control method for optimal performance of exciter is discussed in detail. The simulation results are given in section 5. Finally, a brief conclusion in section 6.

II. POWER SYSTEM MODEL

The IEEE first benchmark model for computer simulation of subsynchronous resonance (SSR) [1] consists of a single machine connected through a series compensated transmission line to an infinite bus. The mechanical system associated with the machine consists of a high pressure (HP) turbine, an intermediate pressure (IP) turbine, two low pressure turbines (LA, LB), the generator (G) and exciter (EXC) as is shown in Fig. 1.

The analysis of subsynchronous oscillations requires the dynamic equations for the turbine-generator mass system.

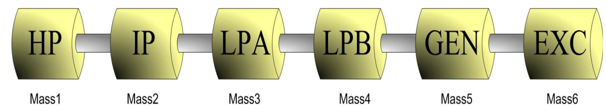

Fig. 1. Mechanical model used for SSR study.

Such a model must necessarily be exceedingly complex because the corresponding mass system is complex and has torsional vibration modes both above and below the rated frequency. However, since torsional oscillations occur essentially in the subsynchronous frequency range, the system can be modelled by a lumped-mass model [19].

Representing the turbine sections as inertias connected by shafts of appropriate stiffness, the dynamic equations for the turbine-generator mass system may be written as (1) (see Fig. 2) [20].

$$[M]\ddot{\delta}+[D]\dot{\delta}+[K]\delta = T_m - T_e = T \tag{1}$$

Where M, D and K are matrices representing the inertias, damping coefficients and stiffness constants of the masses and the shafts respectively. $\ddot{\delta}$, $\dot{\delta}$ and δ are vectors as are T_m and T_e (vectors of mechanical and electrical torques respectively).

The shaft torques may be expressed in terms of the angular position, δ, as (2).

$$\Delta T_{ij} = K_{ij}(\Delta\delta_i - \Delta\delta_j) \tag{2}$$

Where

$$i, j = 1,\ 2,\ ...,\ 6;\ \ i \neq j;\ \ i \succ j$$

The electrical system may be modeled as a Single Machine connected to an Infinite Bus (SMIB) system. Assuming that magnetic saturation is negligible, a nonlinear dynamic model may represent the alternator, as given in (3) - (6) [20].

$$\dot{\omega} = \frac{1}{2H}[T_m - T_e - D\omega] \tag{3}$$

$$\dot{\delta} = \omega \tag{4}$$

$$\dot{E}'_q = \frac{1}{2H}(-E'_q + (x_d - x'_d)i_d + u) \tag{5}$$

$$\dot{E}'_d = \frac{1}{T'_{q0}}(-E'_d + (x_q - x'_q)i_q) \tag{6}$$

With regard to the structure of turbine-generator, there are 27 orders of modes consisting of electric modes in this model and mechanical modes.

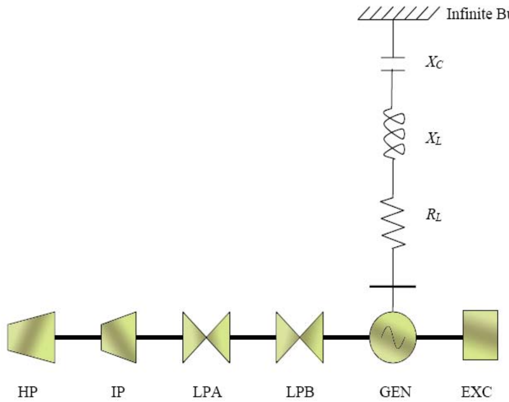

Fig. 2. The IEEE first benchmark model for computer simulation of sub-synchronous resonance.

The modes related to different sections of the system are presented below:

Synchronous generator modes

$$[\Delta X_{sys}] = [\Delta i_d \quad \Delta i_q \quad \Delta i_{fd} \quad \Delta i_{1q} \quad \Delta i_{1d} \quad \Delta i_{2q}]^T$$

Transmission line modes

$$[\Delta X_{TL}] = [\Delta V_{Cd} \quad \Delta V_{Cq}]^T$$

Mechanical system modes

$$[\Delta X_{ms}] = [\Delta\delta_E \ \Delta\delta \ \Delta\delta_B \ \Delta\delta_A \ \Delta\delta_I \ \Delta\delta_H \ \Delta\omega_E \ \Delta\omega \ \Delta\omega_B \ \Delta\omega_A \ \Delta\omega_I \ \Delta\omega_H]^T$$

Governor and turbines modes

$$[\Delta X_g] = [\Delta C_V \quad \Delta P_H \quad \Delta P_I \quad \Delta P_A]^T$$

Excitation system modes

$$[\Delta X_v] = [\Delta e_{fd} \quad \Delta E_R \quad \Delta E_{SB}]^T$$

III. EXCITATION SYSTEM

Exciter systems can be classified according to their origins: AC, DC turning and AC static in many old systems. DC type acts as the original exciter which might be exited by another exciter separately. Modern exciter systems are of AC turning type or AC static type [5]. AC turning type employs an AC turning generator outlet as an original exciter for exciting synchronous DC generator. In this type the AC generator field coil is located on the shaft of the synchronous generator rotor, the stator and rectifier are static. The rectifier system is capable of transferring the DC exciter current only in one or two directions. The DC bridge rectified outlet is applied to the synchronous generator original field coil by a pair of slipping loops. In the exciter system model lacking the brush, the AC exciter armature and the turning rectifier bridge as well as rotor and AC exciter field are static. Most of the AC type exciters absorb their initial power from an AC line, and use the controlled rectifier for the production of DC exciter adjustable for synchronous generator field coil. The applied error signals to the exciter system are usually obtained by comparing the ideal reference rate with the related controlled and rectified quantity of AC. As it is depicted in the Fig. 5, the rectifying and voltage converter model are easily modeled by a time steady with a unit quotient. Normally, the adjusting section comprises error amplifier and restricting parts. The adjusting outlet signal is usually amplified by the exciter to gain the required power and efficiency for exciting the large synchronous generator field coil. The medium exciter DC model comprises field coils, the non-linear path of the magnetic original field exciter, and the armature which is taken into consideration by the *Se* exciter saturated function analyzer. To provide quotient and ideal functioning margin in response to open loop frequency of the exciter adjusting set, stabilizer with a pre-phase production is used.

IV. FUZZY LOGIC

In 1965, Zadeh proposed Fuzzy logic; it has been effectively utilized in many field of knowledge to solve such control and optimization problems [21]. Fuzzy logic has been available as a control methodology for over three decades and its application to engineering control systems is well proven. In a sense fuzzy logic is a logical system that is an extension of multi-valued logic although in character it is quite different. It has become popular due to the fact that human reasoning and thought formation is linked very strongly with the ways fuzzy logic is implemented. In power system area, it has been used to stability studies, load frequency control, unit commitment, and to reactive compensation in distribution network and other areas.

The most important specifications of fuzzy control method are their fuzzy logical ability in the quality perception of system dynamics and the application of these quality ideas simultaneously for power systems [22] and [23]. A simple block diagram of a fuzzy system is shown in Fig. 3.

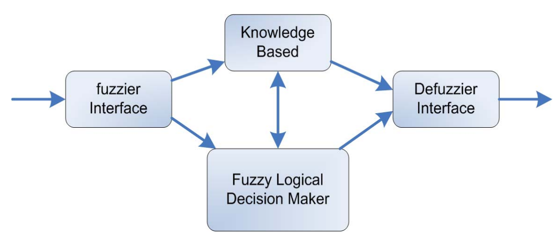

Fig. 3 Details of a fuzzy controller.

Four major units are fuzzification block, a fuzzy knowledge-base block, a fuzzy inference engine and a defuzzification block. The functions of the blocks and working principles of the fuzzy system are briefly summarized [24].

A. Fuzzification

The fuzzification block performs the following tasks:

- Measures the value of input variables.
- Performs a scale mapping that transfers the range of values of input variables into the corresponding universes of discourse.
- Performs the function of fuzzification, which converts input data into suitable linguistic values that may be viewed as labels of fuzzy sets.

The input signals to FLC are scaled using appropriate scaling factors. These scaled input data are then converted into linguistic variables, which may be viewed as labels of fuzzy sets. Fuzzy sets can be characterized by membership functions. There are many types of membership functions e.g., the bell-shaped, linear function, triangular function, trapezoidal function and exponential function.

B. Knowledge-base

The knowledge base is comprised of two components namely called fuzzy sets (data base) and fuzzy control rule base. The concepts associated with fuzzy sets are used to characterize fuzzy control rules and fuzzy data manipulation in an FLC. These concepts are subjectively defined and based on experience. So, it should be noted that the correct choice of the membership functions of a term set plays an essential role in the success of an application [24].

The fuzzy rule base consists of a set of linguistic control rules written in the form:

IF a set of conditions are satisfied (premise), THEN a set of consequences are inferred The collection of fuzzy control rules that are expressed as fuzzy conditional statements forms the rule base or the rule set of an FLC.

In particular, the choice of linguistic variables and their membership function have a strong influence on the linguistic structure of an FLC. Typically, the linguistic variables in an FLC are the state, state error, state error derivative, state error integral, etc.

One of the key problems is to find the appropriate fuzzy control rules. In general, there are four models of derivation of fuzzy control rules [24]:

- Using the experience and knowledge of an expert.
- Modeling the control actions of the operator.
- Using a fuzzy model of a process.
- Using self-organized fuzzy controllers.

C. Fuzzy inference engine

The fuzzy engine is the kernel of a fuzzy logic controller, which has capability of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions using fuzzy implication (fuzzy relation) and the rules of inference in fuzzy logic. This means that the fuzzy inference engine handles rule inference where human experience can easily be injected through linguistic rules.

D. Defuzzification

The defuzzification block performs the following functions:

- Scale mapping, which converts the range of values of output variables into corresponding universes of discourse.
- Transforms the fuzzy control actions to continuous (crisp) signals, which can be applied to the physical plant.

V. The Exciter System with Fuzzy Controller

The PI fuzzy controller consisting of two voltage variation inlets and voltage variation rate are applied for the intended fuzzy controller block in this system, (see Fig. 4).

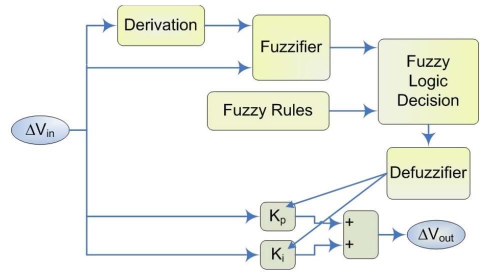

Fig. 4 Structure of fuzzy controller in exciter system.

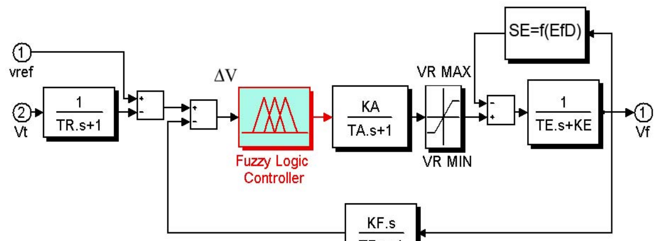

Fig. 5. Excitation system with fuzzy controller.

Respictively, K_p and K_i, in Fig. 4, are proportional and integral coefficient. The gains are defined with fuzzy controller, and they are used to control the signal of ΔV_{in} , in the exciter. In order to do this, the PI control signal is defined with (7) (see Fig. 5).

$$\Delta V_{out} = K_p \Delta V_{in} + \int K_i \Delta V_{in} dt \tag{7}$$

The fuzzy membership functions for the inlet, the inlet variation rate and fuzzy system outlet are defined as the following. For the first inlet, seven membership functions which provide seven different states and for the second inlet three membership functions which provide three states of positive, zero and negative for the voltage variation rate are considered. Also, in order to impose more precise control, the seven membership functions in the fuzzy control outlet are employed, as shown in Fig. 6.

The fuzzy laws are considered as follows.

(If input1 = ... and Input2 = … Then Output =…) and fuzzy laws employed in the knowledge base of the exciter voltage system fuzzy controller are presented in the following Table. I.

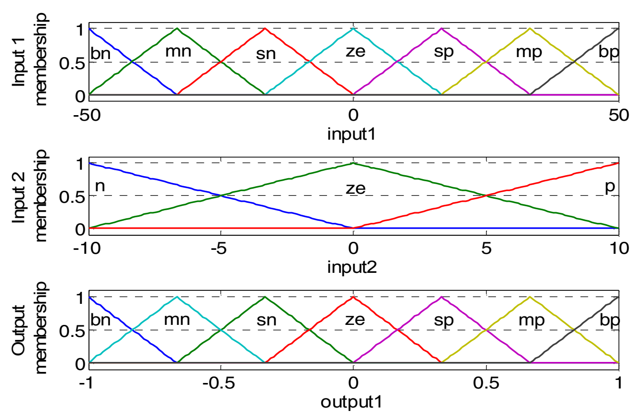

Fig. 6. Membership function for two input and an output in fuzzy controller.

Table I
Fuzzy rules in fuzzy controller

		Derror		
		p	ze	N
Error	bn	Bn	bn	ze
	mn	mn	mn	bn
	sn	ze	ze	mn
	ze	sp	ze	ze
	sp	mp	sp	ze
	mp	bp	mp	mp
	bp	bp	bp	bp

VI. Simulation

For the study of small signal of the sub-synchronous oscillation phenomenon, the standard first model IEEE is used [1]. The simulated system is presented in the Fig. 7.

In this simulation, the line compensation amount by series capacitor is considered to be 55% and a three-phase error in three cycle time occurs in the system. The amount of the parameters of different sections of the system is presented in [1]. The results of the system simulation with exciter voltage controller in two states without fuzzy control and with the application of fuzzy control are analysis. The speed of generator rotor in two states of without and with fuzzy control is presented in the following Fig. 8.

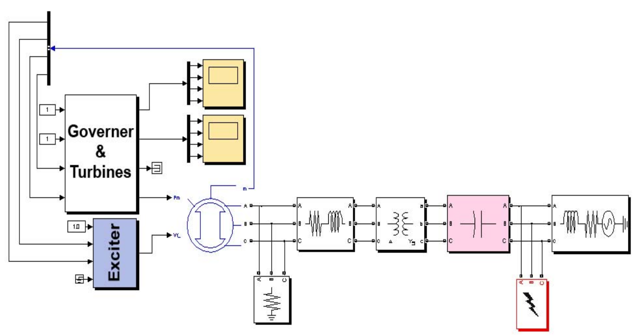

Fig. 7. Simulation of IEEE first benchmark model for computer simulation of sub-synchronous resonance.

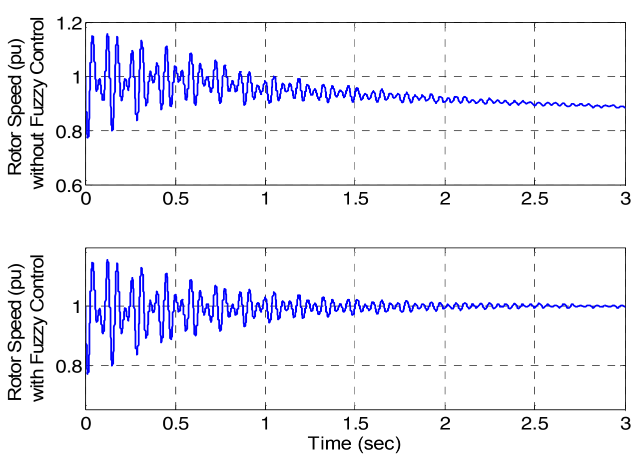

Fig. 8. Rotor speed (without fuzzy control and with fuzzy control).

The illustration of frequency rate variations related to different sections of the shaft (HP, IP, LPA, and LPB) in two states of without and the presence of fuzzy control is depicted in the Fig. 9, to Fig. 12.

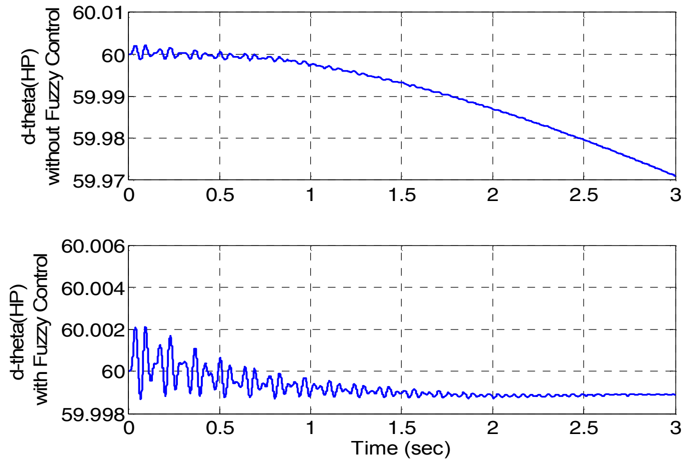

Fig. 9. Theta oscillation of HP turbine
(without fuzzy control and with fuzzy control).

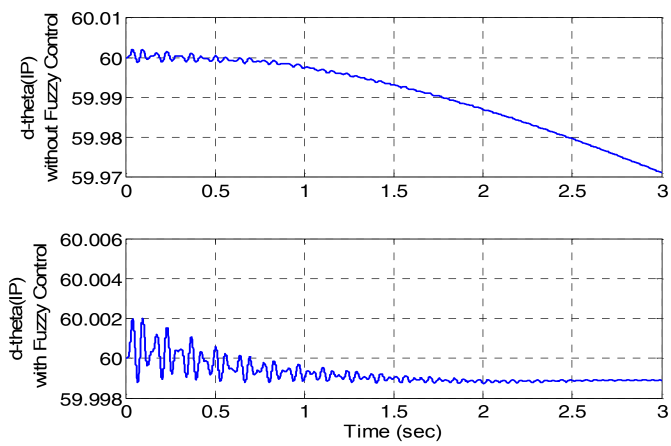

Fig. 10. Theta oscillation of IP turbine
(without fuzzy control and with fuzzy control).

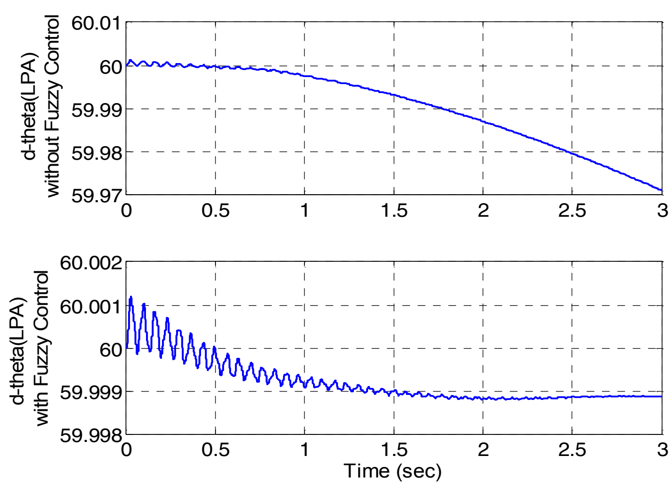

Fig. 11. Theta oscillation of LPA turbine
(without fuzzy control and with fuzzy control).

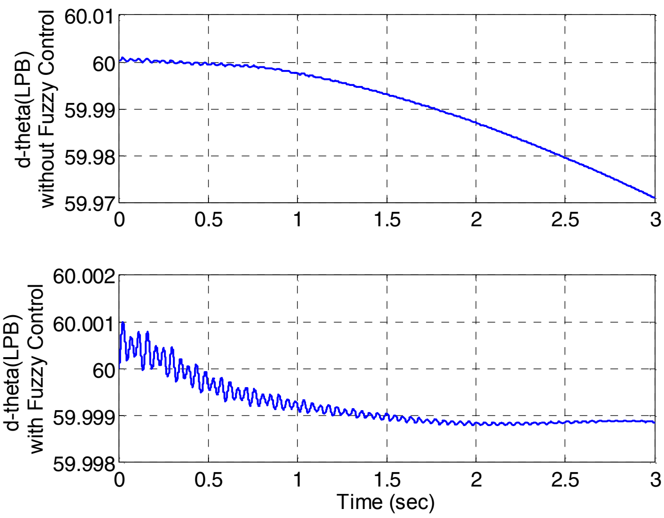

Fig. 12. Theta oscillation of LPB turbine (without fuzzy control and with fuzzy control).

With regard to the presented Figures, the effect of the fuzzy controller function in the exciter control system is depicted. In line with reaching to the control and dumping of oscillations on the generator-turbine shaft, the application of this method along with other controlling methods in power station sector and transfer line section can provide more security.

VII. Conclusion

With regard to the sub-synchronous oscillations resulting from the resonance frequency interference related to the transfer line with series capacitor compensation, with the frequency of torsional modes related to different sections of the generator-turbine shaft, it can lead to uncompensated damage. To damping the oscillations, fuzzy controller was used in exciter. The simulation results depict the improvement of this controller functioning in line with damping the sub-synchronous oscillations.

References

[1] C. Report, "First benchmark model for computer simulation of subsynchronous resonance," *IEEE Trans. Power App. Syst.*, vol. PAS-96, pp. 1565–1572, Sep./Oct. 1977.

[2] Terms, Definitions and Symbols for Subsynchronous Oscillations, IEEE Transactions on Power Apparatus and Systems, Volume PAS-104, Issue 6, pp. 1326 – 1334, 1985.

[3] N. Kumar, "Damping SSR in a series compensated power system," *Power India Conference, 2006 IEEE 10-12*, 7 pp, April 2006.

[4] R. D. Margetts, "Static exciter system for large turbo-generators," Refurbishment of Power Station Electrical Plant, 1988. *International Conference on 7-8,* pp. 124 – 127, Nov 1988

[5] "IEEE guide for the preparation of excitation system specifications," 28 Sept. 1990.

[6] "Principles of static exciters, design aspects and installation Rees, R.; Excitation and stability of generators," *IEE Colloquium on 28*, Jan 1992.

[7] Yong H. Song, Allan T. Johans, "Flexible AC Transmission Systems (FACTS)", IEE Inc., 1999, ISBN 964-6426-41-7.

[8] K. Kabiri, S. Henschel, J. R. Marti, H. W. Dommel, "A discrete state-space model for SSR stabilizing controller design for TCSC compensated systems," *IEEE Transactions on Volume 20, Issue 1*, pp.466 – 474, Jan 2005.

[9] Qianjin Liu; Changchun Zhou; Angquist, L.; Rudin, S., "Using TCSC scheme for SSR mitigation in a radial transfer corridor"**,** Power System Technology, PowerCon 2006, pp. 1 – 6, 2006.

[10] Kakimoto, N.; Phongphanphanee, A., "Subsynchronous resonance damping control of thyristor-controlled series capacitor", Power Delivery, IEEE Transactions on Volume 18, Issue 3, pp. 1051 – 1059, 2003.

[11] Padiyar, K.R.; Prabhu, N., "Design and performance evaluation of subsynchronous damping controller with STATCOM", Power Delivery, IEEE Transactions on Volume 21, Issue 3, pp. 1398 – 1405, 2006.

[12] Jowder, F.A.R.A.; Ooi; B.-T., "Series compensation of radial power system by a combination of SSSC and dielectric capacitors", IEEE Transactions on Power Delivery, Vol. 20, Issue 1, Jan 2005, pp. 458 – 465.

[13] Barati, H.; Ara, A.L.; Ehsan, M.; Fotuhi-Firuzabad, M.; Bathaee, S.M.T., "Application of Static Synchronous Series Compensator to Damp Sub-Synchronous Resonance", Power Electronics, Drives and Energy Systems, 2006. PEDES '06, International Conference on, pp. 1 – 6, 2006.

[14] Wan Bo and Zhang Yan; "Damping subsynchronous oscillation using UPFC - a FACTS device", Proceedings of International Conference on Power System Technology, vol. 4 - PowerCon 2002, 13-17 Oct. 2002, pp. 2298 - 2301.

[15] de Jesus, F.D.; Watanabe, E.H.; Souza, L.F.W.; Alves, J.E.R., Jr., "SSR mitigation using gate-controlled series capacitors", Power Engineering Society General Meeting, 2006. IEEE, 7 pp, 2006.

[16] Tao Yu; Ka Wing Chan; Zhen Ren, "Damping analysis of primary and auxiliary control of HVDC systems", Power Engineering Society General Meeting, 2006. IEEE, 6 pp, 2006.

[17] T. Mok, Y. Ni, and F. Wu "Design of fuzzy damping controller of UPFC through genetic algorithm", *Proceedings IEEE Summer Power Meeting*, *Seattle, WA,* July 2001.

[18] T. Terano, K. AsaI, M. Sugeno, "Applied fuzzy systems," *Academic Presss Inc.*, pp.86-93, 1994.

[19] Prabha Kundur, "Power System Stability and Control".

[20] Padiyar K. R., "Power System Dynamics – Stability and Control", BS Publications.

[21] Zadeh, L., *Fuzzy sets*, Information Control 8, 1965.

[22] T. Mok, Y. Ni, and F. Wu, "Design of fuzzy damping controller of UPFC through genetic algorithm, " Proceedings IEEE Summer Power Meeting, Seattle, WA, July 2001.

[23] T. Terano, K. AsaI, M. Sugeno, "Applied fuzzy systems, " Academic Presss Inc., pp.86-93, 1994.

[24] C. C. Lee, "Fuzzy Logic in Control Systems: Fuzzy Logic Controller-Part I, " *IEEE Trans. On Syst. Man Cybern.*, vol. 20, no. 2, pp. 404-418, March/April 1990.