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Mitigating SSR in Hybrid Wind-Steam Turbine with TCSC Based Fuzzy Logic Controller and Adaptive Neuro Fuzzy Inference System Controller

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Abstract *– The increasing requirement to the clean and renewable energy has led to the rapid development of wind power systems all over the world. With growing usage wind power in power systems, impact of wind generators on subsynchronous resonance (SSR) is importance. SSR is a well-known phenomenon in a series compensated power systems which can be mitigated with Flexible ac transmission systems (FACTS) devices. In this paper for damping the SSR, a Thyristor Controlled Series Capacitor (TCSC) has been used. This paper used wind and steam turbine as a hybrid energy production system. In order to have an optimal control on pitch angle in high speed of wind, fuzzy logic damping controller (FLDC) and Adaptive Neuro Fuzzy Inference System (ANFIS) have been used. The main objective of this paper is to investigate the ability of the Thyristor Controlled Series Capacitor (TCSC) for mitigation of SSR. In order to conduct the studies, the IEEE second benchmark model on SSR is adapted with the combination of synchronous wind generator based wind turbine. Finally the operation of two controllers have been compard.*

Keywords*: 3 to 5 keyword or phrases.*

ORIGINAL ARTICLE

Nomenclature

General

fe	Electrical frequency of the power system
f0	synchronous frequency of the power system
Xc	reactance of series capacitor
Xl	leakage reactance of compensated line
Cp	power coefficient
A	Area swept by the rotor $A = \pi R^2$ R the radius of the blade [m]
Vw	Wind speed
ωw	Angular velocity of rotor [rad/s]
Vω	peed upstream of the rotor [m/s]
R	Rotor radius [m]

INTRODUCTION

With raising worries about environmental pollution and possible energy lack, great labors have been taken by the governments surrounding the world to achieve renewable energy programs, established on Hydropower, Biomass/Bioenergy, Geothermal Energy, Wind Energy and Photovoltaic (PV) Cells, etc [1].

Wind power is the most fast growing technology for renewable power generation systems [2]. The first wind turbines have been appeared at the beginning of the last century and its technology was increased step by step from the early 1970s. At the end of 1990s, wind energy has reappeared as one of the most important maintainable energy resources, partly because of the increasing price of the oil, safety worries of nuclear power and its environmental issues [3].

Based on predictions 12% of the total energy demand all over the world will create from the renewable wind power by the end of 2020 [4]. Therefore with the fast development of installed capacity of wind farms, the large wind turbine generators (WTGs) are widely used into electric power grids.

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Series capacitive compensation is a very economical method to enhance the system stability and power transfer capability especially where large amounts of power must be transmitted over long transmission lines. However, this also leads to occur the phenomenon of subsynchronous resonance (SSR) [5],[6]. SSR could contain either torsional interactions (TI) or induction generator (IG) effect [7].

In recent years, there are many researches which have been done in order to damp the SSR. M. S. El-Moursi et al are proposed a novel STATCOM controller for mitigating SSR [8]. Impacts of Large-Scale Wind Power Integration on Subsynchronous Resonance have been analyzed by Tang Yi, and Yu Rui-qian [9]. R. K. Varma et al Mitigated Subsynchronous Oscillations in a Series Compensated Wind Farm with Thyristor Controlled Series Capacitor (TCSC) [10].

This paper focuses on a Thyristor Controlled Series Capacitor (TCSC) based on a supplementary controller for damping SSR. In this paper wind and steam turbine have been used by means of a hybrid energy production system. The IEEE second benchmark model on SSR is occupied with integrating aggregated synchronous generator-based wind turbine to carry out the studies. This paper shows that the TCSC with fuzzy logic damping controller (FLDC) and Adaptive Neuro Fuzzy Inference System (ANFIS) in supplementary controller is able to mitigate SSR.

System Configuration

The arrangement of the study system has been shown in fig 1. This fig shows the IEEE Second Benchmark Model (SBM) combined with TCSC in line 1 which is mainly used for SSR studies [11].

This system comprise of steam and wind turbines with synchronous generator supplying power to an infinite bus per two parallel transmission lines, and one of them is compensated by a series capacitor by TCSC. A 600 MVA steam turbine-generator and 60MVA wind turbines (which comprise of 40 turbines and each turbine generate 1.5MVA) are coupled to an infinite bus, and the rated line voltage is 500KV, while the rated frequency is 60Hz. The shaft system comprise of four masses: a high pressure turbine (HP), low pressure turbine (LP), the generator (G), rotating Exciter (EX). Elastic shaft linked all masses together mechanically.

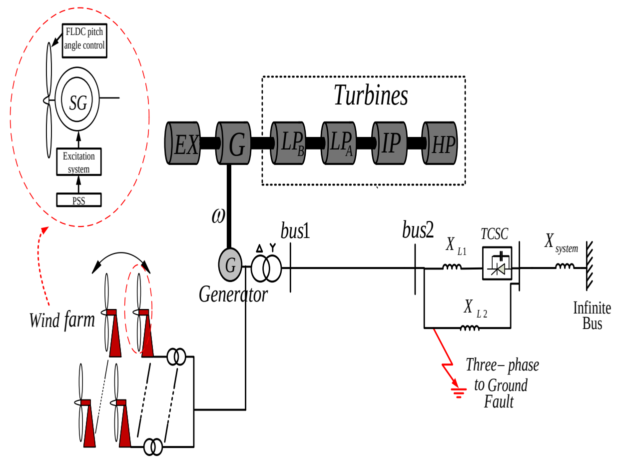


Fig. 1. IEEE SSR second benchmark model supplied by the TCSC

Subsynchronous Resonance

SSR is a potential phenomenon which may appear in a series compensated power system when the mechanical system (turbine-generator) exchanges energy with the electrical network [12],[13]. The power system compensated via a series capacitor has a sub-synchronous natural frequency (fe) which is assumed by:

$$f_e = f_0 \sqrt{\frac{X_c}{X_l}} \qquad (1)$$

The generated subsynchronous currents will outcome in rotor torque at the complementary frequency, i.e.

$$fr = f0 - fe \qquad (2)$$

If fr=f0-fe is near to one of the torsional frequencies of the rotor shaft, the torsional oscillations will be excited and this condition lead to detrimental phenomenon namely SSR [5]. Two types of SSR connections which may occur in a power system are as follows [14]:

1. Self-excitation or steady state SSR
2. Transient torques or transient SSR

Self-excitation is separated to two major parts: Induction Generator Effect (IGE), and torsional interaction (TI). The IGE is not possible in series compensated power system. But, the TI and transient SSR are usually happen in series compensated power systems [15].

Modelling of Wind Turbine

A fixed wind speed turbine system based on a synchronous generator (SG) has been investigated in this work; wind speed is 13.5 m/s and the base speed is 11 m/s. Following equations described, power extracted from the wind.

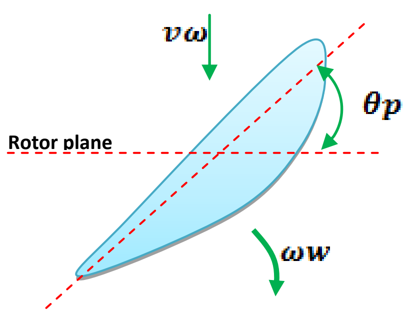
$$P_w = C_p \times \frac{1}{2} \times \rho \times A \times V \times \omega^3 \tag{3}$$

$$C_p = \frac{1}{2} \times \left[\frac{116}{\lambda i} - 0.4\theta p - 5 \right] e^{\frac{-21}{\lambda i}} + 0.0068\lambda \tag{4}$$

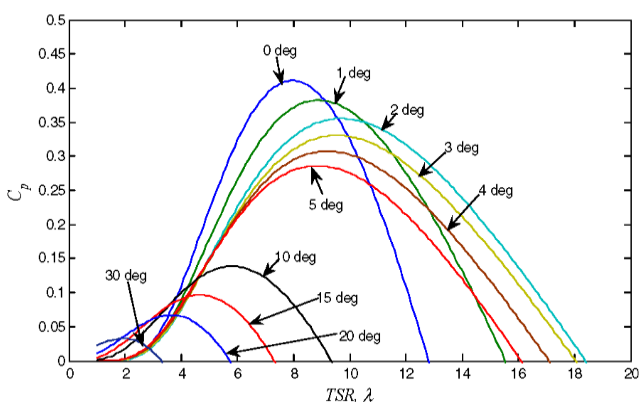
$$\lambda = \frac{\omega_w}{v_\omega} \times R \tag{5}$$

$$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\theta p} - \frac{0.035}{\theta p^3 + 1} \tag{6}$$

θp is the angle between the plane of rotation and the blade cross-section chord [16],[17].



(a)



(b)

Fig. 2. Blade pitch angle θp (a), Power coefficient versus blade pitch angle (b)

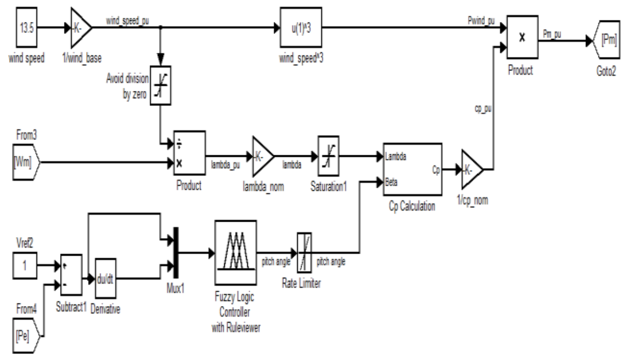


Fig. 3. Wind Turbine modeled with Simulink

Fig 3 displays the model of the wind turbine equipped by FLDC of pitch angle. Wind power plants are not sustainable like fuel energy production. The wind power generators installations must use a system to support the power generator for the time that wind turbine produces energy is little. In this paper wind and steam turbine have been used as a hybrid energy production system.

Modeling of Thyristor Controlled Series Capacitor (TCSC)

A TCSC comprise of a capacitor in parallel with an inductor that is connected to a couple of opposite-poled thyristors. By adjusting the firing angle of the thyristors, the inductor reactance is varied and it can lead to change the effective impedance of TCSC. The TCSC is commonly operated in capacitive region, while inductive mode operation can be used during severe possibilities [18]. Schematic diagram of TCSC has been shown in fig 4.

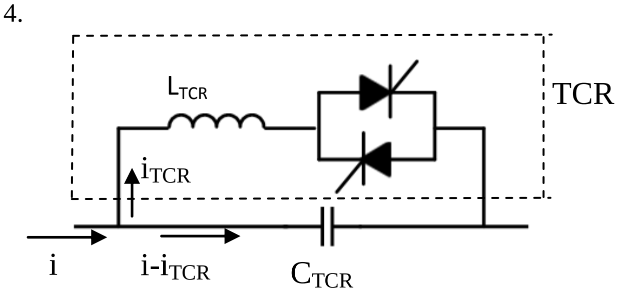


Fig. 4. Schematic diagram of TCSC

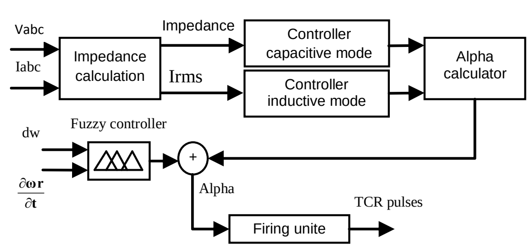


Fig. 5. schematic of Auxiliary FLDC controller of TCSC

DESIGN OF FUZZY LOGIC DAMPING CONTROLLER (FLDC) CONTROLLER

In recent years, Fuzzy Logic Damping Controllers (FLDCs) have been appeared as an effective implement to stabilize the power network. [19], [20]. FLDCs are more robust and effective than Conventional Damping Controllers (CDCs) in the power. In this paper two Fuzzy Logic Damping Controllers (FLDCs) have been applied to pitch angle control in wind turbine and TCSC controller.

Power deviation (ΔP) and its derivatives are inputs of fuzzy controllers and pitch angle (θp) is output of fuzzy controller.

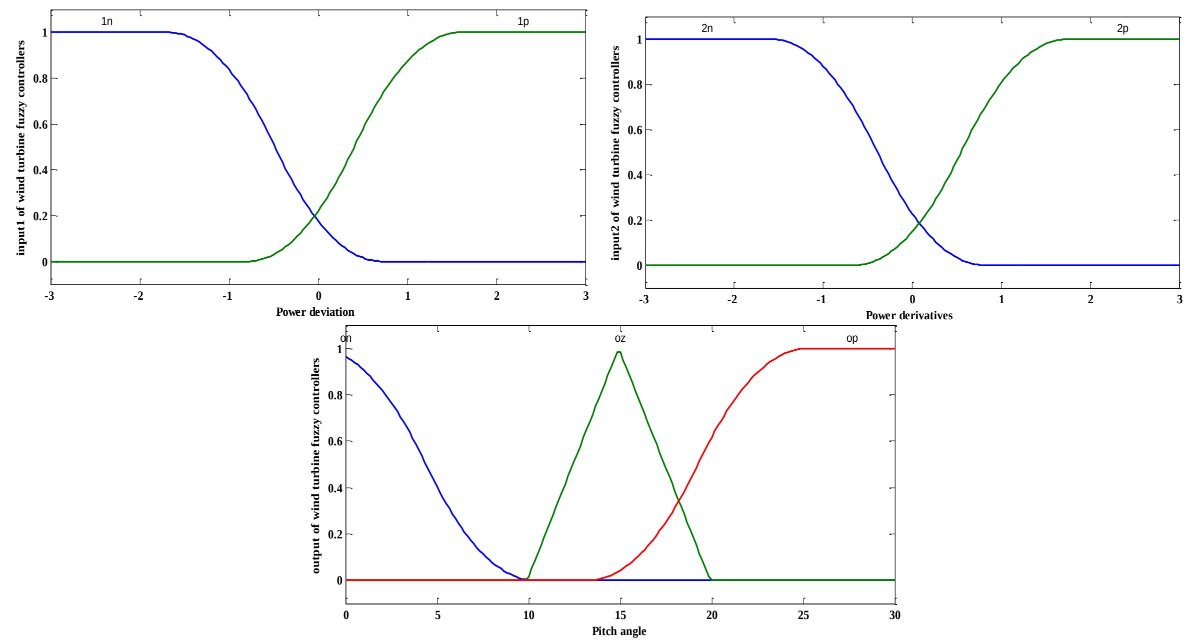


Fig. 6. Membership functions for the FLDC of pitch angle controller

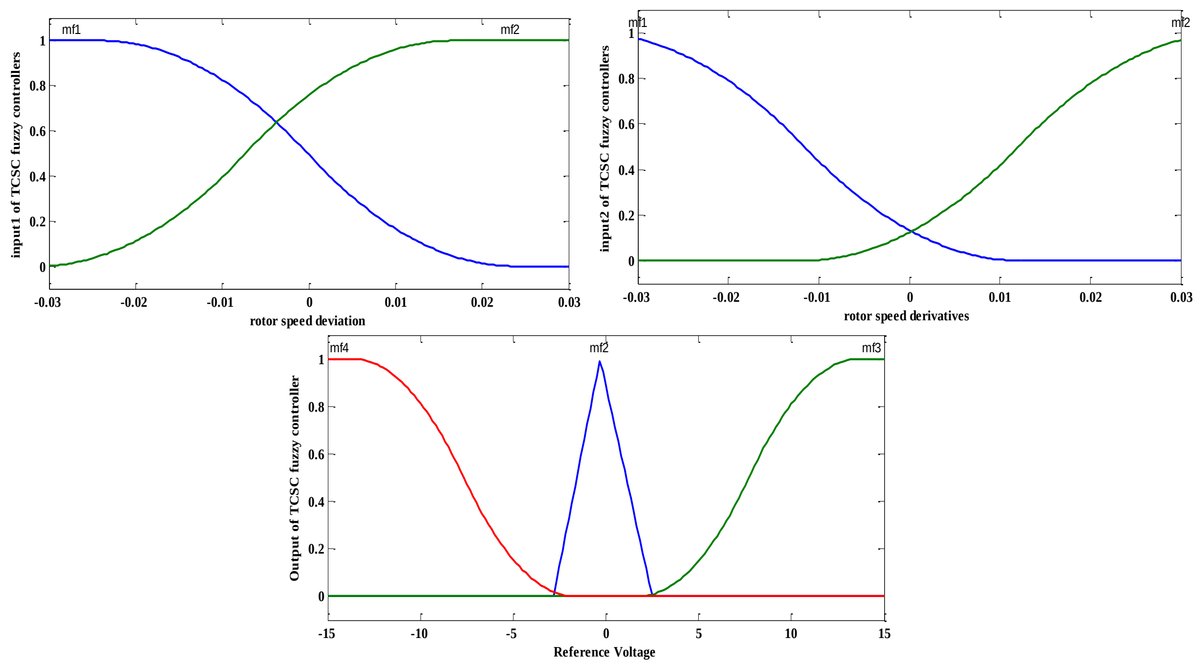


Fig. 7. Membership functions for the FLDC of TCSC controller

The control rules of the fuzzy controllers are showed below. The fuzzy sets have been determined as: N: negative, Z: zero, P: Positive, respectively.

1. If (ΔP is P) and ($\frac{\partial \Delta P}{\partial t}$ is P) then (θp is N)

2. If (ΔP is P) and ($\frac{\partial \Delta P}{\partial t}$ is N) then (θp is Z)

3. If (ΔP is N) and ($\frac{\partial \Delta P}{\partial t}$ is P) then (θp is Z)

4. If (ΔP is N) and ($\frac{\partial \Delta P}{\partial t}$ is N) then (θp is P)

In TCSC controller, rotor speed deviation ($\Delta\omega$), its derivatives have been used as the fuzzy controllers inputs and firing angle is output of fuzzy controllers. The control rules of the fuzzy controllers are showed below. The fuzzy sets have been determined as: N: negative, Z: zero, P: Positive, respectively.

1. If ($\Delta\omega$ is P) and ($\frac{\partial \Delta\omega}{\partial t}$ is P) then ($\Delta\alpha$ is P)

2. If ($\Delta\omega$ is P) and ($\frac{\partial \Delta\omega}{\partial t}$ is N) then ($\Delta\alpha$ is Z)

3. If ($\Delta\omega$ is N) and ($\frac{\partial \Delta\omega}{\partial t}$ is P) then ($\Delta\alpha$ is Z)

4. If ($\Delta\omega$ is N) and ($\frac{\partial \Delta\omega}{\partial t}$ is N) then ($\Delta\alpha$ is N)

$$\alpha = 90 + \Delta\alpha \tag{7}$$

STATCOM BASED ANFIS CONTROLLER

The ANFIS was first introduced by J. Jang in 1993 [21]. ANFIS is a class of adaptive networks functionally equivalent to fuzzy inference systems [22].

The ANFIS uses a hybrid learning process to discriminate consequent parameters of Sugeno-type fuzzy inference systems. The hybrid learning rule, which combines the gradient descent technique and the Least Square Estimator, was proposed in to train the ANFIS network for a specific problem [23]. In this paper to overcome the above worries ANFIS has been adopted to estimate the modeled dynamics. Both Neural Network and Fuzzy Logic are model-free estimators and share the common ability to attend the vagueness and noise.

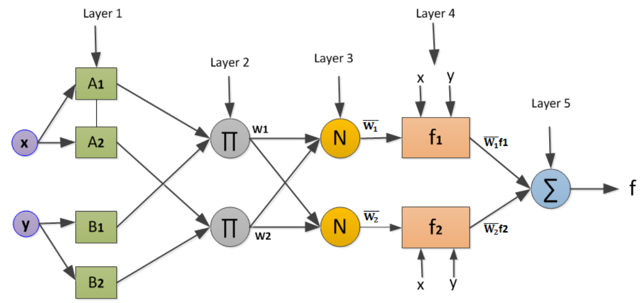


Fig. 8. Corresponding ANFIS architecture

The ANFIS system comprise the main components of a fuzzy system except that the calculations at each stage are carry out by a layer of hidden neurons and the neural network's learning capacity is Provided to increase the system knowledge (Fig. 9).

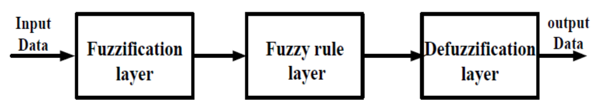


Fig. 9. ANFIS architecture

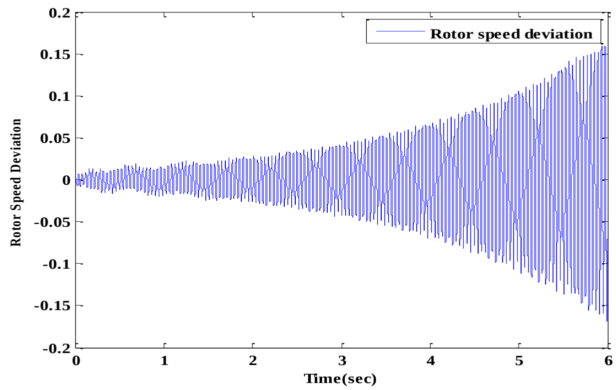
(1) Fuzzification layer: In this layer every neuron characterizes an input membership function of the antecedent of a fuzzy rule.

(2) Fuzzy rule layer: In this layer fuzzy rules are extracted and the value at the end of each rule characterizes the rule initial weight, and will be regulated to its suitable level at the end of training.

(3) Defuzzification layer: In this layer each neuron characterizes a consequent proposition and its membership function can be applied by combining one or two sigmoid functions and linear functions. [24].

RESULTS AND SIMULINK IN MATLAB

For verifying the efficacy of the offered control method to mitigate the SSR phenomenon, the IEEE Second Benchmark combined with the TCSC is modeled in MATLAB/Simulink. Two cases for studying are considered. Initially, the power system without any damping controllers and secondly with FLDC and ANFIS controllers is simulated. When fault is cleared, large oscillations will be happened among the different parts of the turbine-generator shaft, as shown in Fig. 10.



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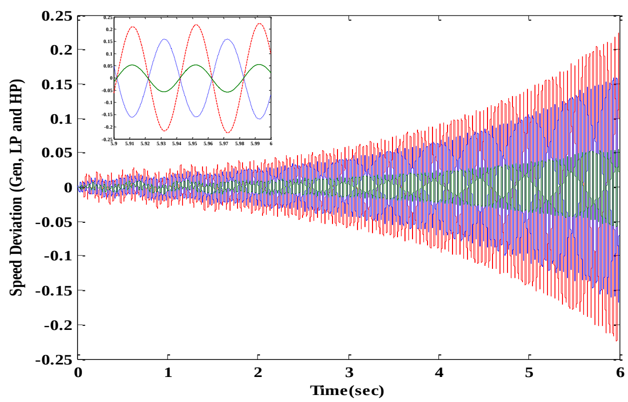

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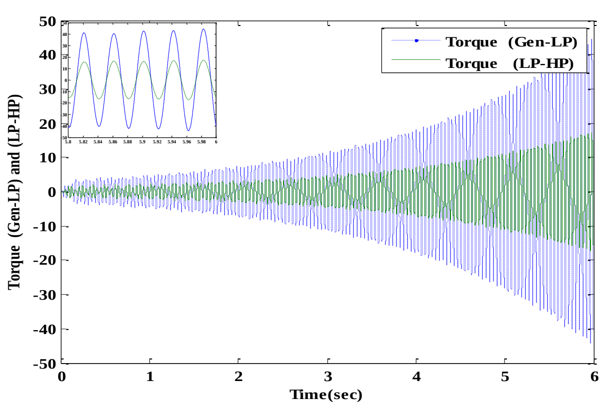

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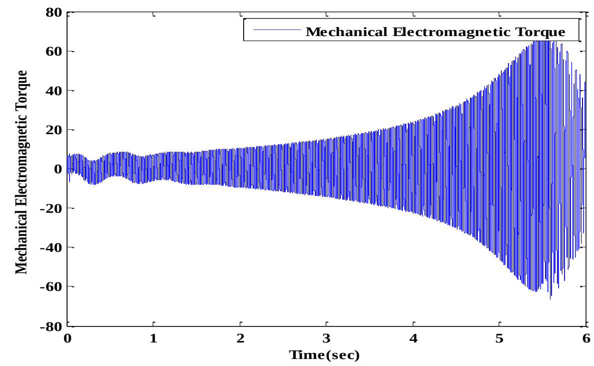
Fig. 10. Simulation results for un-damped mode: (a): rotor speed deviation, (b): speed deviation between generator, Low pressure and high pressure turbine, (c): torque between generator, Low pressure and high pressure turbines.

SSR oscillations in wind turbine have been shown in fig 11.



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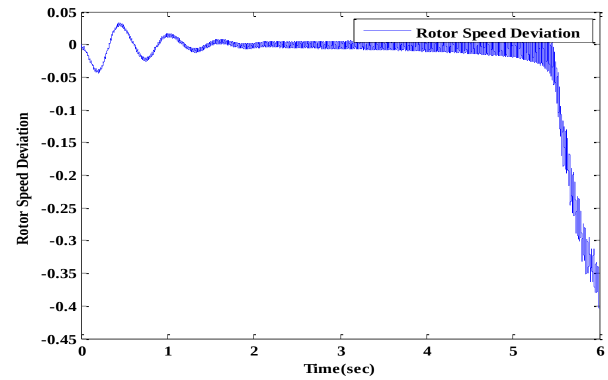

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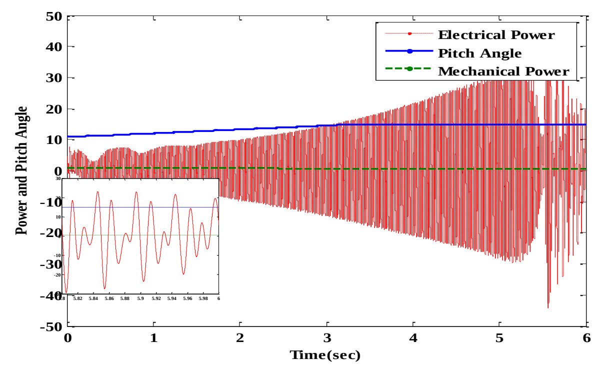

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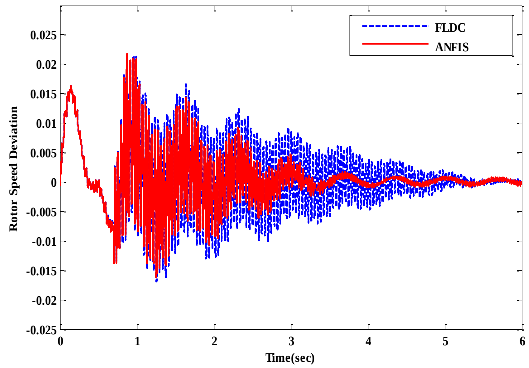
Fig. 11. Simulation results for un-damped mode: (a): mechanical electromagnetic torque, (b): rotor speed deviation in wind turbine, (c): mechanical and electrical power and pitch angle.

Fig 11 shows the oscillations in wind turbine due to SSR phenomenon without TCSC.

In this section, a novel FLDC and ANFIS controllers have been added to the TCSC for observing specification deviation of the system. Rotor speed, rotor speed deviation and torques of generator are shown in Fig. 12.



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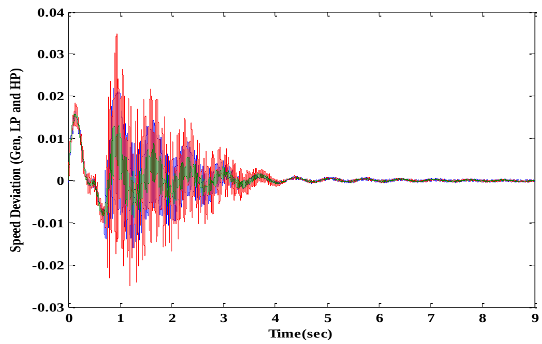

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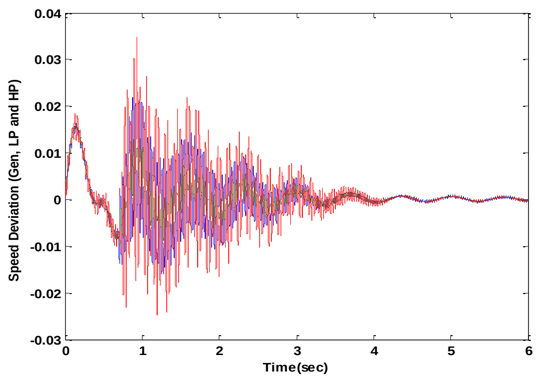

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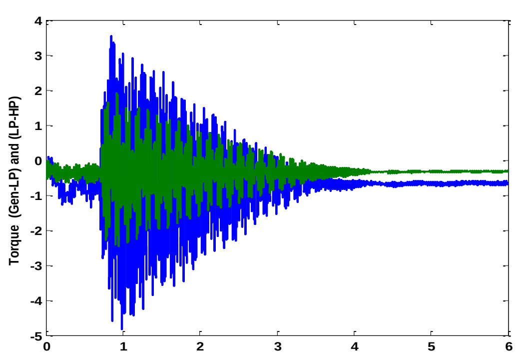

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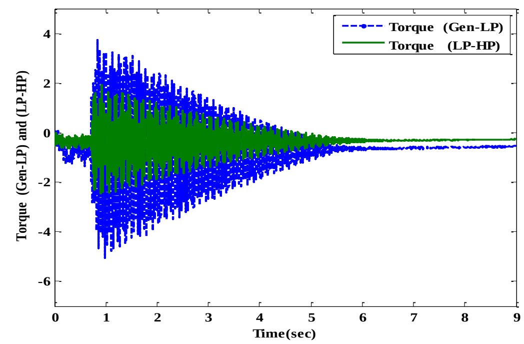

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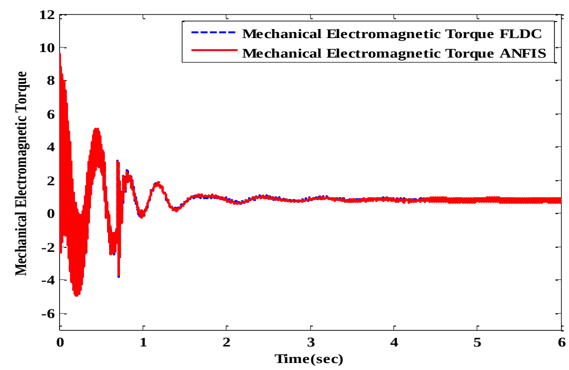
Fig. 12. Simulation results with damping SSR by TCSC with FLDC and ANFIS controller



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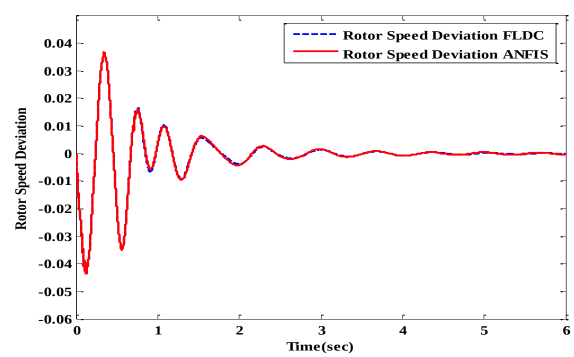

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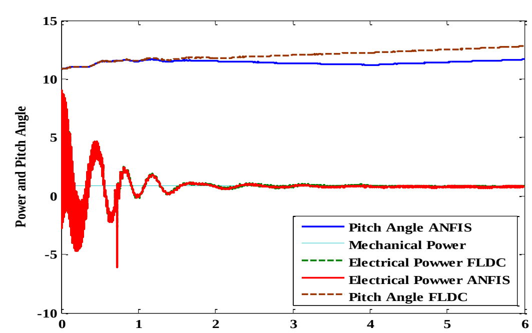

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Fig. 13. Simulation results for damping SSR by TCSC with FLDC and ANFIS controllers

CONCLUSIONS

The increasing requirement to the clean and renewable energy has led to the rapid development of wind power systems all over the world. With growing usage wind power in power systems, impact of wind generators on sub synchronous resonance (SSR) is importance.

This paper proposed a technique for damping the SSR by TCSC. The IEEE second benchmark system equipped by steam and wind turbine as a hybrid energy production system was studied. A TCSC is originally employed to increase power transfer capability of the transmission. As shown The TCSC with auxiliary FLDC and ANFIS controllers can be able to damp the oscillations of SSR phenomenon.

With applied FLDC and ANFIS controllers to TCSC and applied them for controlling pitch angle of wind turbine, TCSC mitigated the SSR and mechanic and electric power of wind generator were closed to together. By this work wind generator produced power in near the 1pu. Results show that the ANFIS controller damped SSR in lower settling time and overshoot than the fuzzy controller in steam turbine.

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