Mitigating of Sub-synchronous Resonance in a Series-Compensated Hybrid System with Steam and Wind Turbine Using FACTS Controllers

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ABSTRACT:
The growing requirement to the clean and renewable energy has led to the rapid development of wind power systems all over the world. With increasing use of wind power in power systems, impact of the wind generators on sub-synchronous resonance (SSR) is going more important. The SSR is a well-known phenomenon in a series compensated power systems which can be mitigated with series or parallel flexible ac transmission systems (FACTS) devices. In this paper, wind turbines and steam turbines have been used as a hybrid energy production system. For damping the SSR, thyristor controlled series capacitor (TCSC) as a series FACT devise and unified power flow controller (UPFC) as a series-parallel FACT device have been used. In order to have an optimal control on pitch angle in high speed of wind, a novel method using imperialist competitive algorithm (ICA) has been used. Furthermore, supplementary controllers for UPFC and TCSC have been design and adaptive neuro fuzzy inference system (ANFIS) and fuzzy logic damping controllers (FLDC) are added to these FACTS devises to mitigate the SSR. Finally, the results of two FACTS devises have been compared. Furthermore, the results obtained from imperialist competitive algorithm (ICA) are compared with PID controller optimized by Particle Swarm Optimization (PSO) algorithm.

KEYWORDS: Imperialist competitive algorithm (ICA), Adaptive neuro fuzzy inference system (ANFIS), Thyristor controlled series capacitor (TCSC), Unified power flow controller (UPFC), Sub-synchronous resonance (SSR).

NOMENCLATURE

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 $A=\pi\times R^2$ R, the radius of the blade [m]
Vw	Wind speed
ωw	Angular velocity of rotor [rad/s]
Vω	Wind speed upstream of the rotor [m/s]
R	Rotor radius [m]
θp	Pitch angle [°]
ρ	Air density, which is equal to 1.225 Kg/m^2 at sea level at temperature T=25 $^\circ c$
λ	The tip speed ratio
Δp(t)	The difference between mechanical and electrical power in wind turbine

1. INTRODUCTION

Wind power is one of the most fast developing technologies for renewable power generation systems [1]. At the commencement of the last century, the first wind turbines have been appeared, and its technology was improved step-by-step since the early 1970s. At the end of 1990s, wind energy has been appeared again as one of the most significant maintainable energy resources, partly because of the increasing price of the oil, safety worries of nuclear power and its environmental issues [2]. Hence with the fast progress of installed capacity of wind farms, the large wind turbine generators (WTGs) are extensively used into electric power grids. The generated power by wind farm should be transmitted through the transmission system that can endure large power flow.

One of the economical techniques to increase the system stability and power transfer ability is series capacitive compensation, specifically where large amounts of power must be transmitted through long transmission lines. However, this also leads to occur the phenomenon of sub-synchronous resonance (SSR) [3, 4]. SSR is a well-understood phenomenon that can be damped by series or parallel flexible ac transmission system (FACTS) devices [5]. In this paper wind and steam turbines have been used as a hybrid energy production system. For damping the SSR, thyristor controlled series capacitor (TCSC) as a series FACT devise and unified power flow controller (UPFC) as a series-parallel FACT devise have been used. A novel method using imperialist competitive algorithm (ICA) has been used to have an optimal control on pitch angle in high speed of wind. Also supplementary controllers for UPFC and TCSC have been design and adaptive neuro fuzzy inference system (ANFIS) controllers are added to these controllers to mitigate the SSR. Finally the results of two FACTS devises have been compared.

2. SUB-SYNCHRONOUS RESONANCE

SSR is a potential phenomenon which could appear in a series compensated power system when the mechanical system (turbine-generator) exchanges energy with the electrical network [6,7]. The power system compensated by a series capacitor, has a sub-synchronous natural frequency (f_e) which is given by:

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

The generated sub-synchronous currents will consequence in rotor torque at the complementary frequency, i.e.

$$f_r = f_0 - f_e \quad (2)$$

If $f_r = f_0 - f_e$ be close to one of the torsional frequencies of the rotor's shaft, the torsional fluctuations will be excited and this situation lead to damaging phenomenon namely SSR [3]. Two types of SSR connections which could occur in a power system as follows [8]:

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

Self-excitation is divided to two main 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 [2].

3. SYSTEM CONFIGURATION

Figures 1and 2 show the configuration of the study system. In this paper for studying the SSR, IEEE Second Benchmark Model (SBM) combined with TCSC and UPFC in line 1 has been used [9]. The system contain steam and wind turbines with synchronous generator for supplying power to an infinite bus per two parallel transmission lines, and one of them is compensated by a series capacitor. Steam turbine-generator produces 600 MVA and wind turbines produce 60MVA (which comprise of 40 turbines and each turbine generates 1.5MVA). They are coupled to an infinite bus, and the rated line voltage is 500KV, while the rated frequency is 60Hz.

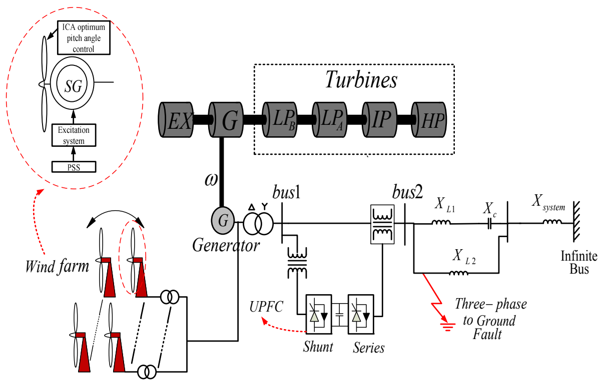


Fig. 1. IEEE SSR second benchmark model supplied by the UPFC

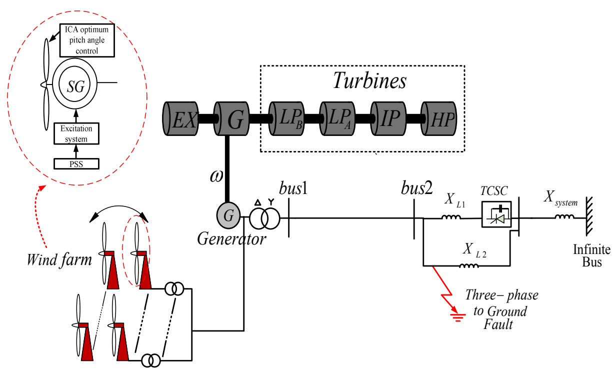


Fig. 2. IEEE SSR second benchmark model supplied by the TCSC

In this paper two study systems are considered. In study system 1, a UPFC is connected parallel at the bus 1 and series at bus 2. In study system 2, UPFC is not considered. Instead, the series capacitor is replaced with a TCSC as shown in Figure 2. The capacitive reactance of the TCSC is the same as variable line series compensation.

4. MODELING OF UNIFIED POWER FLOW CONTROLLER (UPFC)

There are several FACTs devices that can be able to damp SSR, for example: TCSC, SVC, UPFC, STATCOM, SSC and etc. In this paper in study system 1 for damping SSR, a unified power flow controller UPFC has been used. The arrangement of UPFC fundamentally includes two voltage source inverters (VSIs) connected back-to-back with an interconnecting dc storage capacitor. One of them is connected to the system by a shunt transformer and another one is connected to the transmission line by a series transformer [10]. The basic UPFC construction has been shown in figure 3. Figure 4 shows the proposed method of auxiliary FLDC shunt controller.

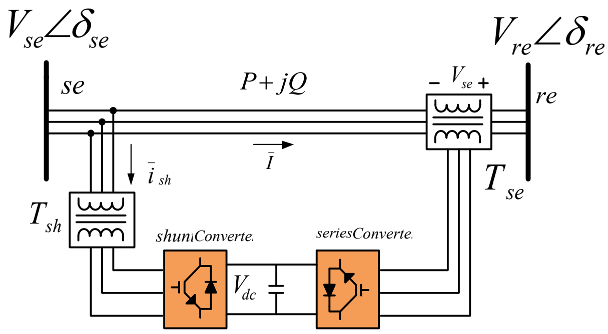


Fig. 3. Structure of an UPFC between buses 1 and 2

An auxiliary ANFIS controller has been added to the shunt part of UPFC for mitigating SSR. The shunt part of UPFC maintains the voltage of bus 1 in nominal value by controlling the reactive power and series part of UPFC controls the active power of power system.

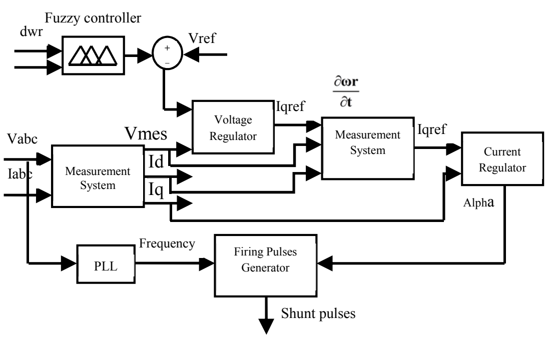


Fig. 4. Schematic of Auxiliary ANFIS shunt controller

In figure 4 V_{abc} and I_{abc} are the voltage and current of bus1, V_{mes} is the magnitude of V_{abc}, I_d and I_q are the d-axis and q-axis of Iabc, d_{wr} is the rotor speed oscillation and alpha is the Firing angle of thyristors.

5. MODELING OF THYRISTOR CONTROLLED SERIES CAPACITOR (TCSC)

A TCSC include a capacitor in parallel with an inductor that is connected to a couple of opposite-poled thyristors. By regulating the firing angle of the thyristors, the inductor reactance is diverse and it can lead to change the effective impedance of TCSC. The TCSC is generally operated in capacitive region, while inductive mode operation can be used during severe possibilities [11]. Graphic diagram of TCSC has been shown in figure 5.

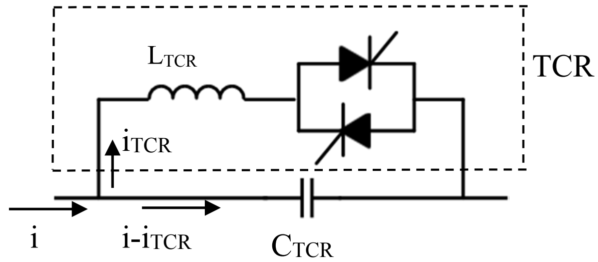


Fig. 5. Schematic diagram of TCSC

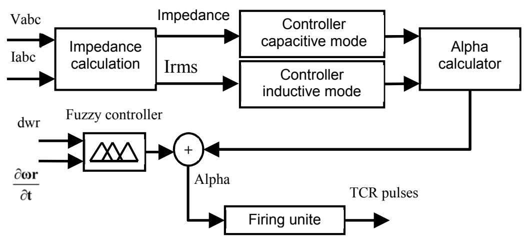


Fig. 6. Schematic of Auxiliary FLDC controller of TCSC

6. MODELLING OF WIND TURBINE

A fixed speed wind turbine system established on a synchronous generator (SG) has been evaluated in this work; wind's speed is 13.5 m/s and the base speed is 11 m/s. the extracted power from the wind turbine is determined by the following equations.

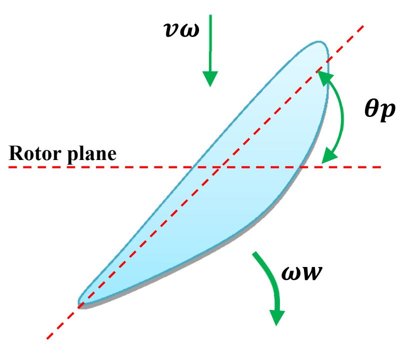
$$P_W = C_p \times \frac{1}{2} \times \rho \times A \times V \times \omega^3 \tag{3}$$

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

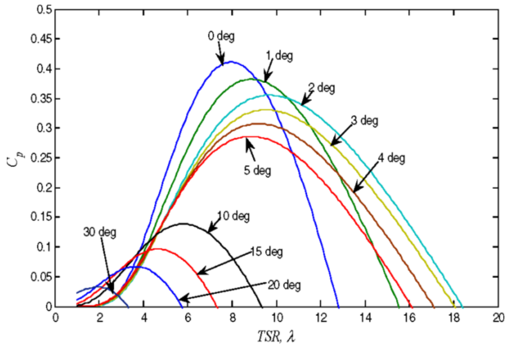
$$\lambda = \frac{\omega_W}{v_\omega} \times R \tag{5}$$

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

As shown in (Figure 7a), θp is the angle between the plane of rotation and the blade cross-section chord [2,12]. Cp witch computed according to equation 4, for various blade pitch angles θp, is show in (Figure 7b).



(a)



(b)

Fig. 7. Blade pitch angle θp (a), Power coefficient versus blade pitch angle (b)

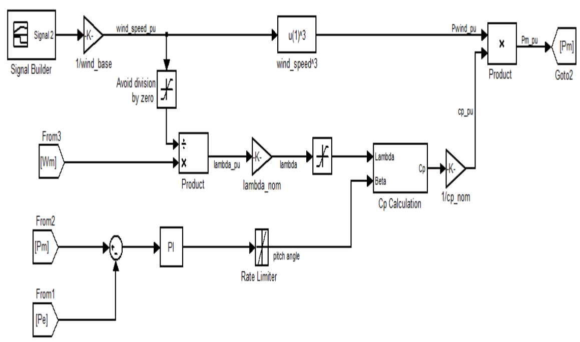


Fig. 8. Wind Turbine modeled with Simulink

Figure 8 shows the model of the wind turbine implemented. The generation power of wind turbine is directly related to the wind's speed. Meanwhile most wind power production is produced at high speed of wind. As an outcome, wind power plants are not maintainable like fuel energy manufacture. The wind power generators installations must utilize a system to support the power generator for the time that wind turbine produces energy is low. Nominal values of wind turbine have been shown in Table 1.

Table 1. Parameters of wind turbine model

Wind Speed Base (m/s)	11
Lambda Nom	8.11
Cp Nom	0.48

In case of regulating pitch angle in order to control produced power of wind turbine in high and low wind's speed a novel method using Imperialist Competitive Algorithm (ICA) is presented. In the next part ICA is explained.

7. INTELLIGENT PARAMETER ESTIMATION BASED ON IMPERIALIST COMPETITIVE ALGORITHM (ICA)

Imperialist Competitive Algorithm (ICA) is also a new evolutionary optimization technique which is derivative by imperialistic rivalry. Like other evolutionary algorithms, ICA begins with an initial population which is known as the country; this country is containing of two species of colonies and imperialists which together form empires [13].

In fact, imperialist countries try to overcome other countries and rotating them to their colonies. Also, imperialist countries compete powerfully with each other for taking tenure of other countries; Imperialistic competition among these empires forms the suggested evolutionary algorithm. During this competition the weakest empire downfall and stronger ones will get more potency [14].

The pseudo code of Imperialist Competitive Algorithm is presented below [15]:

1. Select some random points on the function and initialize the empires.
2. Move the colonies toward their relevant imperialist (Assimilation).
3. Randomly change the position of some colonies (Revolution).
4. If there is a colony in an empire which has lower cost

Than the imperialist, exchange the positions of that colony and the imperialist.

5. Unite the similar empires.
6. Compute the total cost of all empires.
7. Pick the weakest colony (colonies) from the weakest

Empires and give it (them) to one of the empires (Imperialistic competition).

8. Eliminate the powerless empires.
9. If stop conditions satisfied, stop, if not go to 2.

In this paper, the ICA is selected to regulate K_p and K_i parameters for pitch angle controlling. The objective function for optimization by ICA and PSO is presented as below:

$$\int_0^{tsim} t \times |\Delta p(t)| dt \qquad (7)$$

Table 2 shows the necessary information for PSO [16] algorithms.

Table 2. Parameters of PSO Algorithm

Population size	40
C1	2
C2	2
W	0.9
Iteration	15

Table 3 shows the necessary information for ICA algorithms.

Table 3. Parameters of ICA Algorithm

Countries	40
Imperialists	8
Decades	15
Revolution Ratio	0.3
Alpha	0.1
Beta	2
Gamma	0.5

8. DESIGN OF FUZZY LOGIC DAMPING CONTROLLER (FLDC) AND ADAPTIVE NEURO FUZZY INFERENCE SYSTEM (ANFIS) CONTROLLER

In recent years, Fuzzy Logic Damping Controllers (FLDCs) have been appeared as an impressive implement to stabilize the power network [17,18]. FLDCs are more robust and operative than Conventional Damping Controllers (CDCs) in the power. In this paper two Fuzzy Logic Damping Controllers (FLDCs) have been applied to UPFC and TCSC controllers as shown in figures 4 and 6. In TCSC and UPFC controllers, rotor speed deviation ($\Delta\omega$) and its derivatives ($\frac{\partial \Delta\omega}{\partial t}$) have been used as the fuzzy controllers inputs and firing angle is output of TCSC and UPFC fuzzy controllers.

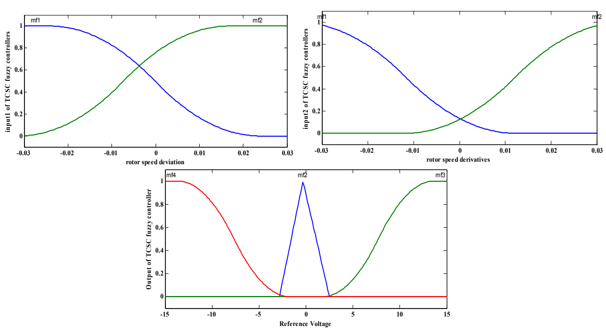


Fig. 9. Membership functions for the FLDC of TCSC and UPFC controllers

The adaptive neuro fuzzy inference system (ANFIS) controller was first presented by J. Jang in 1993 [19]. The ANFIS uses a hybrid learning algorithm to identify resulting parameters of Sugeno-type fuzzy inference systems. The hybrid learning rule, which combines the gradient descent method and the Least Square Estimator, was suggested in to train the ANFIS network for a specific problem [20]. In this paper to overpower 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.

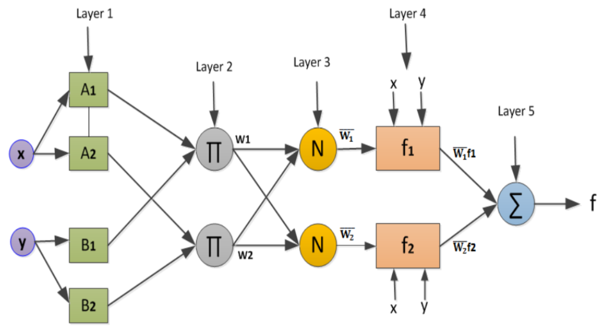


Fig.10. Corresponding ANFIS architecture

The ANFIS system include 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 rise the system knowledge (Figure 11).

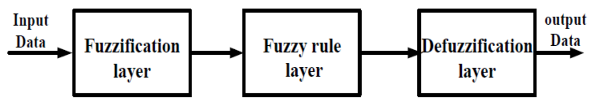


Fig. 11. ANFIS architecture

(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. [21].

9. RESULTS AND DISCUSSION

For confirming the efficacy of the offered control method to mitigate the SSR phenomenon, the IEEE Second Benchmark combined with the TCSC and UPFC is modeled in MATLAB/Simulink. In this paper 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 fluctuations will be occurred between the different parts of the turbine-generator shaft, as shown in Figure 12.

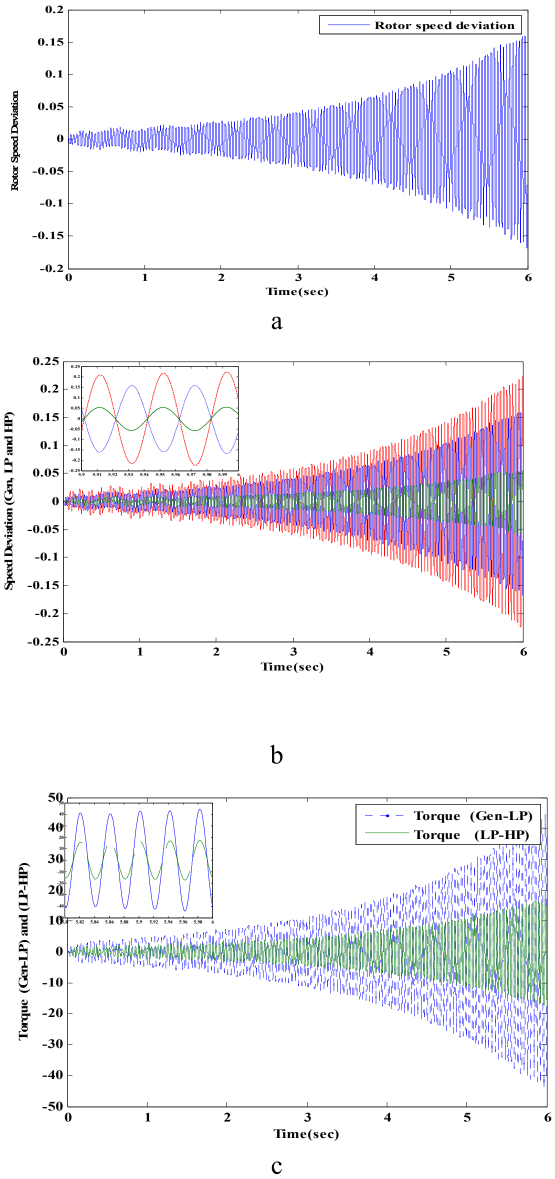


Fig.12. Simulation results for un-damped mode: (a): rotor speed deviation, (b): speed deviation between generator, Low pressure and high pressure turbine, (c): torque between generator, Low pressure and high pressure turbines.

SSR oscillations in wind turbines have been shown in figure 13.

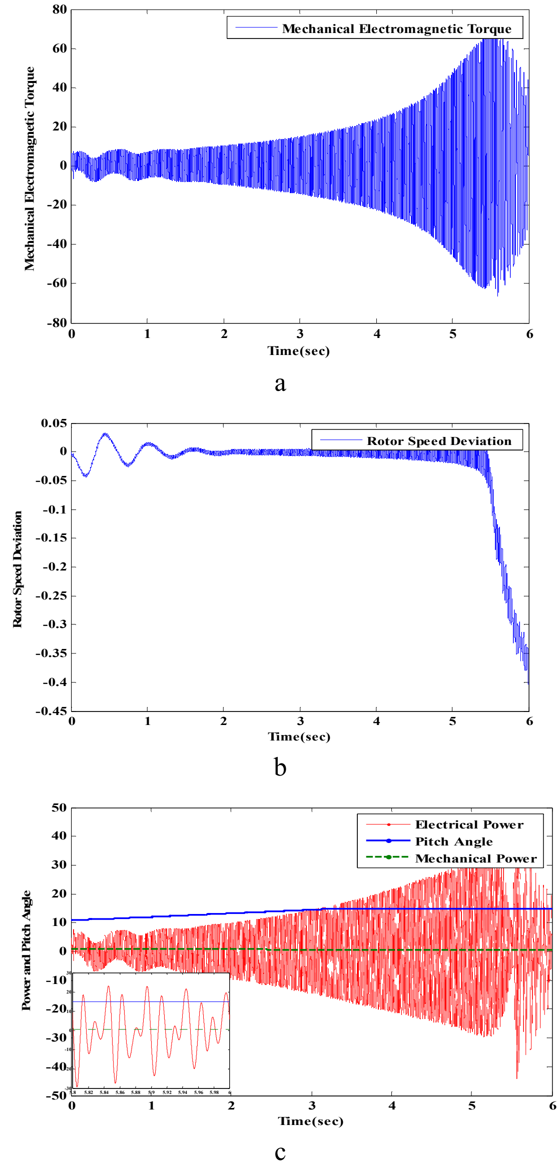
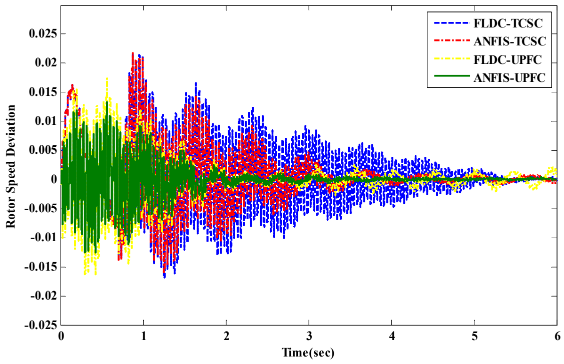


Fig.13. Simulation results for un-damped mode: (a): mechanical electromagnetic torque, (b): rotor speed deviation in wind turbine, (c): mechanical and electrical power and pitch angle.

Figure 13 shows the oscillations in wind turbines due to SSR phenomenon without FACTS devises. In this section, novel FLDC and ANFIS controllers have been added to the TCSC and UPFC for observing specification deviation of the system. Rotor speed, rotor speed deviation and torques of generator are shown in Figure 14.



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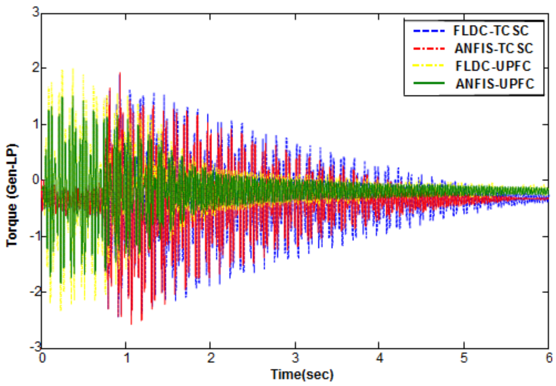

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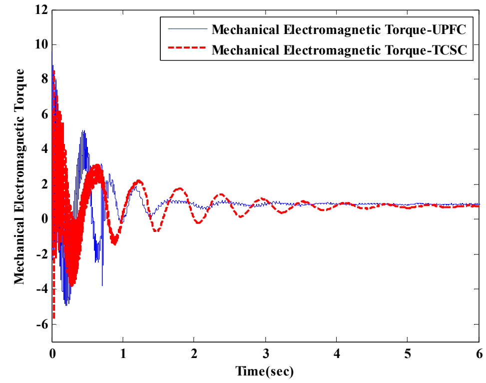
Fig. 14. Simulation results with damping SSR by TCSC and UPFC with FLDC and ANFIS controllers

Figure 14a shows damping of rotor speed deviation and Figure 14b shows mitigating of torque between generator and Low pressure turbines by TCSC and UPFC with ANFIS and FLDC controllers. Figure 14 illustrates that the UPFC with auxiliary controller can be able to mitigate SSR better than TCSC and the operation of ANFIS toward FLDC is better for mitigating SSR.

Figure 15 shows that the PI controller adjusting by ICA and PSO can be able to control pitch angle. With optimal pitch angle control by using PI-ICA in high wind speed, mechanic and electric power were closed to together. By this work wind generator produced power in near the 1pu. According to (figures 15a and 15b) UPFC can damp mechanical electromagnetic torque and rotor speed deviation in less settling time toward TCSC. Figures 15c and 15d show that pitch angle in PI-ICA is less than PI-PSO witch causes to increase the margin stability in wind turbine.



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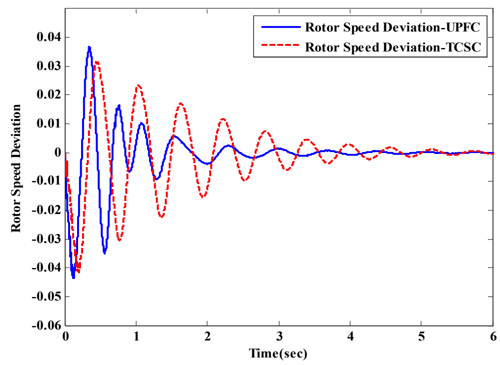

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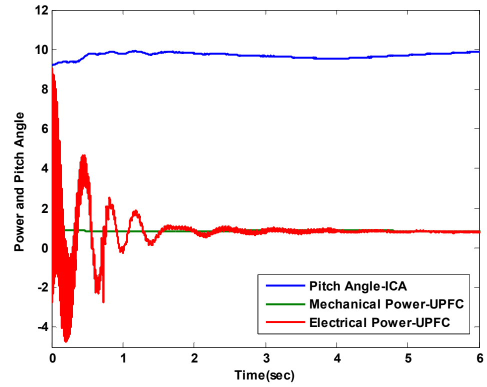

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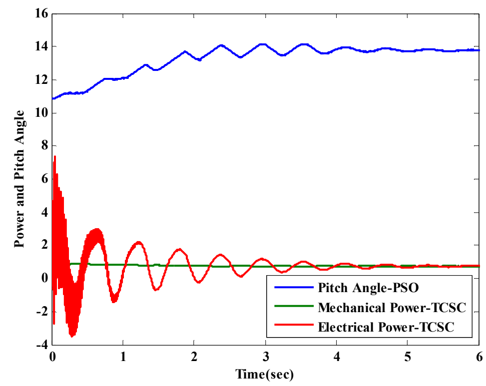

d

Fig. 15. Control the pitch angle in wind turbine by ICA and PSO

Table 4. Optimal parameters of PI controller calculated by ICA and PSO

ICA	
Kp = 6.32	Ki = 38.12
PSO	
Kp = 7.51	Ki = 40.12

10. 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 the wind power application in power systems, impact of wind generators on sub-synchronous resonance (SSR) gets important. In this paper two FACTS devises have been compared for damping the SSR by TCSC and UPFC and also two algorithms have been analyzed for controlling pitch angle in wind turbine by imperialist competitive algorithm (ICA) and Particle Swarm Optimization (PSO). The IEEE second benchmark system equipped by steam and wind turbine as a hybrid energy production system was studied. The UPFC is unable to mitigate SSR inherently. This paper showed that the UPFC with an auxiliary controller can mitigate SSR. Applying this method makes not to require to install the other FACTS devises for mitigating SSR and hence the costs will be reduced.

It is also found that the UPFC can mitigate SSR and has low settling time with respect of TCSC and the performance of ANFIS controller for mitigating SSR is better than FLDC.

In order to control pitch angle of wind turbine the Imperialist Competitive Algorithm (ICA) and PSO algorithm have been used. ICA is a new evolutionary optimization technique which is derivative by imperialistic rivalry. The adjusted pitch angle by ICA is less than PSO; it causes to increase the margin stability of wind turbine. By this method produced power of wind generator is near the 1pu. As result the performance of parallel-series FACTS devises like UPFC are better than series FACTS devises like TCSC for mitigating SSR.

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