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SSSC based SSR mitigation in hybrid system using optimized fuzzy logic controller

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For renewable power generation system wind power has become the most widely used technique. Therefore large wind turbine generators are used widely into electric power grids. The power generated by wind farm should be transmitted that can maintain large power flow. To enhance power transfer capability and the system stability, series capacitive compensation is a very cost-effective technique, since through long transmission lines large amount of power must be transmitted. This leads to occurring of sub-synchronous resonance. The phenomenon SSR can be damped by FACTS devices. In this paper, we proposed a modified IEEE Second Benchmark Model for damping SSR in hybrid system comprises of Steam and wind power generation system by using Static Synchronous Series Compensator (SSSC). Adaptive Neuro Fuzzy Inference System (ANFIS) and (FLDC) Fuzzy Logic Damping Controller are used to have a pitch angle optimal control in high speed of wind.

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Keywords: Sub-Synchronous Resonance (SSR), Static Synchronous Series Compensator (SSSC), DFIG, Wind and Steam turbine, ANFIS

1. Introduction

With the growing demand in electricity, wind power is the most promising renewable power generation system [1-3]. Therefore for electric power grids, the large wind turbine generators were used with the fast growing installed capacity of wind farms. And through transmission system the power produced by wind farm should be transmitted which can sustain large power flow. A very economical solution to transmit large power through transmission lines is a series capacitive compensation which can also enhance power transfer capability and system stability. This guides to the phenomenon of subsynchronous resonance (SSR) taking place [4]-[6]. The interaction between the turbine generator mechanical oscillation mode and the series compensated networks electrical oscillation mode may generate oscillating torques [7][8]. It is understood that SSR can be damped using FACTS devices and to control power system it is an versatile approach [9][10]. FACTS devices were used to control power flow, voltage regulation, oscillation damping and reactive power compensation [11][12]. In mitigating SSR several studies have been investigated. In their balance mode of operation static synchronous series compensator (SSSC), the static synchronous compensator (STATCOM), and thyristor-controlled series capacitor (TCSC) has been used for damping SSR [13]-[15]. The static synchronous series compensator is a solid state voltage source inverter based FACTS devices, with line current it can generate a controllable AC voltage [16].SSSC controls transmission line power flow which emulates as an capacitive or inductive reactance. To design damping controller different techniques have been proposed for SSSC. To develop auxiliary damping control for SSSC phase compensation method were used [17]. The control process is based on linearized machine model which is the major problem associated with these methods. The proportional-integral (PI) controller is the other frequently used approach. Even though PI controller is simple and ease to design, their performance depreciate when large disturbance or wide variation occurs in the system condition [18][19]. To overcome these drawbacks a fuzzy logic controller was introduced which is proven to be an impressive tool. Regarding system operations fuzzy logic control integrates quantitative and qualitative information by some hierarchy. In order to turn up the decisions, the FLC systems deduce the understanding of human. Even in the presence of external disturbances this fuzzy logic control provides the higher performance [20]-[22]. In this paper we focused on static synchronous series compensator for damping SSR. As a hybrid energy production system steam and wind turbine have been used. This paper proves that the ANFIS controller based SSSC able to mitigate SSR.

2. Sub-synchronous resonance

Thephenomenon of sub synchronous resonance occurs when there is a physical interaction between transmission system and generator at AC frequencies fall below the nominal frequency. Due to this SSR can cause increased fatigue of generator turbine shaft systems, either through transient effects or poorly damped oscillation. When correlation exits in the transmission system between the electrical resonant frequencies, the interaction occurs which is caused by series capacitors and mechanical torsional oscillation in the plant. Sub synchronous resonance also occurs in the presence of induction generator effect, this result in the series resonant circuit from the total resistance created by generator, since at sub-synchronous frequencies the transmission system is negative which leads to the negative damping. It is well understood about the induction generator effect, and in modem machines it is likely to pose SSR due to the shaft system manufacturer's ability to avoid torsional oscillation at low mechanical frequencies with most distinct effect. Due to SSR Shaft gets damaged, it occur when turbine generator provides positive mechanical damping at given torsional frequency is inadequate to rise above the series resonant electrical network which provides the negative contribution to damping at equivalent sub-synchronous frequency. Mainly to conventional synchronous machines the SSR phenomenon were applied with long turbine shaft systems. Normally in series compensation SSR occurs in transmission lines. The sub-synchronous natural frequency (f_e) of power system which is compensated by series capacitor is given by

$$f_e = f_o\sqrt{X_c/X_l}$$

The phenomenon SSR arise when f_r=f_0-f_e *becomes* close to torisional frequencies which excite the torsional oscillations. Transient torques and self excitation are the two significant parts of SSR. Under this, self excitation is further divided into Torsional Interaction (TI) and Induction Generator Effect (IGT). In series compensated power system IGE does not exist, but torsional interaction and transient SSR exist.

3. Doubly FED induction generator

Doubly fed induction generators has became the most common type of variable-speed wind generation system. To feed the wound rotor of the machine, a series voltage source converter design is employed.

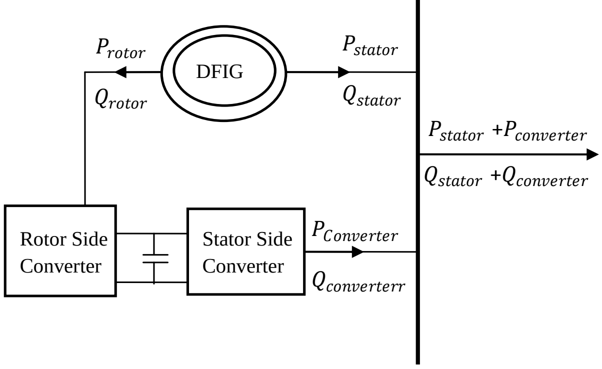


Fig. 1.Doubly fed induction generator.

The mechanical speed of the machine is controlled by operating the rotor circuit at a variable AC frequency. In this design the machine net power out is a combination of output power of the machine's stator and from the rotor, through the converter into the system as shown in Fig. 1. The design of fixed induction generator speed, which normally utilizes a conventional induction machine, and thus not has issues like injecting harmonic into the system, since it has simple design and do not incorporate power electronics. The higher efficiency is the major advantage of the variable speed designs, which is achieved by capturing the wind energy by varying the machine speed with wind speed and also it has better power quality.In addition, DFIG can absorb reactive power and thus control their evident power factor. In contrast, the reactive power is consumed by the standard induction generator design, and both at the wind turbine location and substation connecting wind farm, it employs the shunt compensation.

4. Modeling of SSSC

Among the series FACTS devices SSSC is a most important one. It is a solid state VSI (Voltage Source Inverter) of variable magnitude, which injects a sinusoidal voltage in series with the transmission line. The voltage injected is in quadrature with line current and a small part of injected voltage provides loss in the inverter since it is in phase with line current. This injected voltage in series with transmission lines which emulates a capacitive or an inductive reactance, and as inserted by injected voltage source this emulated reactance influences the transmission line electric power flow. A SSSC operated as a series compensator without an external electric energy source, whose output voltage is controllable independent and in quadrature with line current, for decreasing or increasing the overall drop of reactive voltage across the line and thus controlling the active power transmission.

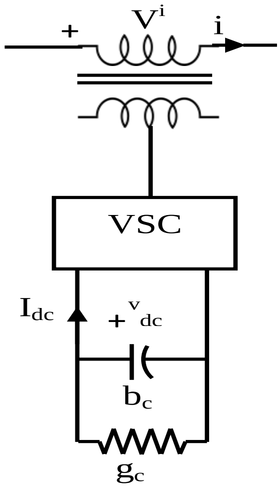


Fig. 2.SSSC Model.

To enhance the power system dynamic behaviour, SSSC may include energy absorbing devices or transiently rated energy by additional short-term real power compensation, which decrease or increase the overall voltage drop across the line. The SSSC model is shown in Fig. 2. The SSSC gets realized by the grouping of three level configurations and 12 pulses. The harmonic distortion reduced greatly on the AC side by using the topology three level converters.

Then by modelling the converter operation the comprehensive 3 phase model of static synchronous series compensator is developed by switching functions [24]. By using Kron's transformation SSSC can be modelled by transforming current to D-Q variables and the three phase voltages, when switching functions are estimated by their fundamental frequency components by neglecting harmonics. As shown in Fig. 3. X_{st} and R_{st} are the reactance and resistance of the interfacing transformer of VSC. By modulating the conduction period, converter output voltage V^i is achieved while maintaining the dc voltage constant. The output voltage of converter can be represented in frame D-Q of reference as:

$$V^i = \sqrt{V_D^{i2} + V_Q^{i2}}$$

$$V_D^i = k_m V_{dc} \sin(\emptyset + \gamma)$$

$$V_Q^i = k_m V_{dc} \cos(\emptyset + \gamma)$$

Where, $k_m = kcos\beta_{se}; k = \frac{2\sqrt{6}}{\pi} fora\ 12\ pulseconverter$

It is convenient to define from control point of view that reactive *($V_{R(Se)}$)* voltage and active voltage *($V_{P(se)}$)*are injected bySSSC in terms of V_Q^iandV_D^iin D-Q frame as follows,

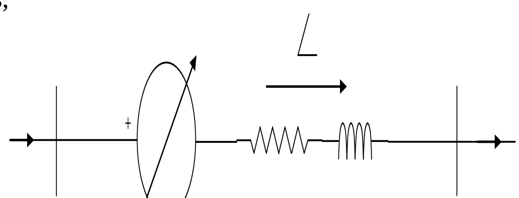


Fig. 3.Equivalent Circuit of SSSC.

$$V_{R(se)} = V_D^i cos\emptyset - V_Q^i sin\emptyset$$

$$V_{P(se)} = V_D^i sin\emptyset - V_Q^i cos\emptyset$$

Here positive $V_{P(S)}$ means that to meet loss it draws real power and positive *($V_{R(S)}$)* means the inductive voltage which is injected by SSSC.

5. SSSC and TCSC comparisons

Unlike thyristor-controlled series capacitors schemes, the static synchronous series compensator offers compensation features and inherent functional characteristics, steaming from voltage source inverter which is a unique attributes for series line compensation. The features and characteristics of SSSC are summarized as follows.

1. Over an inductive range and identical capacitor autonomously of the line current of the magnitude, SSSC is capable of generating controllable voltage compensation internally.
2. For the purpose of keeping the high ratio effective XLff, idependently of series compensation, it can offer compensation for line reactance and line resistance with the potential to interface with external dc power supply.
3. With a stored energy, highly efficient damping is possible in power oscillation by modulating the series reactive compensation to decrease and increase the transmitting power, simultaneously inserting alternating virtual negative and positive real impedance with widespread machine swings.
4. It has a significant impedance of voltage source type versus characteristic of frequency, and with reactive line impedance it rejects the classical series resonance.

6. Proposedsystem configuration

The system configuration has been shown in Fig. 4. Combined with the SSSC, the Fig. 4.shows the modified. IEEE Second Benchmark Model with inclusion of DFIG which is primarily used for SSR as in [23]. The system comprises of wind and steam turbines which is compensated by SSSC. The wind farm based on DFIG comprises of wind turbine and steam turbine generators are connected to an infinite bus. The steam turbine system comprises of turbines high pressure (HP), low pressure (LP), the generator (G) and rotating exciter (EX).

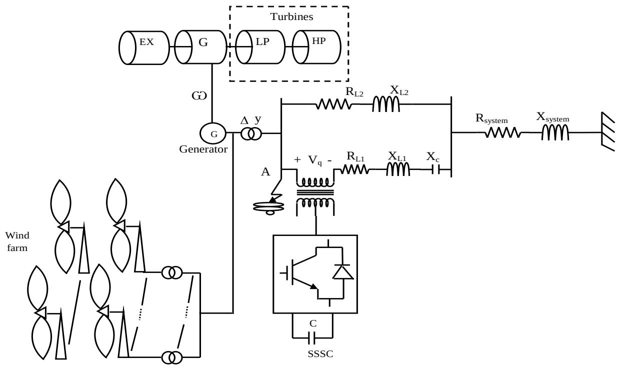


Fig. 4.Proposed system configuration.

7. Design controllerfor SSR mitigation

Among FACTS devices SSSC is a familiar series connected controller based on a voltage source converter (VSC).A typical SSSC model with DC link capacitor, a three phase VSC, and an interfacing transformer is shown in Fig. 5at the output of VSC a filtering stage is also considered foralleviating the harmonic pollution in the injected voltage. SSSC can be considered as the advanced type of controlled series compensation.

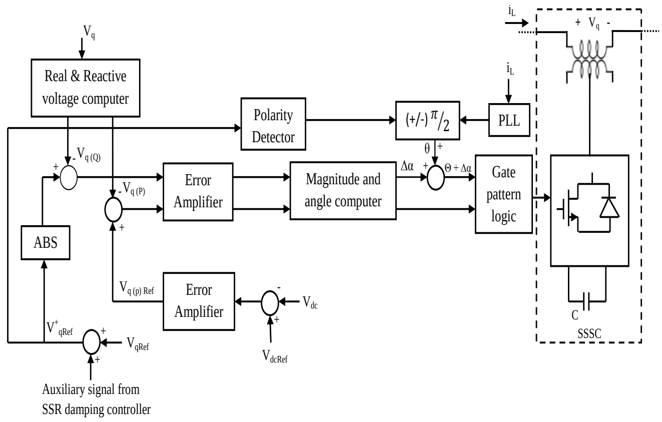


Fig. 5. Design controller for SSR mitigation.

The SSSC main control system is shown in Fig. 5. $V_{qref}$is therequiredamount of series reactive voltage and for the series compensation its find out the reactive power exchange. To be more accurate, in series with the transmission line the SSSC provides variable *Xq*, which is used change the line reactance, by injecting series voltage namely *Vq*. The power oscillation damping and power flow control is achieved by in this way of compensation. The SSSC variable reactance is expressed as follows

$$X_q = \frac{V_q}{i_L}$$

The SSSC primary task is to control the line power flow, the essential damping is not provided by SSSC control system. To achieve other auxiliary duties such as power oscillation damping or SSRD, the SSSC signals should be modulated.

It is essential to apply coordinating fine-tuning with the secondary SSRD controller of the SSSC, in order to afford an efficient damping of SSR. To show the ability of SSSC controller in mitigating SSR, two cases namely FLDC and CDC are examined. And to optimize the parameters of CDC, utilizing the PSO algorithm to recover the damping of the CDC and the result is compared with those of FLDC. To verify the higher performance of FLDC, the time domain simulations are implemented.

8. Design of FLDC and ANFIS controller

Nowadays to stabilize the power network, Fuzzy logic damping controllers (FLDCs) have been emerged as an efficient tool. The main advantage of Fuzzy logic damping controllers over conventional damping controllers in power system are as follows

1. In FLDC exact mathematical model is not required
2. With inaccurate inputs they can act
3. Nonlinearity control
4. They are more effective and robust than the CDCs.

For mitigating SSR, in this paper ANFIS controller is applied to SSSC and FLDC is applied to the wind turbine pitch angle controller. As the fuzzy controller input, Power deviation (Δp) and its derivatives ($\partial \Delta P / \partial t$) have been used. And for output of fuzzy controller pitch angle (Θ_p) have been used.

The fuzzy controller's rules are shown below. The sets of fuzzy have been determined as P:Positive, Z:Zero and N:Negative respectively.

1. If (ΔP is P) and ($\partial \Delta P / \partial t$ is P) then (Θ_p is N)
2. If (ΔP is P) and ($\partial \Delta P / \partial t$ is N) then (Θ_p is Z)
3. If (ΔP is N) and ($\partial \Delta P / \partial t$ is P) then (Θ_p is Z)
4. If (ΔP is N) and ($\partial \Delta P / \partial t$ is N) then (Θ_p is P)

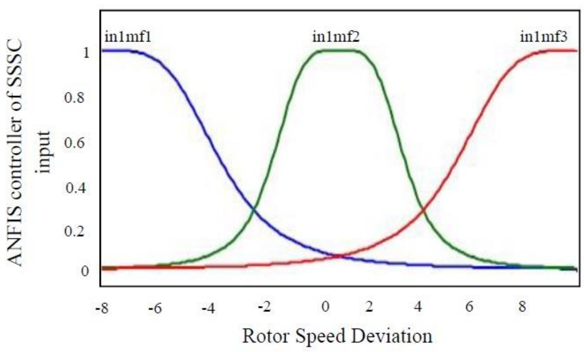


Fig. 6. The ANFIS membership function for SSSC controller.

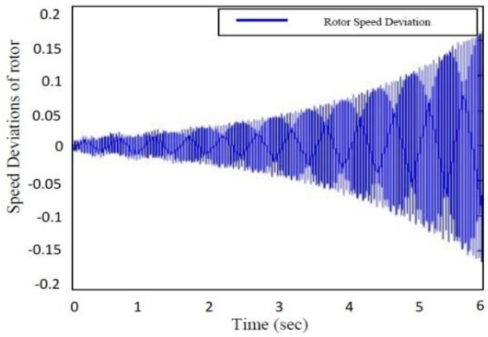
To identify the subsequent parameters of sugeno type fuzzy inference system, a hybrid algorithm ANFIS were used. For SSSC controller, as an ANFIS input and output, the rotor speed deviation (Δω) and the reference voltage is considered. The ANFIS of SSSC controller membership function is shown in Fig. 6.

1. If (Δω is P) then (V_{ref} is 1-1.29075)
2. If (Δω is Z) then (V_{ref} is 1-0.03385)
3. If (Δω is N) then (V_{ref} is 1-(-1.17375))

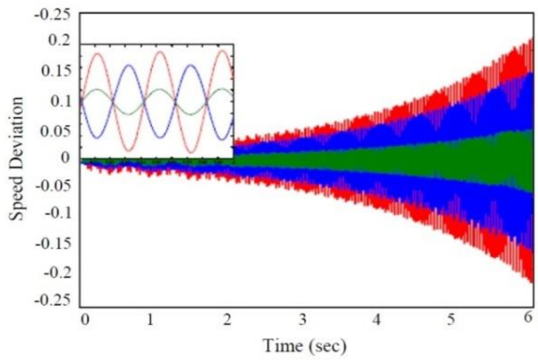
The ANFIS system contains the main mechanism of a fuzzy system apart from the each stage calculation are carried out by a hidden neurons and to increase the knowledge of the system the neural network's learning capacity is provided.

9. Result

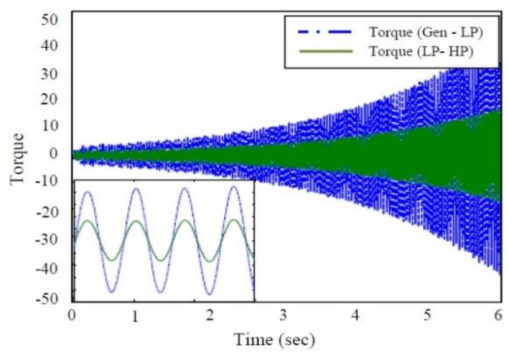
To prove the efficiency of the proposed control method, the modified IEEE Second Benchmark is combined with SSSC to mitigate the SSR phenomenon. Two cases of simulation were considered, firstly the simulation results were produced for power system without damping controllers and secondly result were produced using ANFIS controller. When fault is cleared, between the turbine generator shaft the large oscillation will be taken place. The SSSC without ANFIS controller the SSR cannot be mitigated as shown in Fig. 7. The wind turbine SSR oscillation without SSSC is shown in Fig. 8. In this paper, along with SSSC, a novel ANFIS controller is added to observe the specification variation of the system. The rotor speed deviation, rotor speed and generator torque is shown in Fig. 9. The ANFIS controller in SSSC can able to mitigate SSR is shown in Fig. 10. The electrical and mechanical powers were closed together by using FLDC in high speed wind, with optimal pitch angle control.



(a) Speed deviations of rotor

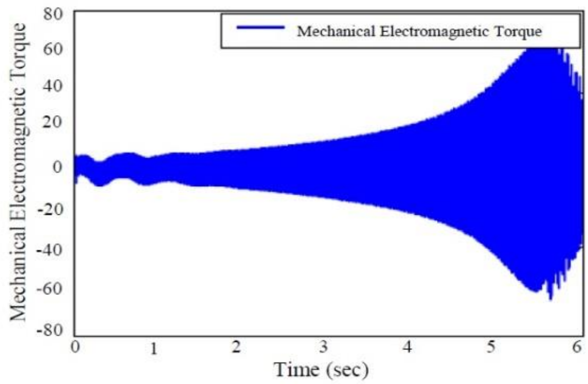


(b) Deviation of speed between generator, LP and HP turbine

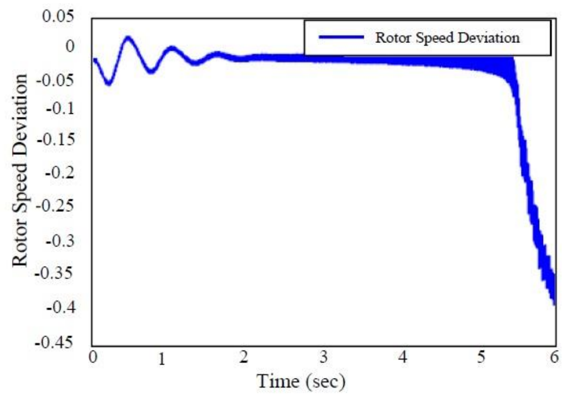


(c) Torque in generator, LP and HP turbines

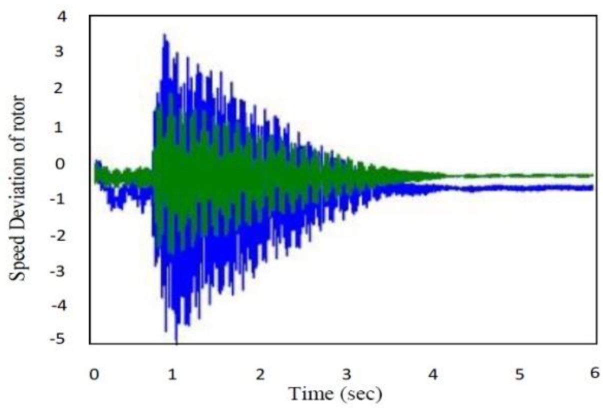
Fig. 7. Un-damped mode simulation results.



(a) Mechanical electromagnetic torque

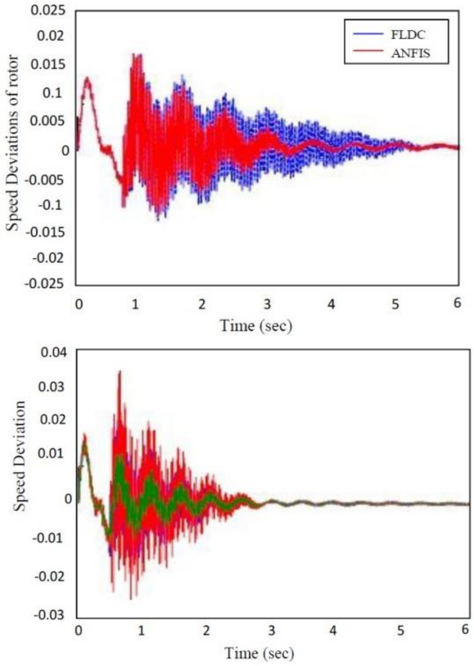


(b) Wind turbine rotor speed deviation

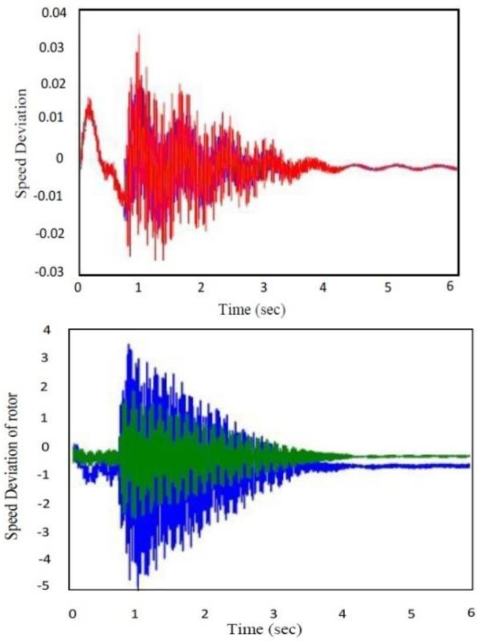


(c) Electrical power, mechanical power and pitch angle

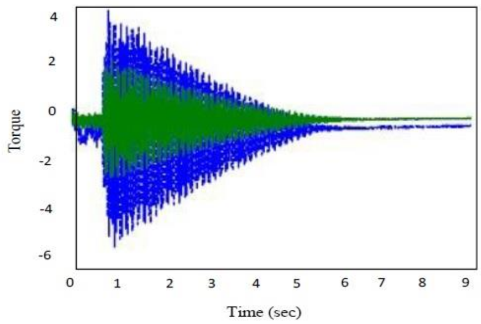
Fig. 8. Un-damped mode simulation results.



(a) Speed deviation of rotor

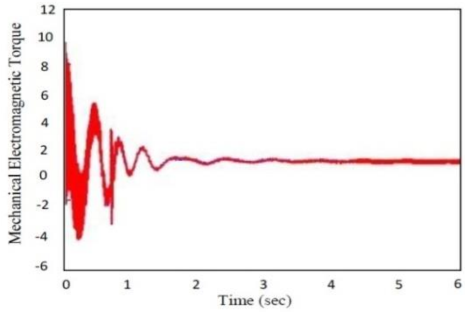


(b)Deviation of speed between generator, LP and HP turbine

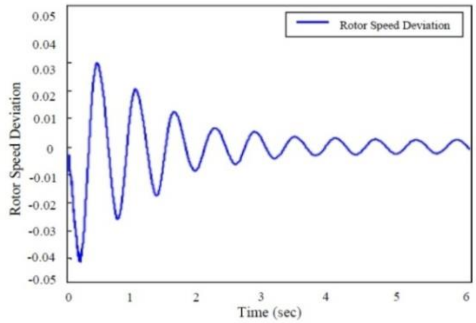


(c) Torque in generator, LP and HP turbines

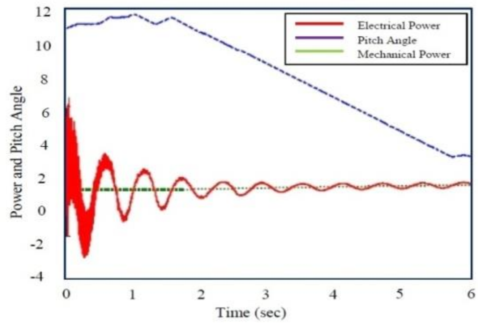
Fig. 9. Simulation results with damping SSR using SSSC with ANFIS controller.



(a) Mechanical electromagnetic torque



(b) Wind turbine rotor speed deviation



(c) Electrical power, mechanical power and pitch angle

Fig. 10.Simulation result for damping SSR using SSSC with FLDC for pitch angle controlling and ANFIS controller.

10. Conclusion

In power system the use of wind power going on increasing, the impact on subsynchronous resonance became more important. In series compensated power system the subsynchronous resonance is a major problem. In this paper we proposed a method for damping the SSR using SSSC. The modified IEEE Second benchmark model as a hybrid energy production system equipped with wind and steam turbine was analysed. The SSSC is employed originally to increase the capability of power transfer transmission. The SSSC without auxiliary damping controller cannot mitigate the SSR phenomenon. The proposed FLDC and ANFIS controller is applied to SSSC and applied for pitch angle control of wind turbine. The SSR is migrated by SSSC and the electric and mechanic wind generator powers were closed together. The results show that the proposed method provides stable performance and is able to mitigate SSR over a wide range of operating conditions and proven to be very effective.

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