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FUZZY LOGIC CONTROLLED STATCOM WITH A SERIES COMPENSATED TRANSMISSION LINE ANALYSIS

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Keywords: **Doubly fed induction generator; Sub-synchronous resonance; Static compensator; Static synchronous series compensator; Fuzzy logic controller.**

Series compensation of transmission line networks is increasingly being considered for bulk power transfers from large wind farms. Series-compensated long transmission lines with wind turbine generators experience sub-synchronous resonance (SSR). To prevent SSR, it is necessary to reduce its occurrence as much as possible. To solve this issue, this paper proposes an effective FACTS (flexible ac transmission system) based voltage control device, namely a static compensator (STATCOM) and static synchronous series compensator (SSSC) to moderate the SSR. In this work, the fuzzy logic control based on STATCOM and SSSC is developed to enhance the stability margin of a wind turbine. Detailed eigenvalue analysis was carried out to demonstrate the successful mitigation of SSR by two controllers in a series of compensated wind farms. To find the dominant control scheme, the eigenvalues of the proposed controllers are compared with PSCAD/EMTDC simulations. Finally, a comparison study is carried out between the two proposed SSR controllers. The results have been validated with the IEEE 1st SSR benchmark system. The results demonstrate that fuzzy logic controller (FLC) based SSSC performs better than STATCOM.

1. INTRODUCTION

Recently, energy generation with renewable energy sources has played a vital role in power systems worldwide. Wind energy-based power generation occupies a significant part in energy production next to the power generation by solar [1, 2]. The wind energy generation system [WEGS] with a doubly fed induction generator (DFIG) has been widely utilized for power production. Moreover, it operates at a constant frequency at a variable speed [3]. However, as wind power is usually located far away from the load distribution centers near the consumers, power transportation over long distances becomes a significant problem [4]. Hence, using a series compensation capacitor, a large amount of wind power is transmitted to the grid with higher stability [5–8]. However, integrating this series compensation in the transmission line will cause oscillations at a particular frequency. The frequency at which these oscillations occur will usually be lesser than that of the system frequency [9]. This is termed SSR, which causes mechanical damage to the shaft system. Suppose this frequency overlaps with any mode frequency of the Turbine-generator (TG) system's s there will be a significant rise in oscillations and may result in fault/disturbance over the transmission line [10]. The current produced during SSR also affects the protection of equipment in the system.

Hence, to diminish the consequences of SSR in a system, some other topologies, like power system stabilizers (PSS) have been adopted to mitigate SSR [11]. Apart from these, numerous FACTS devices such as thyristor switched series capacitors (TSSC), and UPFC suppresses SSR. By examining various FACTS controllers in earlier research works, the SSSC and STATCOM have proved superior over others preciously in reactive power compensation [12]. Hence, by introducing SSSC and STATCOM on the wind farm's generator terminal, the SSR could be mitigated along with reactive power compensation. Hence, shunt and series (SSR) controllers have been chosen for SSR alleviation. However, while finding a solution to the SSR problem, it is essential to esteem how fast the designed system will detect the SSR and activate proper protection against the system to avoid damage to the turbine [13]. The fuzzy-PID and fuzzy-PI current controllers and the distribution static synchronous compensator (D-STATCOM) were presented to improve power quality issues [14]. A rotor of the self-excited asynchronous generator (SEAG) was proposed, which is driven by an auxiliary prime mover in wind power conversion applications, and a static converter (SC) connected to an isolated DC load is used to supply active power to the load [15]. Gavrilas M. et al (2021) proposed a static var compensator (SVC) to improve transient voltage stability in power systems by maintaining a certain level of voltage oscillations at the system's buses during the transient regime following a network disturbance [16].

Thus, from the literature survey, it is observed that most of the researchers have undergone studies using PI controllers. However, the controllers, such as PI, PID, *etc*., need a rigorous mathematical model of the system to determine Kp and Ki values hence, they are more sensitive to variations in the system's parameters. So, they need to meet the necessities of the robust performance of the system. At that time, intelligent controllers brought a new revolution in the industrial drive system. These types of controllers are gaining more interest in controller design. Keeping this in view, the following research assistance has been performed in this proposed research work:

- Mitigation of SSR is carried out by injecting voltage in the transmission line using SSSC/STATCOM.
- The SSSC utilized in this work comprises multi-pulse (48-pulse) VSI and phase-shifting transformers, which are zigzag in nature.
- Fuzzy controller is introduced to alleviate the consequences of SSR and to fast up the response time of the SSSC/STATCOM.
- The efficacy of the proposed SSR controllers is examined using IEEE's first benchmark model. Hence, to achieve

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this, a Mathematical model of the test system is formulated, and their respective eigenvalues are determined.

- Transient analysis of SSR is carried out using the PSCAD/EMTDC tool, and the results are compared with an eigenvalue analysis.

2. **PROPOSED SYSTEM MODEL**

In this test system, the SSSC is connected to the Transmission line (TL) to alleviate SSR. In this topology, to alleviate SSR, the voltage produced by the capacitor bank (which is fixed) is nullified by the voltage of the series converter. Thus, the current /voltage at the sub-synchronous frequency can be obtained as follows. The terminal grid voltage occurred during rotor oscillations at the rated speed given by

$$V(t) = V_{s,f}{}^{(dq)}(t) + V_{s,subs}{}^{(dq)}(t) + V_{s,sups}{}^{(dq)}(t) \quad (1)$$

where *f* is the frequency (fundamental), the subscript *Subs* represents sub-synchronous frequency, and the subscript *Sups* represents super synchronous frequency. During super synchronous frequency, damping will be positive. So, it is not considered in this research work for analysis. Hence, the eq. (1) can be rewritten as

$$V_s{}^{dq}(t) = V_{s,f}{}^{(dq)}(t) + V_{s,subs}{}^{(dq_m)}(t)e^{-\mathrm{j}\omega_m t} \quad (2)$$

Thus, the sub-synchronous component can be formulated as denoted in

$$V_{s,f}{}^{(dq)}(t) = H_f(P)\left[V_s{}^{dq}(t) - V_{s,subs}{}^{(dq_m)}(t)e^{-\mathrm{j}(\omega_m t)}\right] \quad (3)$$

$$i_f{}^{dq}(t) = H_f(P)\left[i^{dq}(t) - i_{subs}{}^{(dq_m)}(t)e^{-\mathrm{j}(\omega_m t)}\right] \quad (4)$$

$$V_{s,subs}{}^{dq_m}(t) = H_{subs}(P)\left[V_s{}^{dq}(t)e^{\mathrm{j}(\omega_m t)} - V_{s,f}{}^{dq}(t)e^{\mathrm{j}(\omega_m t)}\right] \quad (5)$$

$$i_{sub}s^{dq_m}(t) = H_{subs}(P)\left[i^{dq}(t)e^{\mathrm{j}(\omega_m t)} - i_f{}^{dq}(t)e^{\mathrm{j}(\omega_\mathrm{m} t)}\right] \quad (6)$$

Then, according to the d-q frame from eqs. (5) and (6) can be written as

$$V_{s,subs}{}^{dq}(t) = H_{subs}(P + \mathrm{j}\omega_\mathrm{m})\left[V_s{}^{dq}(t) - V_{s,f}{}^{dq}(t)\right] \quad (7)$$

$$i_{s,subs}{}^{dq}(t) = H_{subs}(P + \mathrm{j}\omega_m)\left[i_s{}^{dq}(t) - i_{s,f}{}^{dq}(t)\right]. \quad (8)$$

From this analysis, the current represented in eq. (8) should be zero to mitigate SSR. Thus, it can be obtained by injecting sub-synchronous voltage using SSSC/STATCOM in this proposed work. The voltage injection at the bus connection with the FACTS controller depends on the sub-synchronous current flow from the transmission line to the wind generator. Figure 1 displays the schematic diagram of the proposed sub-synchronous controller.

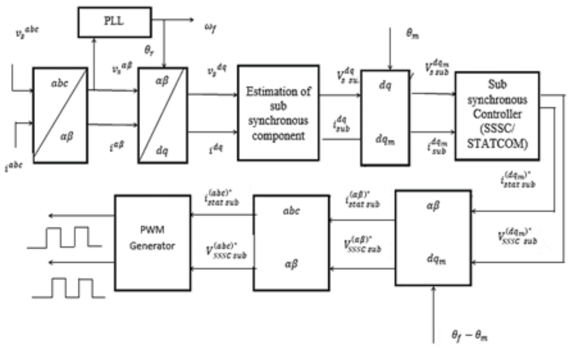

Fig. 1 – Schematic diagram of this proposed sub-synchronous controller.

The figure clearly states that the line's three-phase voltage and current are converted into 2 phase (d-q) coordinates. As a result, sub-synchronous components are transformed into the d-q frame by integrating it with oscillating frequency. The extracted sub-synchronous component is then fed into the SSR controller. The output obtained from the controller is again converted into 3-phase components and given to the pulse generator for activating 48 pulses VSC. Meanwhile, FLC maintains the SSR controller's dc side voltage constant.

2.1. DESIGN OF FUZZY LOGIC CONTROLLER

The FLC formulated in this work employed with

- 7 fuzzy sets (PB, PM, NB, PS, ZE, NM, NS,) for both input &output variables.
- Mamdani-type fuzzy inference system for implication and triangular membership function.
- Centroid approach for defuzzification.

Figure 2 indicates the MF of the input and output variables.

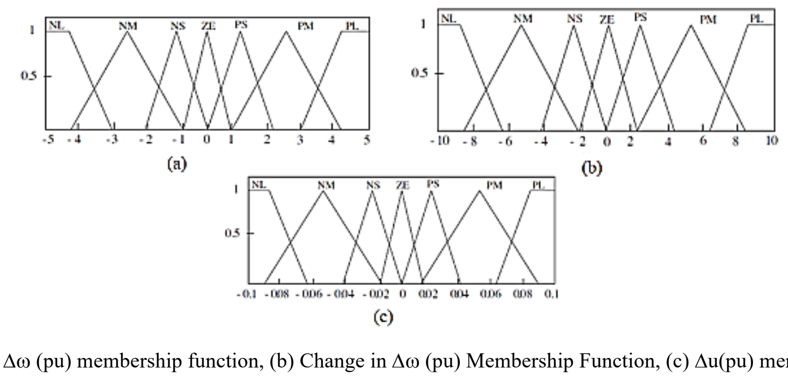

Fig. 2 – FLC (a) Δω (pu) membership function, (b) Change in Δω (pu) Membership Function, (c) Δu(pu) membership function.

The rule base of the proposed FLC controller is stated in Table 1. The e and Δe are given regarding fuzzy sets. The conditions for seven sets of rules are used to nullify the error to increase the dynamic response of the controller. In previous studies, the PI-controlled FACTS devices were operated to stop power oscillations and frequency deviation. Due to the slow tuning process, the time of fault clearance and magnitude of transient voltage and current could not be effectively controlled. This problem has been eliminated using a fuzzy controller to minimize the system error in the control loop linked with the triggering circuit of thyristors. The rule base of the proposed FLC controller is stated in Table 1. The error and change in error are given concerning fuzzy sets.

Table 1

Rule base of fuzzy controller

Δe/e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	ZE
NM	NB	NB	NM	NS	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PS	PM	PB	PB
PB	ZE	PS	PM	PM	PB	PB	PB

3. RESULTS AND DISCUSSIONS

Thus, to examine the effectiveness and performance of the proposed scheme, the IEEE FBM with STATCOM and SSSC has been examined and discussed here. The series compensation level is raised from 10 % to 100 % to evaluate the simulation results. The test system is carried out using PSCAD/EMTDC software.

3.1. ANALYSIS OF DAMPING TORQUE

The effect of electrical damping torque is computed for both SSSC/STATCOM. Figure 3 displays the damping ratio variation with SSSC and STATCOM. The graph shows that for both STATCOM/ SSSC implemented systems, the damping ratio decreases when the series compensation level is increased from 10 to 100 %, thereby improving the system's stability. Similarly, for SSSC, the damping ratio varies from 0.05 to 0.019, enhancing the system's stability. Hence, it is concluded that the system's stability increases automatically whenever the series compensation level increases.

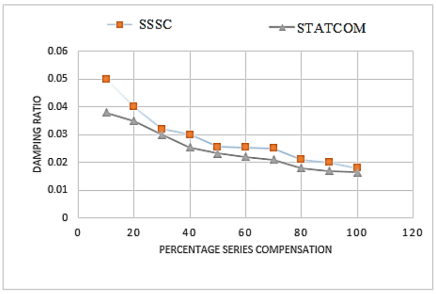

Fig. 3 – Damping ratio Vs level of series compensation.

3.2. VALIDATION OF EIGENVALUE ANALYSIS

The size of the proposed wind farm with 500 MW and 60 MVA is considered in this analysis.

Table 2

Rule base of fuzzy controller system eigenvalues for 500 MW power penetration with STATCOM

Modes	90 % Series Compensation		85 % Series Compensation		80 % Series Compensation	
	Absence of STATCOM	In the presence of STATCOM	Absence of STATCOM	In the presence of STATCOM	Absence of STATCOM	In the presence of STATCOM
Electrical	1.823±85.354j	-0.189± 74.45j	0.989 ± 87.69j	-1.087 ± 76.43j	0.147 ± 117.91j	-1.189 ± 87.92j
Rotor	-5.754±43.334j	-3.591 ± 38.43j	-4.833 ± 41.991j	-3.739 ± 38.58j	-3.831 ± 8.412j	-3.779 ± 39.71j
Turbine	-0.3575±3.342j	-0.371 ± 3.533j	-0.353 ± 3.3275j	-0.479 ± 2.741j	-0.371 ± 3.520j	-0.523 ± 2.182j
Control	--	-2.424 ±29.441j	--	-2.79 ±29.79j	--	-2.88 ±29.89j
parameters of	--	-6.861±5.6761j	--	-7.19 ±5.96j	--	-7.79 ±5.10j
STATCOM	--	-0.2353 ±3.471j	--	-0.261 ±3.62j	--	-0.290 ±3.61j
Modes	70% Series Compensation		60% Series Compensation		50% Series Compensation	
	Absence of STATCOM	In the presence of STATCOM	Absence of STATCOM	In the presence of STATCOM	Absence of STATCOM	In the presence of STATCOM
Electrical	0.092 ± 119.91j	-2.211 ± 100.81j	0.0539 ±129.79j	-3.419 ±116.78j	0.0379 ± 134.8j	-4.341±130.8j
Rotor	-4.731 ± 8.511j	-4.779 ± 39.64j	-4.889 ± 9.499j	-4.989 ± 45.59j	-4.987 ± 9.912j	-4.989 ± 51.5j
Turbine	-0.389 ± 3.632j	-0.416 ± 2.281j	-0.488 ± 4.619j	-0.509 ± 4.469j	-0.563 ± 4.978j	-0.631 ± 4.66j
Control	--	-3.89 ±30.89j	--	-4.10 ±37.89j	--	-5.11 ±39.21j
parameters of	--	-7.89 ±5.579j	--	-8.69 ±5.88j	--	-8.89 ±6.21j
STATCOM	--	-0.379 ±3.569j	--	-0.490 ±3.89j	--	-0.521 ±4.12j

Table 3

System eigenvalues for 500 MW power penetration with SSSC

Modes	90% Series Compensation		85% Series Compensation		80% Series Compensation	
	Absence of SSSC	Presence of SSSC	Absence of SSSC	Presence of SSSC	Absence of SSSC	Presence of SSSC
Electrical	1.823±85.354j	-1.196 ± 65.45j	0.989 ± 87.69j	-2.179 ± 56.4j	0.147 ± 117.9j	-2.989 ± 79.51j
Rotor	-5.754±43.334j	-3.591 ± 38.43j	-4.833 ±41.91j	-3.739 ± 38.5j	-3.831 ± 8.41j	-3.779 ± 39.71j
Turbine	-.3575±3.3442j	-0.371 ± 3.533j	-0.353 ±3.327j	-0.479 ± 2.74j	-0.371 ± 3.52ij-	-0.523 ± 2.182j
Control	--	-2.424 ±29.441j	--	-2.79 ±29.79j	-	-2.88 ±29.89j
parameters	--	-6.861±5.6761j	--	-7.19 ±5.96j	--	-7.79 ±5.10j
of SSSC	--	-0.2353 ±3.471j	--	-0.261 ±3.62j	--	-0.290 ±3.61j
Modes	70% Series Compensation		60% Series Compensation		50% Series Compensation	
	Absence of SSSC	presence of SSSC	Absence of SSSC	presence of SSSC	Absence of SSSC	presence of SSSC
Electrical	0.092 ± 119.91j	-3.351 ± 92.91j	0.0539 ±129.79j	-4.339 ± 100.6j	0.0379 ± 134.8j	-5.859 ± 122.45j
Rotor	-4.731 ± 8.511j	-4.779 ± 39.64j	-4.889 ± 9.499j	-4.989 ± 45.59j	-4.987 ± 9.912j	-4.989 ± 51.59j
Turbine	-0.389 ± 3.632j	-0.416 ± 2.281j	-0.488 ± 4.619j	-0.509 ± 4.469j	-0.563 ± 4.978j	-0.631 ± 4.662j
Control	--	-3.89 ±30.89j	--	-4.10 ±37.89j	--	-5.11 ±39.21j
parameters	--	-7.89 ±5.579j	--	-8.69 ±5.88j	--	-8.89 ±6.21j
of SSSC	--	-0.379 ±3.569j	--	-0.490 ±3.89j	--	-0.521 ±4.12j

Tables 2 and 3 depict the proposed system's eigenvalues, whose compensation values vary from 50 % to 90 %, including FLC-based STATCOM and SSSC. Table 2 depicts the eigenvalue analysis of the test system with the presence and absence of STATCOM. In this discussion, oscillatory modes (electrical, rotor, and turbine) are considered for analyzing the effect of SSR. Among those, the effect of SSR over electrical mode is given more importance because of the high sensitivity nature of this mode. From Table 2, it is observed that when there is an increase in compensation level, the stability of the electrical mode decreases and becomes unstable in the absence of STATCOM. Insufficient transmission capabilities, inadequate generators, and poor maintenance practices contribute to instability, voltage collapses, and blackouts in wind power plants.

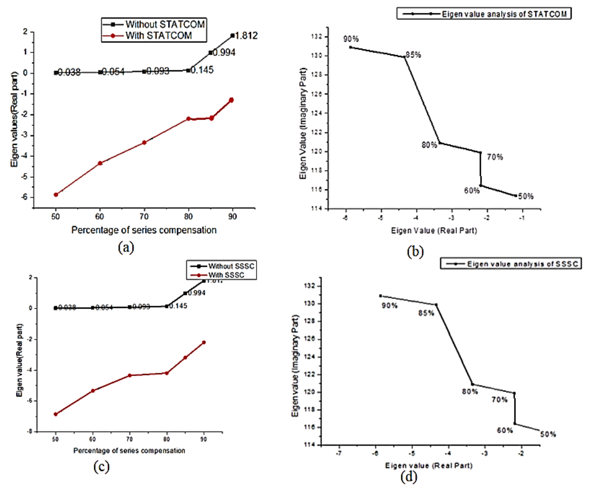

Fig. 4 – (a) Eigenvalue over series compensation level (STATCOM), (b) Eigenvalue analysis (STATCOM), (c) Eigenvalue over Series Compensation Level (SSSC), (d) Eigenvalue analysis (SSSC).

Hence, STATCOM with an FLC controller is incorporated into the test system to increase stability. While considering the test system with STATCOM, it is observed that the stability of the electrical mode is enhanced. Thus, the inclusion of FLC-based STATCOM improves the electrical mode stability. Figure 4 displays the real part value of the eigenvalues without and with STATCOM. From Fig. 4, it is observed that when the level of compensation increases, the stability of the electrical mode decreases and becomes unstable in the case of the absence of STATCOM. Consequently, the system's stability increases after inserting STATCOM with increased compensation. The system's eigenvalues with SSSC and FLC controller are depicted in Table 3.

The enhancement of stability of electrical mode with FLC-based SSSC is represented in Figure under different compensation levels. As seen in Table 3, while considering the test system with SSSC, it is observed that the stability of the electrical mode is enhanced. Thus, the inclusion of FLC-based SSSC also improves the electrical mode stability. From the figure, it is proven that FLC with SSSC further improves the stability of the electrical mode than STATCOM.

For example, at 50 % of the compensation value, the eigenvalue of electrical mode is about -5.859 ± 122.45 j for SSSC. It is about -4.341 ± 130.87 j for STATCOM, which denotes that a more negative real part in SSSC ensures the system's stability over STATCOM. Hence, it is concluded that FLC-based SSSC performs better than FLC-based STATCOM. The SSR controllers (FLC-based STATCOM and SSSC) do not affect the other two modes. So, they are not taken into consideration.

3.3. TRANSIENT SIMULATIONS

Simulating the test system in the time domain is performed in this section using PSCAD/EMTDC. With 3Φ faults, the simulations are performed in transient conditions. When the fault occurs, the T_e oscillates and settles down gradually. Finally, results can be obtained using correlations between small signal analysis and time domain results. Figure 5 depicts the self-excitation of a wind farm connected to 50 % and 70 % series compensation with an SSR controller.

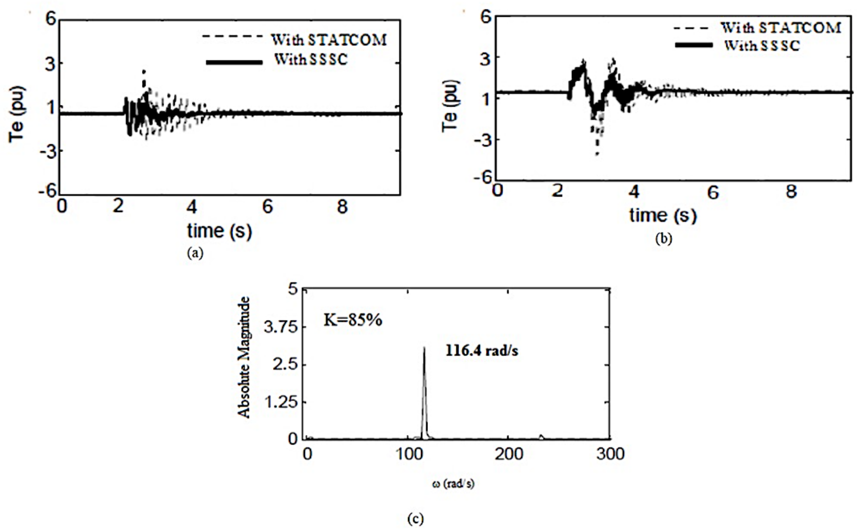

Fig. 5 – (a) Electromagnetic torque at 50 % series compensation, (b) Electromagnetic torque (Te) at 70 % series compensation, (c) FFT of Te with 85 % compensation.

From the above figures, it is notable that for 70 % compensation, the oscillations will be higher than the 50 % compensation level. Hence, it is concluded that if the level of compensation of the TL line is varied, the system oscillation frequency will vary accordingly. From the figure, it is confirmed that both STATCOM and SSSC controllers stabilized the oscillation of electromagnetic torque (Te). However, by analyzing the peak torque deviations, the deviations based on SSSC are mitigated compared to STATCOM. Therefore, the performance of SSSC is superior to STATCOM and reduces the peak overshoot. Hence, it is concluded that SSSC will be more appropriate for wind generators than for all compensation levels.

In addition, it can be seen from the figures that the SSR model can be suggestively enhanced, and the system can be quickly recovered to stable operation by using the proposed FLC-based SSSC than STATCOM. From the eigenvalue analysis with 85 % compensation, more oscillation is observed in the absence of FACTS devices. The FFT analysis of the T_e is shown in the figure. The figure shows that the appraised frequency is about 116.4 rad/s, the same as that of the calculated damped frequency of the electrical model (about 116.43 rad/s) revealed in Tables 2 and 3. From this, the eigenvalue investigation in the steady state is validated.

Similarly, the FFT of T_e for 500 MW of wind farm shows a frequency (oscillatory) of about **119.9 rad/s**, which is perfectly matched with the estimated eigenvalues (**119.84 rad/s)** for both SSSC and STATCOM though it is not revealed here. This association between the FFT analysis and the calculated eigenvalue confirms the effectiveness of SSSC over STATCOM due to the variations in shaft torque and electromagnetic torque, as depicted in Fig. 6.

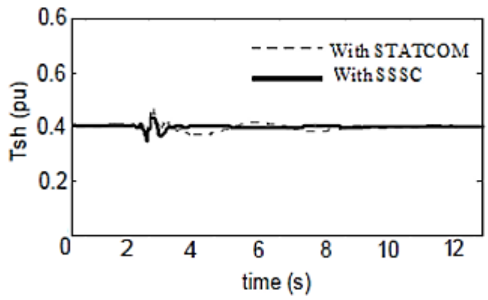

Fig. 6 – Shaft torque (500 MW wind farm).

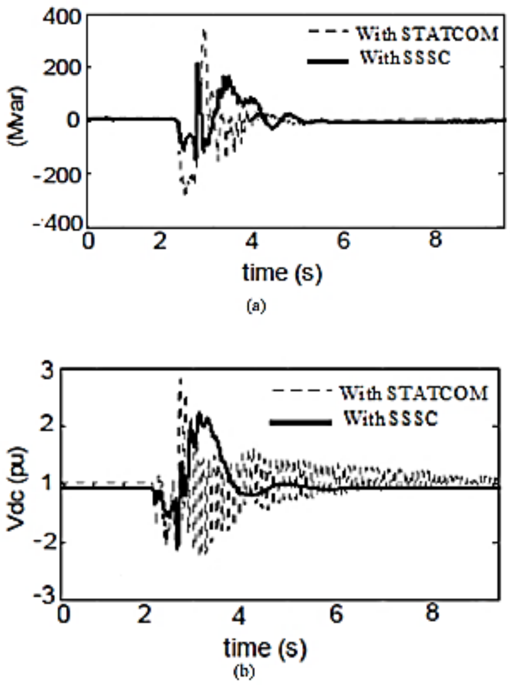

Fig. 7 – (a) Reactive power, (b) Dc link voltage.

From Fig. 6, it is effectively proven that SSSC significantly reduced the peak overshoot in the shaft torque. Similarly, the effect of STATCOM and SSSC over other parameters, such as reactive power, dc link voltage, *etc*., is projected in Fig. 7.

Regarding reactive power compensation, SSSC exhibits a faster response than STATCOM. The STATCOM supplies more reactive power (VAR) compared to SSSC. The stability margin of electrical mode state variables is very high for SSSC. Both the STATCOM and SSSC offer fast response times but are more expensive.

On the other hand, the absence of STATCOM and SSSC can result in a cheaper substitute with a relatively long response time. As capacitors are used, reactive power is significantly reduced during faults. Thus, STATCOM and SSSC installation is a robust option.

During dc-link voltage control, the oscillations will increase in the STATCOM-controlled system. In the case of SSSC controlled system, it reaches the constant value quickly, and hence, the SSR can be mitigated earlier compared to STATCOM. Similarly, it is also seen that the proposed FLC controller with SSSC successfully maintains a constant dc voltage without any deviation. This, in turn, depicts the effectiveness of the proposed FLC controller. The reactive power generation through the voltage source converter of STATCOM depends on the potential difference between the converter bus and transmission line bus bar. The line reactance has been minimized by shunt compensation using STATCOM/SSSC controller in the transmission line.

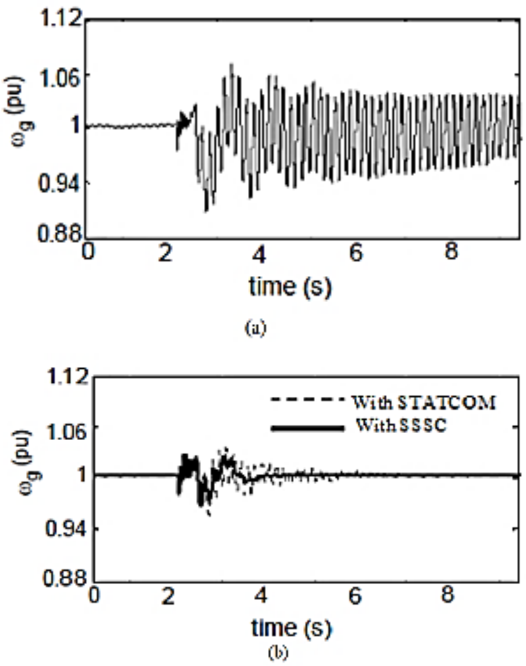

Fig. 8 – (a) Generator rotor speed without STATCOM/SSSC, (b) Generator speed STATCOM/SSSC.

Figure 8 represents the rotor speed of the generator with and without the STATCOM and SSSC controller. The above figures prove that the SSSC controls generator speed more effectively than the FLC-based STATCOM. The variation in rotor speed is reduced from 1.06 to 1.03 pu and 1.6 to 1.01 pu for STATCOM and SSSC at a time of 10 s. Hence, from all the above analysis, it is concluded that the suggested FLC-based SSSC reveals enhanced performance in alleviating SSR than STATCOM.

4. CONCLUSION

In this research paper, an FLC-based voltage controller is proposed to mitigate the effect of SSR on a wind farm. Two types of FACTS-based voltage controllers, named STATCOM and SSSC, are preferred in this article. The SSR mitigation is analyzed by investigating the eigenvalues of the system. In addition, the FFT, torque, dc-link voltage, and generator speed are also investigated for both STATCOM and SSSC. The results obtained from these analyses are verified using PSCAD / EMTDC studies. The following conclusions have arrived from analyzing FLC-based STATCOM and SSSC connected to wind farms.

- Both STATCOM and SSSC can effectively alleviate the effect of SSR in all conditions.
- To increase the response time of the SSR controller, FLC is tailored as a voltage controller for both SSR controllers.
- However, the results prove that SSSC will be more effective than STATCOM while alleviating SSR.

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