Damping of Sub-synchronous Resonance Phenomenon in Wind Power Plants Connected to Series Compensated Lines using Bridge Type Fault Current Limiter

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Abstract– This study investigates the mitigation of Sub-Synchronous Resonance (SSR) and short-circuit current limitation in wind power plants connected to series-compensated transmission lines using a novel resistive bridge-type fault current limiter (RBFCL). Series compensation enhances power transfer but introduces SSR, a harmful oscillatory phenomenon that can damage generator shafts, while also reducing line impedance and elevating fault current levels. The paper proposes, for the first time, the application of an RBFCL to simultaneously address both challenges. The research employs an aggregated model of a 200 MW wind farm based on squirrel-cage induction generators. The SSR mechanism is analyzed from the perspectives of Induction Generator Effect (IGE) and torsional interactions. The RBFCL's operation is detailed, featuring a bridge configuration with a DC reactor and a parallel limiting resistor controlled by semiconductor switches to insert impedance during faults and damp oscillations. Simulations conducted in PSCAD/EMTDC compare three scenarios: no controller, RBFCL, and conventional Flexible AC Transmission System (FACTS) devices like Static Synchronous Compensator (STATCOM) and Thyristor-Controlled Series Capacitor (TCSC). The results demonstrate that the RBFCL outperforms the other methods. It effectively dampens electromagnetic torque oscillations and significantly reduces the amplitude and duration of active power, reactive power, and fault current fluctuations following a three-phase-to-ground fault. Quantitative comparisons reveal that the RBFCL achieves the smallest oscillation amplitudes and fastest damping times. For instance, the maximum active power fluctuation with RBFCL is 0.9 p.u., compared to 1.26 p.u. with TCSC and 3.96 p.u. with STATCOM. Furthermore, the damping time for electromagnetic torque oscillations is 0.725 seconds with RBFCL, versus 1.225 and 1.350 seconds for TCSC and STATCOM, respectively. The study also explores different RBFCL structures (resistive-inductive vs. resistive-capacitive), concluding that the resistive-inductive configuration offers superior performance in damping oscillations across all measured parameters. In conclusion, the RBFCL is presented as a cost-effective and efficient dual-function solution, providing robust SSR mitigation and fault current limitation, surpassing the capabilities of traditional STATCOM and TCSC controllers in enhancing the stability and safety of series-compensated wind power systems.

Keywords: Sub-synchronous resonance phenomenon, bridge type resistive fault current limiter, wind power plant, series compensated line

1. Introduction

The issue of renewable energy has been booming in the world and even in Iran for many years, and important steps have been taken to develop the use of these unlimited resources. Iran is a country with a high capacity for producing renewable energy or clean energy, and in the Clean Air Law, the Ministry of Energy is required to provide at least 30% of the annual increase in the country's required capacity from renewable energy. With the advancement of power electronic equipments and the emergence of FACTS devices, the use of these devices to increase the transmission power has been welcomed [1 and 2]. However, with the entry of these devices into the electricity industry, we have also faced challenges. For example, the use of FACTS devices in wind power plants connected to compensated lines can cause a phenomenon called sub-synchronous resonance (SSR). This phenomenon has a destructive effect on critical equipment, such as the shaft (rotor) of generators, which can even lead to their bending or breaking. On the other hand, in series

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compensated lines, due to decreasing line reactance, we encounter an increase in the short-circuit current level, so this is also another challenge that needs to be solved. Therefore, considering all the above issues, for the first time, we have designed a type of fault current limiter to solve the two basic challenges of sub-synchronous resonance and also the increase in the short-circuit current level, which is used in wind power plants connected to series compensated lines.

The use of FACTS controllers is the most popular solution to reduce SSR in WPPs connected to series capacitive compensation [3-11]. In [3,4] , SSR issues in WPPs and methods for reducing SSR using static variable compensators (SVCs) has been discussed. In [5,6], the use of gate-controlled series capacitors (GCSCs) is proposed to reduce SSR in SCC WPPs. In [7], the use of thyristor-controlled series capacitor (TCSC) is proposed as an effective solution to reduce SSR. Also, a comparison between SVC and TCSC for SSR modulation is presented. In [8], static synchronous controller (STATCOM) is proposed to modulate SSR in wind power plants connected to series compensated lines. In [9], the role of UPFC controller in order to reduce SSR in wind power plants is confirmed. The use of bypass and blocking filters is another solution to reduce SSR in wind power plants [10]. In [11], firstly, several multi-frequency oscillation events caused by large-scale wind power plant combination are evaluated, then multi-frequency oscillation problems, including torsional oscillation of wind turbines, Sub-synchronous oscillation and hypersynchronous oscillation, are studied. However, these solutions are expensive for high voltage level [12, 13]. On the other hand, connecting wind farms to series compensated transmission lines leads to an increase in the short-circuit current level, beyond the maximum breaking capacity of the circuit breakers. This can seriously threaten the safety and stability situation of the power system. To address this challenge, fault current limiters (FCLs) are introduced as a promising and cost-effective solution [14, 15]. The application of FCLs for integrating wind farms into the power system has been reviewed in many published papers [16–24]. FCL technologies used in wind farms are generally classified into superconducting type FCLs (SFCLs) [16–18] and power electronics type FCLs (SSFCLs) [20–24]. In [29] published in 2024, TCSC compensator is used for sub-synchronous oscillation damping. Due to its intrinsic characteristic, TCSC usually provides a level of damping in the sub-synchronous frequency range even without an auxiliary controller. In this reference, a small-signal phasor model of TCSC is proposed to study sub-synchronous oscillation due to induction generator effect and torsional interactions, which accurately shows its intrinsic damping capability in the sub-synchronous frequency range. Reference [30] presents methods for evaluating and analyzing sub-synchronous oscillations with wind turbines connected to photovoltaic systems in series compensated electrical networks. In this reference, sub-synchronous oscillations due to induction generator effect and torsional interactions are evaluated. Then, a comparative comparison between fixed series capacitors and thyristor controlled series reactor (TCSR) is performed, which shows the superiority of TCSR with a 30% reduction in the amplitude of active and reactive power oscillations. Finally, reference [31] uses static synchronous series compensator (SSSC) to modulate sub-synchronous oscillations. In this reference, using time domain simulations, the effect of improved SSSC is achieved by faster transient response, better oscillation damping, and improved stability margins compared to traditional methods. With this background, in this paper, the application of Resistive Bridge Fault Current Limiter (RBFCL) to overcome all the challenges introduced in wind power plants is proposed for the first time. PSCAD/EMTDC software is used to analyze the effectiveness of RBFCL on SSR mitigation.

2. Sub-synchronous resonance

Sub-synchronous resonance is evaluated from two perspectives:

A: Self-excitation (SE) type or stable sub-synchronous resonance:

- ❖ Self-excited sub-synchronous resonance consists of two parts:
- ❖ Only the so-called rotor electrodynamics (IGE) of the induction generator effect are included. When the rotating magnetic motive force (mmf) produced at sub-synchronous frequency moves slower than the rotor speed, the resistance seen at sub-synchronous frequency from the armature terminal point of view becomes negative, so the slip of the induction generator will also become negative. Now, when the magnitude of this negative resistance exceeds the sum of the armature and network resistances, a self-excitation state is created at this frequency [25,26].
- ❖ It includes the dynamics of the electrical and mechanical system, which in TI terminology is called torsional interaction. Torsional oscillations in the frequency range of 10 to 50 or 60 Hz occur when the rotor of each generator rotates elastically relative to the other rotor [25,26].

B: Transient torques, also called transient SSR:

This type of so-called sub-synchronous resonance (TA) includes electrical system dynamics and mechanical system dynamics, with the difference that its onset is associated with severe disturbances such as faults that can induce transient torque oscillations in the generator rotor [25,26].

2.1 System Study

The system under study includes a wind turbine connected to a series compensated line in Fig. 1-a and its steady-state equivalent circuit is shown in Fig. 1-b.

By connecting a series capacitor compensator to the power system, it causes a sub-synchronous current to appear at the following frequency:

$$f_n = f_0\sqrt{\frac{k\,\Sigma X}{X_C}} \tag{1}$$

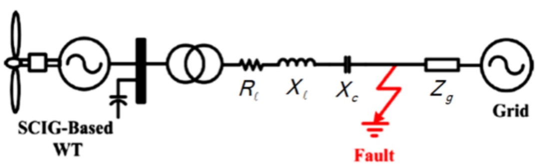

Fig. 1.a

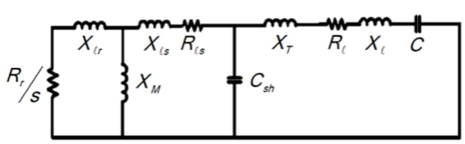

Fig. 1.b

Fig.1. The system under study (1-a) and the equivalent circuit (1-b)

Which is $X_L = X_T + X_l$ and $\sum X = X_L + X_{ls} X_{lr}$ [30].

In equation (1), f_0 is the system frequency characteristic, X_T is the transformer reactance characteristic, X_l is the line reactance characteristic, and the coefficient k represents the degree of compensation, which we define as a relation $k = \frac{X_C}{X_L}$ [27].

The sub-synchronous current passes through the rotor circuit and results in an electric rotor torque at the following frequency:

$$f_r = f_o - f_n \tag{2}$$

The sub-synchronous current produces stator voltages at sub-synchronous frequencies, which can lead to sub-synchronous stator currents to cause the SSR phenomenon.

3. Model of the studied system with the presence of the RBFCL limiter

The modified first-order IEEE benchmark model for study in this research is designed as shown in Fig2.

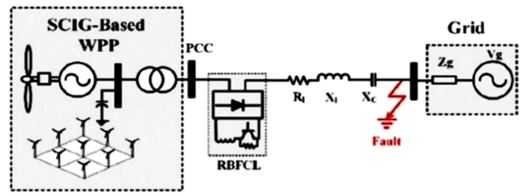

Fig. 2. Modified first-order model of the IEEE benchmark standard

In this paper, the studied wind power plant with a capacity of 200 MW (100 turbines of 2 MW) based on squirrel cage induction generator has been evaluated. The mechanical power obtained from wind energy by wind turbines is written as follows based on [28]:

$$P_m = 0.5\rho\pi R^2 C_P(\lambda,\beta)V_w^3 \tag{3}$$

In equation 3, the parameters ρ, V_w and R are the air density, wind speed, and propeller blade radius, respectively.

Also, C_P represents the power factor, which is actually a function of the ratio of the tip speed (λ) and the angle of the propeller blades (β). The mechanical and electrical parameters of the system under study are presented in Table 1.

In this study, the wind turbine excitation system is based on the two-mass rotor model. The excitation system consists of blades with hub and gearbox which are represented by the coefficient. Also, the induction generator rotor is represented by the coefficient and the generator rotor coefficient for connecting the gearbox and rotor is represented by the stiffness coefficient. This model can be represented by equations (4 to 6) as follows [28].

$$\frac{d\omega_g}{dt} = \frac{1}{2H_g}(-T_g + K_{tg}(\delta_t - \delta_g) - D_{tg}(\omega_t - \omega_g)) \tag{4}$$

$$\frac{d\delta_{tg}}{dt} = (\omega_t - \omega_g) \tag{5}$$

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}(-T_t + K_{tg}(\delta_t - \delta_g) - D_{tg}(\omega_t - \omega_g)) \tag{6}$$

3.1 SSR analysis based on IGE with the presence of RBFCL limiter

The induction generator effect (IGE) is an intrinsic electrical phenomenon. It is caused by the difference in the speed of the rotating magnetic drive (sub-synchronous frequency) and the speed of the generator rotor relative to the system frequency, as shown in Fig. 3.

Therefore, at sub-synchronous frequencies, the slip is defined by equation(7):

$$S = \frac{f_n - f_m}{f_n} \tag{7}$$

Table 1. Parameters of the studied system

characteristics	*value*

Network characteristic	voltage	132 kV
	frequency	50 Hz
Induction Generator	Wind turbine power	2 MW
	Induction generator voltage	690 V
	frequency	50 Hz
	Number of Poles	4
	Inertia Constant	2 s
	Stator Resistance	0.005 p.u
	Stator Inductance	0.11 p.u
	Rotor Resistance	0.008 p.u
	Rotor Inductance	0.125 p.u
	Mutual inductance	4 p.u
RBFCL	Dc Reactor	0.001 p.u
	Parallel AC Resistance	10 Ω

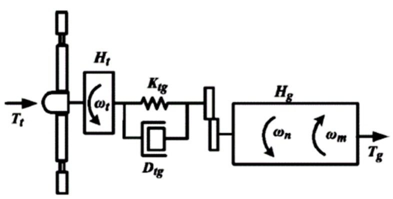

Fig. 3.Excitation system circuit

In equation (7), f_m is the electrical frequency of the rotor. Assuming equation (7) and considering that the frequency value f_n is smaller than the frequency f_m ,therefore we will have negative slip, in other words the rotor resistance $\frac{R_r}{s}$ will be negative. now if the value $\frac{R_r}{s}$ is greater than the sum of the stator resistance and the line resistance, the amplitude of the sub-synchronous currents increases, which leads to the SSR phenomenon.

3-2Function of the power limiting circuit (RBFCL):

Fig. 4 shows a simple power circuit for the RBFCL limiter, drawn as a bridge. In this circuit, a DC reactor is used, modeled by resistance r_D and inductance L_D . Also, a limiting resistor (R_D) is used in parallel with the IGBT semiconductor switch to limit the short-circuit current level.

We denote the source impedance and the load impedance by Z_S and Z_L , respectively. The source impedance can be modeled by $Z_S = r_S + jX_S$ and the load impedance by $Z_L = r_L + jX_L$.

3-3 Operation of the RBFCL limiter control system

The performance of the RBFCL limiter control circuit for normal and fault conditions can also be plotted as Fig. 5.

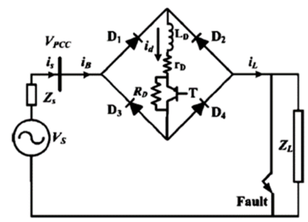

Fig. 4.RBFCL power limiter circuit

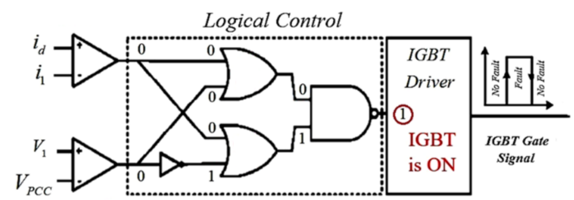

Fig5-a Limiter control system performance under normal conditions

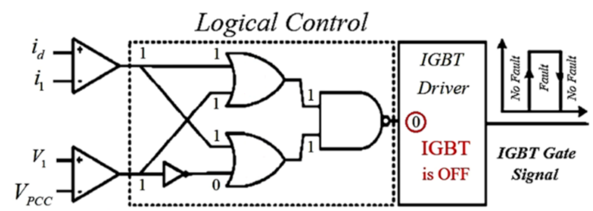

Fig5-b Limiter control system performance under fault conditions

Fig. 5.RBFCL limiter control system

4-Study of SSR phenomenon damping using RBFCL limiter

In this research, the important information of the problem for simulation in PSCAD/EMTDC environment is as follows:

Timed Fault Logic: 10 s
Duration Fault: 0.15 s
V_w*=15 m/s*
Fault type: 3 LG
P=200 MW
K=65%

Considering the problem data, network characteristics, compensation degree, and sub-synchronous resonance type, in order to show the ability of the RBFCL limiter, simulations are performed for the following scenarios:

Scenario One: This is related to the situation where no controller is used.

Scenario Two: This is related to the situation where we use the RBFCL limiter.

First, we examine the electromagnetic torque for the first and second scenarios. According to Fig. 6 and the comparison between the first and second scenarios, it is observed that after the sub-synchronous oscillation is created, in the absence of the controller, the amplitude of these oscillations increases by 10.6 per unit from the moment of fault application to a few cycles after fault removal, and decreases to 5.6 per unit in the twelfth second, and these oscillations are damped after a very long time. But in the second scenario and with the presence of the RBFCL limiter, the electromagnetic torque fluctuations are effectively modulated after several cycles.

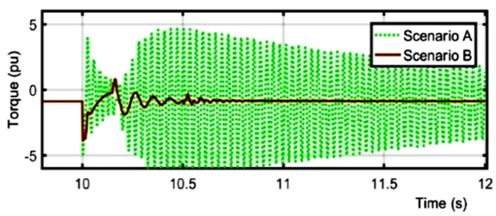

Fig. 6. Electromagnetic torque response under 3LG fault conditions

Fig. 7-a shows the response of a three-phase short-circuit fault current to ground in wind power plants connected to a series compensated line, for the first scenario (without the presence of a controller), where after the fault occurs in the tenth second, the amplitude of the fault current oscillations increases sharply. However, according to Fig. 7-b, it can be seen that the amplitude of the fault current oscillations is significantly modulated by the presence of the RBFCL limiter, and these oscillations are damped after a few cycles.

Fig5-b Limiter control system performance under fault conditions

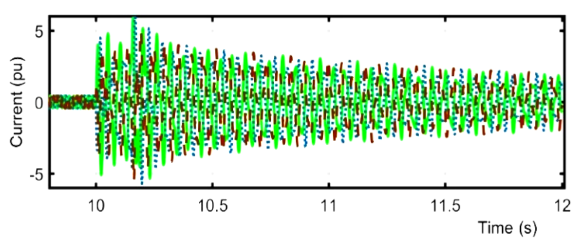

Fig.7-a Fault current response under 3LG fault conditions for scenario A

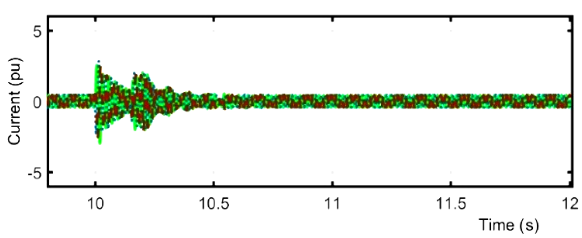

Fig.7-b Fault current response 3LG fault conditions for scenario B

Fig. 7. Wind power plant fault current response to a large disturbance

4.1.Criteria for successful research evaluation using the RBFCL method

In this section, we want to make a comparative comparison between the performance of the new method (RBFCL limiter) and other valid methods such as FACTS device controllers (STATCOM and TCSC) for damping sub-synchronous resonance oscillations. The study and simulation are performed by PSCAD/EMTDC software for the following scenarios:

Scenario A: Sub-synchronous resonance damping using STATCOM.
Scenario B: Sub-synchronous resonance damping using TCSC.
Scenario C: Sub-synchronous resonance damping using RBFCL.
The data for simulation in this comparison is as follows:

Timed Fault Logic: 10 s
Duration Fault: 0.15 s
V_w*=15 m/s*
Fault type: 3 LG
P=200 MW
K=70%

Based on the simulation results in Fig. 8, it is observed that the damping of the power fluctuation amplitude in scenario B (with the presence of TCSC) performs better than scenario A (with the presence of STATCOM), but scenario C, i.e. using the RBFCL limiter, provides the best performance compared to the other two methods.

According to the output response in Fig. 9, it is clear that the electromagnetic torque oscillations achieve by the two controllers STATCOM and TCSC are 10.9 p.u and 2.9 p.u respectively and it shows it is damped well. but in scenario C, the electromagnetic torque oscillation in the presence of RBFCL reaches to 1.81 p.u.

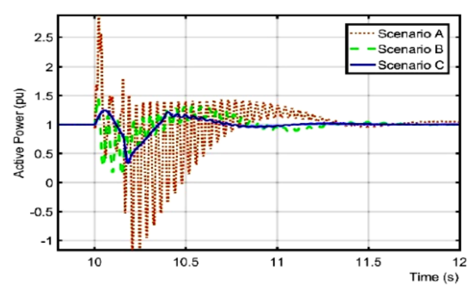

Fig. 8. Active power response of a wind power plant under large disturbance conditions

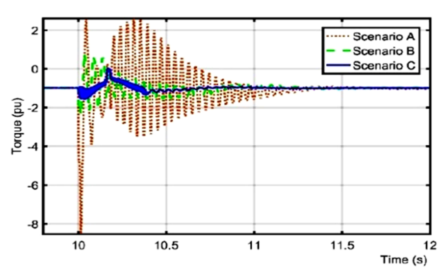

Fig. 9. Electromagnetic torque response of wind power plant in large disturbance

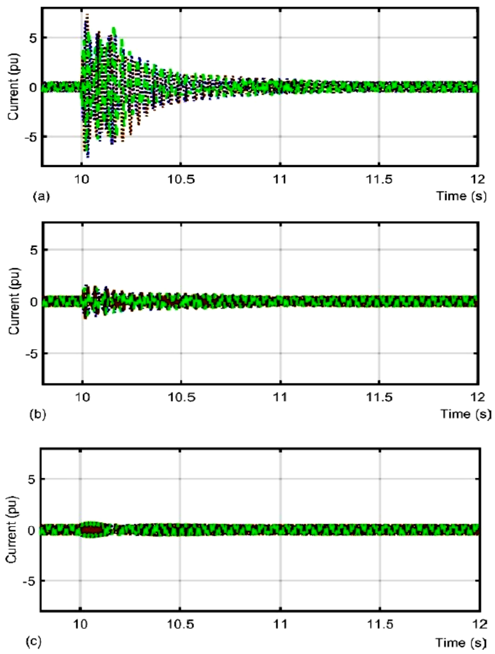

Fig. 10. Wind power plant response to a three-phase short-circuit fault to ground for three scenarios A, B and C

which is its minimum value in the shortest possible time with the presence of the RBFCL limiter and is completely damped after a few cycles.

According to Fig (10-a-b and c), by comparing the response of the three defined scenarios for damping sub-synchronous oscillations of the fault current, the superiority of the RBFCL limiter over the two STATCOM and TCSC controllers becomes more apparent.

4.2Limitations of the development of HFCLs:

- Dependence on superconducting and semiconductor materials: To build a hybrid FCL, a superconducting reactor, semiconductor switches, and high-voltage diodes are required [32].
- High control complexity: Hybrid FCLs are more complex than SSFCLs and SFCLs. This is due to the simultaneous use of power electronics and superconducting systems [32].
- Complex thermal management: The combination of superconducting and semiconductor-based systems requires a complex thermal management scheme [32].
- Harmonic distortion: Similar to SSFCLs, hybrid FCLs use switching to introduce the superconducting reactor into the power circuit. Therefore, harmonic distortion problems are also raised in hybrid FCLs [32].
- Switching losses and high-voltage diode losses: There are power losses in hybrid FCLs, similar to SSFCLs. However, the total losses in hybrid FCLs are lower than those in SSFCLs due to the use of superconductors. Hybrid FCLs also require bidirectional switches [32].
- Cost: The cost of combined FCL is higher than SSFCL, but lower than SFCL [32].

4.3.Reliability of RBFCL limiter:

But from another perspective, we perform an intra-structural comparative comparison of the RBFCL limiter with the inductive resistive type and the resistive capacitive structure to once again confirm the effectiveness of the proposed method in modulating the sub-synchronous oscillation of the active power, reactive power and electromagnetic torque parameters. By creating a large disturbance (3LG error) in the second time, respectively, the response results of the RBFCL limiter with two different structures of resistive inductive and resistive capacitive are shown in Figures (11) and (12).

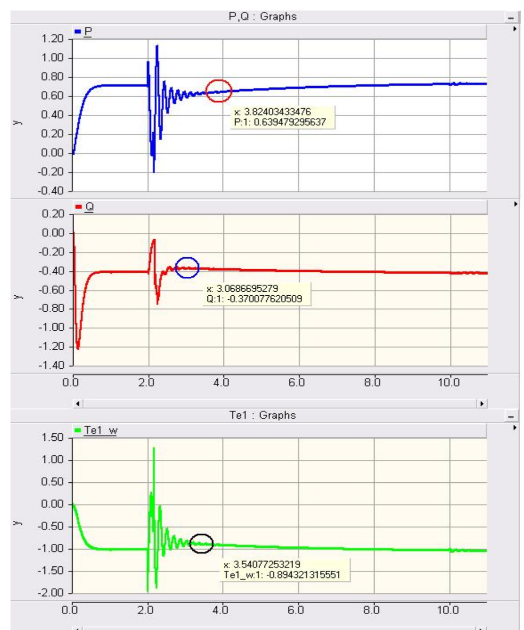

Fig. 11. Response of RBFCL limiter for active power, reactive power and electromagnetic torque parameters with resistive -inductive structure

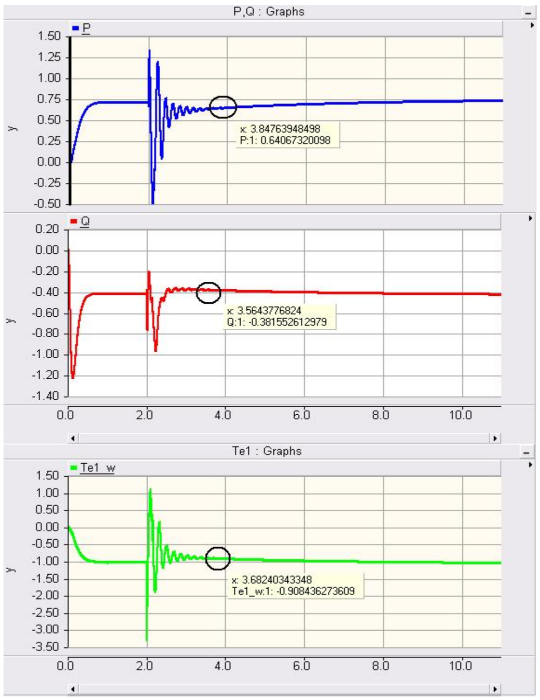

Fig. 12. Response of RBFCL limiter for active power, reactive power and electromagnetic torque parameters with resistive-capacitive structure

According to Figures (11) and (12) and comparing the simulation results, it is observed that the active power fluctuation in the resistive inductive structure with a maximum amplitude of 1.15 per unit and a value of (-0.2) per unit is at a minimum value and is damped at a time of 3.82 seconds. However, using the resistive capacitive structure, the maximum active power fluctuation amplitude is 1.37 per unit and a minimum value of (-0.5) per unit and is damped at a time of 3.84 seconds.

Also, the reactive power fluctuation in the resistive inductive structure with a maximum amplitude of (-0.06) per unit and a value of (-0.7) per unit is at a minimum value and is damped at a time of 3.06 seconds. But using the resistive capacitive structure, the maximum amplitude of the reactive power oscillation is at (-0.2) per unit and at the minimum at (-1) per unit and is modulated in 3.56 seconds.

On the other hand, the electromagnetic torque oscillation in the resistive inductive structure is at the maximum amplitude of (1.27) per unit and at the minimum at (-2) per unit and is damped in 3.54 seconds. But using the resistive capacitive structure, the maximum amplitude of the electromagnetic torque oscillation is at (1.2) per unit and at the minimum at (-3) per unit and is modulated in 3.68 seconds. Therefore, by comparing the simulation results, the superiority of the new method over the resistive capacitive type RBFCL limiter is also confirmed in addition to the FACTS device controllers.

5. Conclusion

This research investigates the role of bridge type fault current limiter on sub-synchronous oscillations modulation for active power parameters, electromagnetic torque and fault current oscillation in wind power plants connected to series compensated lines. Finally, a comparative comparison between the new method and control methods such as TCSC and STATCOM has been done for this paper. Considering what was evaluated and studied in the simulation section, by comparative comparison and based on Tables 2 and 3, it is possible to confirm the successful evaluation criterion and the superior performance of the new method (using RBFCL limiter) in sub-synchronous oscillations modulation compared to other proposed controllers.

Table 2. Comparative comparison for the three defined scenarios

	Maximum active power fluctuation range *(p.u)*	***Maximum amplitude of electromagnetic torque oscillation*** *(p.u)*	***Maximum fault current fluctuation range*** *(p.u)*
With RBFCL	0.9	1.81	1.6
With TCSC	1.26	2.9	3.32
With STATCOM	3.96	10.9	15

Table 3. Time performance comparison for the three defined scenarios

	Active power oscillation damping time *(in seconds)*	***Electromagnetic torque oscillation damping time*** *(in seconds)*	***Fault current oscillation damping time*** *(in seconds)*
With RBFCL	1.23	0.725	0.33
With TCSC	1.5	1.225	0.73
With STATCOM	2.5	1.350	1.183

Comparative comparison of the sub-synchronous resonance oscillation amplitude for the parameters of active power, electromagnetic torque and fault current amplitude based on Table 1 is quite clear that in scenario A, using the STATCOM controller, the largest oscillation amplitude is observed, and in scenario C with the presence of RBFCL, the smallest oscillation amplitude is observed. Also, based on Table 2, the largest time for adjusting the sub-synchronous oscillation amplitude of the mentioned parameters is related to scenario A (STATCOM controller) and the minimum time for adjusting the sub-synchronous oscillation amplitude is related to scenario C (with the presence of RBFCL).

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