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A Review on Subsynchronous Resonance and its Mitigation Techniques in DFIG based Wind Farms

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Abstract- The utilization of the Doubly Fed Induction Generator (DFIG) based wind energy conversion systems is increasing with the benefits of variable speed operation, partial rating power converters and reactive power support. However, the problem of SubSynchronous Resonance (SSR) may occur in an induction generator based wind farms connected to the power system consisting of series compensated transmission line. The SSR in DFIG based wind power generation is of more interest in recent years after a real-time event occurred at the Electric Reliability Council of Texas (ERCOT) grid. In this paper, we present a review on the analysis of SSR and its mitigation concerned to the DFIG based wind farms. The classification of SSR is reviewed and a brief comparison of SSR analysis methods such as frequency scanning technique, eigenvalue analysis and digital simulation method is presented. Also, this paper focuses the review on the impact of various parameters of DFIG wind energy conversion systems which significantly affect the SSR characteristics. Further, a review on the mitigation of SSR using supplementary damping controllers with FACTS devices and converter controllers in DFIG based wind farms is presented with the merits and demerits of each method.

Keywords-Doubly Fed Induction Generator (DFIG), Flexible Alternating Current Transmission System (FACTS), SubSynchronous Resonance (SSR), SubSynchronous Induction Generator Effect (SSIGE), SubSynchronous Control Interactions (SSCI), SSR Damping Controller (SSRDC).

1. Introduction

The integration of renewable energy sources into the existing power system is rapidly growing to meet the huge demand. Among the various renewable sources, the wind power plants find a notable higher penetration into the power system with the benefits of variable speed generators [1-3]. The ever-increasing demand needs large installation of wind turbines globally. If all the countries install 2% of their area with wind plants, it would meet their power demand [4]. The variable speed wind generation system with partial rating power converter (i.e., DFIG based wind plant) is more popular for its economic feature as low per unit generation cost compared to other types [5-11].

The generated electricity from the wind energy is to be integrated into the power system either laying new transmission system or by increasing the power transfer capability of existing transmission system. Instead of going for a new transmission system, the series compensation is an economic and affordable solution to increase the power transfer capability. However, an adverse phenomenon called SubSynchronous Resonance (SSR) can occur when the series compensated transmission line is connected to turbine generator [12-14].

The event of SSR has been recorded consequently in the years 1970 and 1971 at Mohave Generating Station, Southern Nevada for the first time [15]. Also, the potential risk of SSR may occur due to the large-scale integration of the induction generator based wind farms into the power system comprising a series compensated line [16-18]. The first incident of SSR in DFIG based wind power generation is identified at the Zorillo Gulf Wind Farm (Texas) in October, 2009 [19-21]. A survey on SSR in wind farms connected to series compensated transmission system is presented in [22] and [23], which reports that the severity of SSR is more in DFIG based wind farms in comparison to other types of wind farms. The power system needs a suitable controller to mitigate SSR in order to operate the system in a stable and secure manner. There are various SSR mitigation methods existing in the literature.

In this paper, we present a review on the analysis of SSR in DFIG based wind farms. And, we focus the review on SSR mitigation using SubSynchronous Resonance Damping Controller (SSRDC) with various FACTS devices and converter controllers of DFIG. Also, the suitable location of SSRDC in DFIG converter controllers explored in the literature is presented.

The major contributions of this review paper are:

i. A brief report on SSR and its classification is presented to understand the problem of SSR.
ii. Methods of SSR analysis are overviewed.
iii. The factors (system parameters and operating conditions) affecting the SSR are discussed.
iv. Presents the review on SSR mitigation techniques employed with FACTS devices and DFIG converter controllers.
v. Future scope for utilizing DFIG converter controllers to mitigate SSR is addressed.

The structure of this paper as follows: The SSR phenomenon and its classifications are presented in Section 2. The various analyzing techniques and investigations of SSR in DFIG based wind farms are described in Section 3. In Section 4 and 5 the mitigation of SSR using FACTS devices and DFIG converter controllers are presented respectively. Section 6 presents the conclusions and future perspectives.

2. Primer to Subsynchronous Resonance

Subsynchronous Resonance is the phenomenon where the energy exchange occurs between the mechanical system of turbine generator and network at one or more frequencies below the synchronous frequency. This section presents the basic concept and major classifications of SSR. Subsequently, the classification of SSR concern to DFIG based wind farms is also presented.

2.1. Subsynchronous Resonance

The phenomenon of SSR can be understood through a turbine-generator connected to series compensated transmission line as shown in "Fig. 1", whose electrical resonant frequency is given by "equation (1),"

$$f_{er} = f_o \sqrt{X_c / X_T} \tag{1}$$

Where, $f_{er} < f_o$, f_o is the nominal frequency, X_c is series capacitor reactance, and X_T is the sum of the reactance of generator, transformer and transmission line.

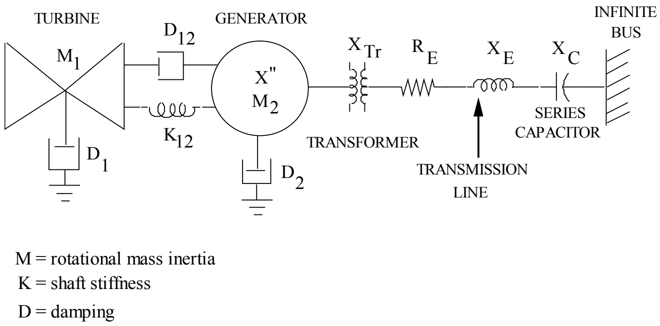

Figure 1. Turbine-Generator with radially connected series compensated transmission line

At resonant frequency f_{er}, the positive sequence components of armature current produces magnetic field which tends to cause rotor currents at a frequency $f_r = f_o – f_{er}$. The induced rotor currents produce armature voltage components at subsynchronous frequency, which may sustain subsynchronous armature currents. However, the subsynchronous frequency currents cause negative damping torque. The effect of negative damping due to subsynchronous currents can eventually lead to the generator shaft failure [24, 25].

At the outset, the SSR is classified into two types as: 1) Self-Excitation or Steady-state SSR, 2) Torque Amplification (TA) or Transient SSR. The steady state SSR includes Induction Generator Effect (IGE) and Torsional Interaction (TI).

The torsional interaction and torque amplification are due to the electromagnetic torque of frequency $f_o – f_{er}$ which is produced by the interaction of rotor magnetic field (at f_o) and armature magnetic field (at f_{er}) [26, 27].

2.1.1. Self -Excitation

The two types of self-excitation are explained below.

2.1.1.1. Induction Generator Effect

The flow of positive sequence components of armature current at resonant frequency f_{er} causes a rotating magnetic field with an electrical angular speed of $2\pi f_{er}$. As the speed of rotor is faster than rotating magnetic field at subsynchronous frequency, the slip at subsynchronous frequency (S_{ssr}) is negative (since $f_o > f_{er}$) and is given by "equation (2),"

$$S_{ssr} = (f_{er} - f_o) / f_{er} \tag{2}$$

Also, the equivalent rotor resistance of the generator viewed from the armature terminals is negative as given by the following "equation (3),"

$$R_{eq}^{ssr} = R_r / S_{ssr} \quad (3)$$

When the magnitude of negative rotor resistance is larger than the sum of armature and network resistances there exists self-excitation of induced currents at the subsynchronous frequency. This phenomenon is referred as Induction Generator Effect (IGE).

2.1.1.2. Torsional Interaction

The oscillations of generator rotor at natural torsional frequency (f_n) produces armature voltage components at subsynchronous frequency $f_{en} = f_o - f_n$. If the frequency of subsynchronous voltage component (f_{en}) is close to the electrical resonant frequency f_{er}, then the resulting stator flux tends to produce an electromagnetic torque which reinforces the torsional oscillations of generator rotor. This interplay between the electrical network and mechanical system of the turbine generator is called Torsional Interaction (TI). Hence, the TI occurs when the complement of any of the natural torsional mode frequencies is close to the electrical resonant frequency.

The negative damping due to IGE and TI leads to self-excitation of the generator at subsynchronous frequencies. The IGE is a pure electrical phenomenon, whereas the TI involves the interplay between the electrical network and mechanical system of the turbine generator.

2.1.2. Torque Amplification

A large disturbance in the network can cause transient electrical torque on the generator rotor. In general, the transient electrical torque has several components including subsynchronous torques. The subsynchronous torques can amplify to a larger magnitude when the complement of electrical resonant frequency (f_o–f_{er}) is close to any of the torsional mode frequency (f_n). This phenomenon is referred as Torque Amplification (TA). The cumulative effect of several occurrences of TA can cause fatigue damage of shaft.

2.2. Classification of SSR in DFIG based wind farms

In DFIG based wind farms, the shaft stiffness coefficient of mechanical system and hence torsional frequencies are low. Hence, the corresponding electrical resonant frequency should be high to cause TI and TA. This is possible only at higher level of compensation [28]. In addition, the classifications of SSR extend further in DFIG based wind farms due to the participation of power converter control interactions. The major classifications of SSR in DFIG based wind farms are [29]: 1) SubSynchronous Induction Generator Effect (SSIGE), 2) SubSynchronous Torsional Interactions (SSTI), and 3) SubSynchronous Control Interactions (SSCI).

2.2.1. SubSynchronous Induction Generator Effect (SSIGE)

SSIGE is same as the induction generator effect. When the magnitude of negative rotor resistance of the DFIG is larger than the sum of armature and network resistances, then self-excitation of induced currents at subsynchronous frequency exists. This phenomenon is referred as the SSIGE [30].

2.2.2. SubSynchronous Torsional Interactions (SSTI)

The SSTI phenomenon exists when the DFIG converter controls interact with the generator mechanical system, which can reduce the damping of torsional oscillations. The SSTI does not relate to the electrical network [28, 31].

2.2.3. SubSynchronous Control Interactions (SSCI)

The SSCI occurs due to the interaction of DFIG converter controls and electrical network. The frequency of interaction depends on the operating conditions, controller and network configurations. The SSCI may cause oscillations to grow faster than SSTI and SSIGE [32-34].

3. Techniques and Analysis of SSR in DFIG based Wind Farms

In this section the most commonly used techniques for SSR analysis are reviewed. Subsequently, the analysis of SSR and the impact of DFIG converter controllers on the damping of SSR explored in the literature are presented.

3.1. Techniques of SSR analysis

The frequency scanning is the most powerful technique to identify the steady state SSR at an operating point using the impedance viewed from generator terminals into the transmission network [35-37]. The eigenvalue analysis gives a clear insight into the steady state SSR in a single calculation, which is based on the linear differential equations of the system at a particular operating point. The electromagnetic transient analyses (using PSCAD/EMTDC time domain simulation) are used to analyze the transient state SSR based on the nonlinear equations, which represent detailed model of the system. The analytical frequency scanning techniques with d-q axis representation of system provide results comparable to digital time simulation method [38].

The investigations on SSR using Nyquist criterion by developing impedance models of DFIG and network reveals the effect of wind speed on SSR [39]. The bifurcation analysis adopted in [40,41] demonstrates the subsynchronous interactions due to DFIG controller parameters. A case study has been carried out for a part of ERCOT grid with a reactance based approach in [42], and the screening techniques are employed for SSCI, SSTI in [43]. The comparisons between different techniques of SSR analysis are summarized in “Table 1”.

Table 1. Comparison between methods of SSR analysis

Methods	Merits	Demerits	Applications
Frequency scanning analysis	• Simpler method • Computationally attractive [24] • Cost-e□ective [27,35]	• Approximate method [27] • Indicates the risk of SSR only [27] • The results need to be validated through time domain simulation for accuracy [27]	• To identify IGE and TI [27] • To identify the operating conditions of the system which influences SSR
Eigenvalue analysis	• Accurate method [35] • Provides damping of all the modes of the system • Provides clear insight into IGE and TI [24, 25]	• Fails to identify TA [27] • Unable to include nonlinearities [27] • Switching characteristics of devices are neglected [27] • Expensive method [35] • Not suitable for systems having 20 buses and more [35] • Require detailed system representation [36, 37]	• Useful in designing of SSR countermeasure controllers [27] • Useful to study IGE and TI • To identify the operating conditions of the system which influences SSR
Digital simulation method	• Enables accurate investigations of SSR under various disturbances [27, 36, 37]	• Not suited for self-excitation study [27] • Large simulation time required to analyze IGE and TI under no disturbance [27] • Requires detailed system representation [36, 37]	• To validate results of eigenvalue and frequency scanning methods [27] • Suitable to analyze TA [27]

3.2. Analysis of SSR in DFIG based wind farm

The modal identification and analysis of SSR phenomenon can be carried out through the well-documented methods such as eigenvalue analysis, frequency scanning techniques and electromagnetic transient based digital simulation.

3.2.1. Modal identification

In [44], the modal analysis of a single machine connected to infinite bus system with DFIG based wind farms present four system modes namely: 1) A mechanical mode (~0.5*Hz*) related to dynamics of the shaft and turbine, 2) An electromechanical mode (~ 10*Hz*) related to the rotor dynamics, 3) An electrical mode (~ 50*Hz*) related to the dynamics of the stator, and 4) A non-oscillating mode (~ 0.05*Hz*) of the rotor d-axis flux dynamics. Furthermore, the impact of drive train parameters (inertia, stiffness), generator parameters (mutual inductance, stator resistance), operating points (active and reactive power loading, rotor speed and terminal voltage level), and external line reactance value (grid strength) on the system modes are elaborated. The results explore that the increase in mutual inductance increases the damping of electromechanical and mechanical modes. However, the mutual inductance and the drive train parameters have insignificant effect on the electrical modes. The increase in the stator resistance increases the damping of all oscillating modes. Also, the effect of various operating points on system modes reveals that the initial rotor speed has insignificant effect on the electrical mode and the reactive power loading does not influence the small signal stability. Whereas, the change in initial terminal voltage does not have significant effect on the stator mode and non-oscillating mode. However, the increase in terminal voltage decreases the stability of electromechanical and mechanical modes. And the increase in external line reactance (grid strength) value reduces the damping of the stator and non-oscillating modes. However, in [44] the closed loop controllers are not considered and hence the results of small signal analysis may not reflect DFIG dynamics.

The eigenvalue analysis and participation factors are used to identify the four system modes in [45]. The impact of control parameters, different compensation levels and wind speeds on system modes are presented. The results show that the damping ratio of SSR mode decreases with the increase in compensation level [45]. However, when the wind speed increases, the damping ratio of SSR mode increases. And the shaft mode is dominant mode for higher wind speeds. Further, in [45], the residue analysis shows the RMS voltage across series capacitor is the better control signal for SSRDC than the current through the transmission line. The impact of RSC control on SSR modes in [45] explore that the increase in torque loop gain reduces the stability of SSR mode, electromechanical mode, and shaft mode. Also, the system modes are identified using participation factors and eigenvalue analysis in [46]. The single and two mass drive train models of DFIG are considered without and with stator transients in [47]. The three oscillating modes without and with stator transients of drive train models are identified as high (~ 50Hz), middle (~ 15Hz) and low (~ 3Hz) oscillating modes.

3.2.2. Impact of DFIG converter controllers and operating conditions

In [48], the impact of wind speed, DFIG controllers and network parameters on the system stability are analyzed through the eigenvalue analysis and participation factors. The results show that the rotor side current controller parameters have a significant impact on the location of the dominant eigenvalue. And for higher compensation levels, the dominant mode becomes less stable. The DFIG test system with IEEE First Bench Mark (FBM) model to analyze the IGE and TI is considered in [49]. The results show that the network damping increases at high wind speeds and reduces with the increase in compensation level. Also, it is found that the TI occurs only for high compensation levels, whereas the change in wind speed does not affect the TI. Therefore, the IGE is more critical than TI.

The impedance based Nyquist stability criterion is used to analyze SSR in [50]. The results show that the low wind speed and higher PI controller gain of rotor side converter (RSC) current control loop lead to instability of the system. However, the outer control loops of converters are neglected. In [51], a detailed improved impedance model of wind farm is developed along with grid side converter (GSC) of DFIG, DC link, and RSC's outer control loop with number of DFIG's. The results of quantitative analysis show that the increase in wind speed increases the system damping and the number of online generators has nonlinear impact on the SSR. Also it reports that the equivalent resistance of the system reduces with increase in RSC's inner current control loop gain which leads to prone SSR. In [52], the impedance models of positive sequence and negative sequence circuits of the DFIG based system are developed for SSR analysis under unbalanced operation. In which, the different levels of compensation and wind speeds are chosen to compare the occurrence of SSR in two circuit models. The results show that, the negative sequence components do not have a significant effect on SSR in comparison to positive sequence components.

In [53], a real-time event occurred in North China having twenty-three wind farms is simulated. It is noted that the number of Wind Turbine Generators (WTG) in service has a nonlinear effect on the damping. Also, the effect of RSC and GSC controllers of DFIG are analyzed. The results reports that the RSC controller of DFIG, in particular the current tracking control loop has significant impact on the SSR. Thus, the interaction of DFIG controllers also affects the IGE. The field data of SSR events occurred at Guyuan system is compared with the results of theoretical model in [54]. The results show that the SSR increases even at the low levels of compensation due to SSCI.

In [55], considering the multiple machine models with three different systems delivering same output power is compared for SSR analysis. It concludes that the simplified models cannot provide the accurate analysis and occurrence of SSR. In [56], the frequency scanning and eigenvalue analysis are used to find the cause for oscillation modes in multi machine power system. It reports that the state variables related to the network and generator are the major participants of subsynchronous oscillation mode which mainly depend on the rotor voltage controllers.

The SSCI phenomenon due to rotor current controller is investigated in [30]. It is seen that the increase in rotor controller gain causes the SSR mode to move to the right-half plane. Also, [32] illustrates the negative damping effect of SSCI on SSR due to RSC current controller. In [57], it is reported that the proportional parameter of inner loop current controller quadrature component is most sensitive to SSCI. The investigations in [29] show that the decrease in wind speed and increase in compensation level reduces the damping of IGE. The oscillations due to interaction between DFIG controllers and the network (SSCI phenomenon) grow faster than the SSTI and IGE. In [58], [59], the impedance based analysis using Nyquist stability is elaborated to study the impact of controller parameters and series compensation level on the SSR. The investigation in [58] explores the dependency of DC link voltage controller bandwidth on the GSC. The results of [59] show that the rotor side current controller has a significant effect on DFIG overall impedance.

A group of DFIG wind farms of equal capacity with different wind speeds is considered in [60]. The dependency of SSR damping on the ratio of number of high speed wind farms to the low speed wind farms is explored. It is found that the SSR damping improves as the number of high speed wind farms increases. Further in [61], the SSR analysis for the two clusters of DFIG wind farms located at different distances from the bus bar is reported. The results show that: 1) the overall system stability is significantly affected by the closer cluster than farther, 2) the stability improves with the increase in the power share of farther cluster (within the capacity) the wind farm, and 3) the high impedance of cables between bus bar and wind farm clusters increases the system stability and oscillation frequency.

The investigations in [62] show that the stable region of SSR increases as: 1) the increase in rotor speed and output power, 2) the reduction in number of DFIGs in operation and inner loop gains of RSC. In [63], the contribution of DFIGs electromagnetic torque variation on SSR is discussed. The analysis show that the rotor torque variation provides the positive damping on SSR and stator torque variation provides negative damping on SSR. In [64], the results illustrate that the slip of the DFIG has proportional relation with the series compensation level and the grid reactance, however inversely proportional to the wind speed and the grid resistance. Noting that, the increase in slip tends to reduce the damping of subsynchronous mode. In [65], the SSR analysis is presented at different operating conditions.

4. Mitigation of SSR in DFIG based Wind Farms using FACTS devices

The FACTS controllers play a major role in mitigating the SSR in power system to enhance the stability. The literature review on FACTS controllers to mitigate SSR in DFIG based wind farm connected to the series compensated transmission line is as follows.

In [66], the effectiveness of SVC with a damping control loop for suppression of SSR in DFIG based wind farm connected to series compensated transmission line is explored. In which, the line current is chosen as an input feedback control signal for the damping controller. The reactive power support, easy implementation and utilizing locally available input control signal are additional benefits of this method; however the gain of controller is fixed [66].

An auxiliary damping controller with adaptive gain technique for SVC controller is presented in [67]. The reason behind the design of adaptive controller is the gain of SSR damping controller at one wind generation level is not suitable for other generation levels. The objective of the auxiliary damping controller shown in "Fig. 2" is to obtain a suitable reference value of SVC susceptance (B_{ref_ssr}) through gain adaption, high pass filter (G_{HPF}) and lead-lag compensator (G_{lead}, G_{lag}). The gain adaption (k_{damp}) helps to change the controller gain in a possible range. The input control signal of auxiliary damping controller is the line power (P_{line}), which is calculated from the line current (i_{line_abc}) and bus voltage at the SVC connection point (u_{SVC_abc}).

To mitigate SSR in DFIG based wind farms, an auxiliary damping controller with GCSC is proposed in [46], [69], and [68]. "Figure. 3(a)" shows the block diagram of GCSC controller with SSRDC and Power Scheduling Controller (PSC). The main objective of PSC is to regulate the reactance of GCSC in order to maintain the specified active power flow in transmission line. The PSC consists of lead compensator and PI controller which is designed to derive the reactance X_{psc} from the reference and measured value of line current (I_{ref} and I_{line}). Whereas SSRDC derives the reactance X_{aux} from the input control signal. The output of PSC and SSRDC are then processed to obtain effective reactance of GCSC (X_G). The reference value of line current (I_{ref}) is calculated from the optimum wind power through MPPT curve. In [68], the line current is used as Input Control Signal (ICS) to the SSRDC. However in [46], [69] effectiveness of the rotor speed (W_r), line current (I_{line}) and the voltage across GCSC (V_{CG}) as input control signal is examined using residue and root locus techniques at different operating conditions. The analysis concludes that the voltage across GCSC (V_{CG}) is an optimum ICS for SSRDC, and the SSRDC with high gain improves the damping of SSR.

The SSR damping using TCSC with fixed firing angle and impedance control modes in [70] proves that, the TCSC compensated wind farm is less prone to SSR and instability due to RSC current controller is also reduced. In [71], a comparison of TCSC, GCSC and GSC control of DFIG for mitigation of SSIGE is presented. The remarks are presented in three folds as: 1) the TCSC can improve the damping of SSR mode without an auxiliary controller, while reduces the damping of super-synchronous mode. However, adding a SSRDC to the control loop of TCSC can damp the SSR without affecting other modes. The block diagram of TCSC control with SSRDC is shown in "Fig. 3(b)". 2) Like TCSC, the GCSC is not able to increase the damping of SSR. However, the incorporation of SSRDC with GCSC in a similar way to "Fig. 3(b)" can improve the damping of SSR. Though, the damping of SSR can be done using FACTS devices, it is not a cost effective solution. 3) Utilizing the GSC control of DFIG with an auxiliary damping controller for damping SSR is appreciable. The voltage across the series capacitor is used as ICS to the SSRDC.

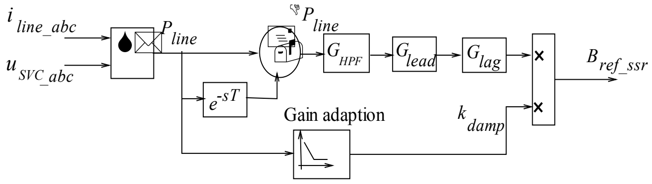

Figure 2. SVC control with damping controller [67]

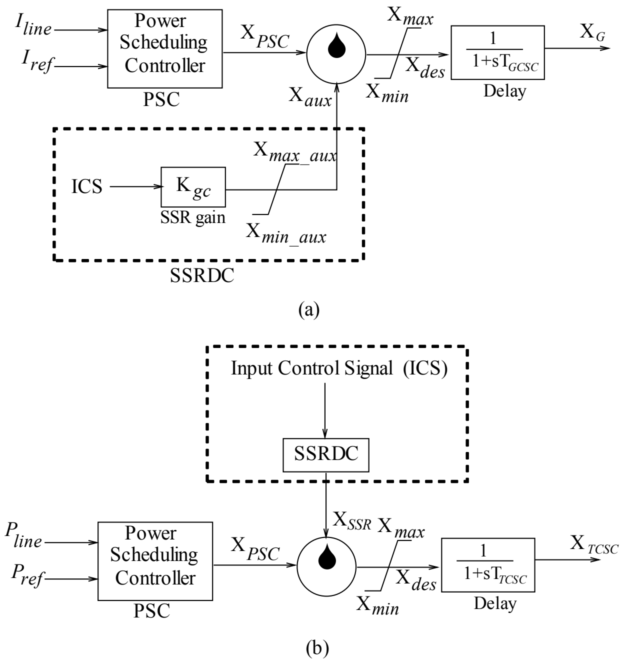

Figure 3. (a) The block diagram of GCSC controller with SSRDC [69] (b) The block diagram TCSC control with SSRDC [71]

5. Mitigation of SSR Using DFIG Converter Controllers with SSRDC and other methods

The mitigation of SSR using converter controllers of DFIG is a cost effective solution rather than using FACTS devices. This section explores the review on utilizing the converter controllers of DFIG and other methods to damp SSR.

5.1. Mitigation of SSR using DFIG converters with SSRDC

The structural similarity of GSC with DC link as a STATCOM has led idea to check the control capability of GSC to damp SSR in [72], [73]. A supplementary damping controller (SSRDC) is embedded into the d-axis voltage control loop of the GSC, which modulates the voltage reference signal to damp SSR in [72]. The deviation of the DFIG rotor speed is used as feedback signal to SSRDC. In [73], the effectiveness of SSRDC with series capacitor voltage (V_c) as input is examined through modulating the reference signals of DC link voltage (V^*_{dc}) and the terminal voltage (V^*_t) as shown in "Fig. 4". Though, SSR is well damped in both cases, the magnitude of oscillations in electromagnetic toque and dc link voltage is greater when the DC link voltage is modulated.

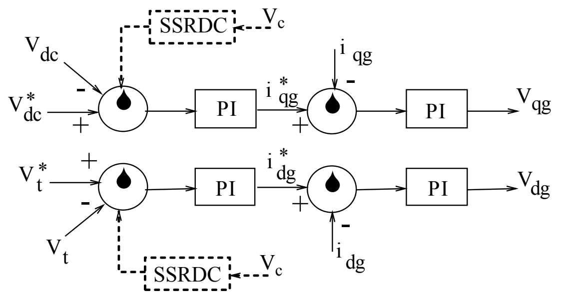

Figure 4. The GSC of DFIG with an auxiliary SSR damping controller [73]

However, the voltage across the capacitor is not locally available at the wind farm, it should be transmitted through communication which may cause delay to the controller. Therefore, a SSRDC with observed state feedback controller is designed using an optimal quadratic technique to modulate the terminal voltage reference of GSC in [74]. The controller uses the locally available stator current (d-q components) as input control signal. In [75], the control capability of GSC to damp SSIGE shows satisfactory performance. The impact of inner and outer loop PI controller parameter variation on SSIGE is analyzed for various wind speeds and compensation levels.

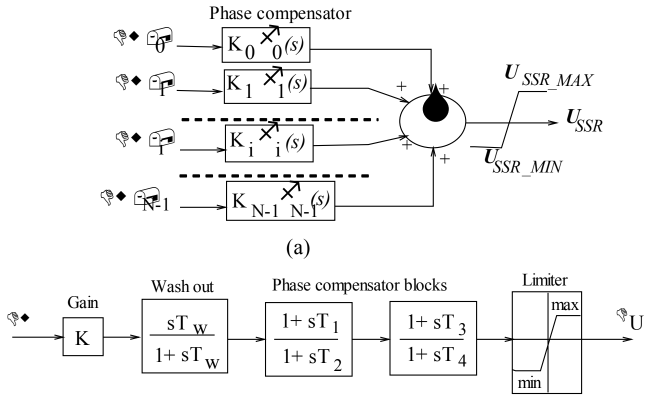

Figure 5. (a) GSC supplementary damping controller with N-channels [76], (b) Conventional damping controller with lead-lag networks [77]

The SSR in nearby turbine generator is alleviated by using SSRDC at the reactive power control loop of GSC in [76]. The SSRDC having N-channels with the modal speeds ($\Delta\omega,i$) as input control signals is shown in “Fig. 5(a)”. The output of SSRDC (U_{SSR}) is used to modulate reactive power output of GSC. A Particle Swarm Optimization (PSO) based Conventional Damping Controller (CDC) is compared with Fuzzy Logic based Damping Controller (FLDC) in [77]. “Figure. 5(b)” shows CDC with lead-lag networks. The FLDC shows good performance compared to PSO based CDC over the wide range of operating conditions to eliminate SSR.

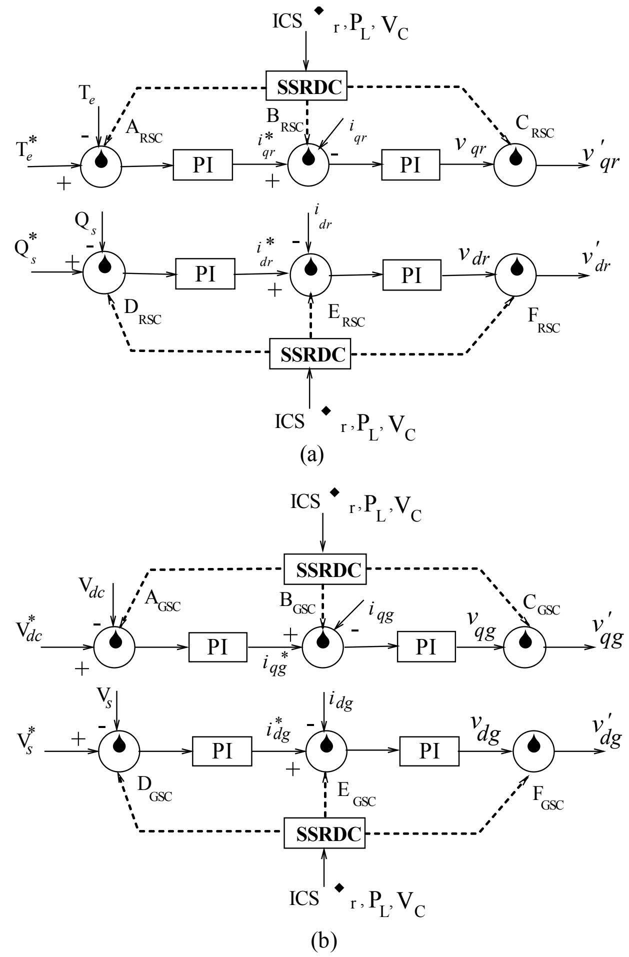

Figure 6. (a) RSC controller of DFIG (b) GSC controller of DFIG [79]

Though, the capability of GSC to damp SSR is explored, an ambiguity exists in best location of SSRDC at GSC and input control signal to SSRDC. The optimum insertion location of an auxiliary damping controller in GSC through modal analysis and root locus techniques is analyzed in [78]. The results shows that the q-axis inner loop of GSC as the optimum point and the electrical power of DFIG as optimum input control signal. While, the investigations to insert SSRDC at an optimal location with optimum input control signal in RSC and GSC are well portrayed using residue analysis and root locus method in [79], [80]. The SSRDC is examined at the different locations of RSC and GSC controllers, indicated in “Fig. 6” as A_{RSC}-F_{RSC} and A_{GSC}-F_{GSC}, respectively. The rotor speed (ω_r), transmission line real power (P_L) and voltage across the capacitor (V_c) are considered as input control signals. The optimum input control signal for SSRDC is found through residue based analysis. The analysis shows that the magnitude of residues with SSRDC at RSC controllers is small, which requires high gain to shift the SSR mode into a stable region. However, the high gain RSC controllers may destabilize the other modes. Hence, the investigations in [79], [80] strengthen the optimal locations for SSRDC as D_{GSC}, E_{GSC} and F_{GSC} as shown in “Fig. 6”, and optimal input control signal as voltage across the series capacitor (V_c). In [80], the Gain Schedule Adaptive (GSA) control is used to calculate the gain (K_{SSR}) in order to enhance the capability of SSRDC for various operating conditions.

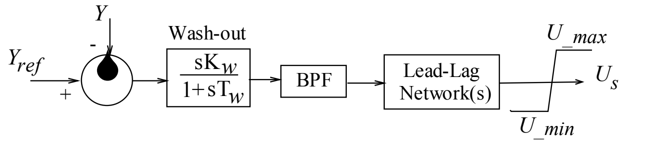

Figure 7. The block diagram of Lead-Lag supplementary controller [81]

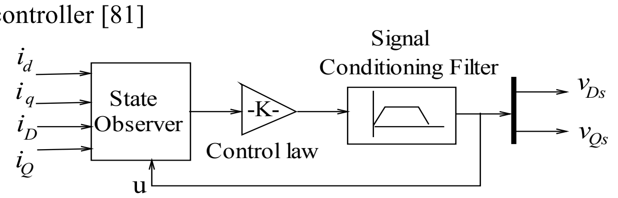

Figure 8. The supplementary SSI damping controller [30]

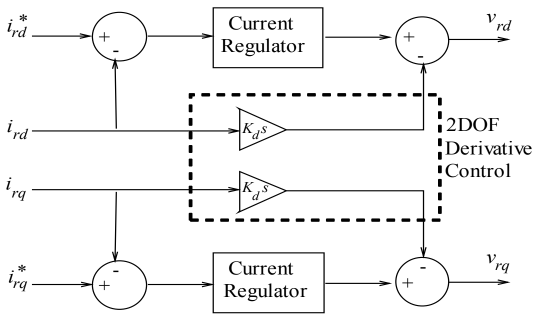

Figure 9. Current control loop of RSC with 2DOF [82]

The effectiveness of SSR damping controller at reactive power control loop of GSC is analyzed with four wind farms through three case studies in [81]. In the three case studies, one of the four wind farms is considered to be a DFIG, full-scale frequency converter (FFC) and DFIG based offshore wind farm connected to HVDC, while other three remain DFIG based wind farms. "Figure. 7" shows the lead-lag based damping controller implemented at all wind farms in case-1, only at FFC based wind farm in case-2 and only at multi-module converter (MMC) of onshore HVDC link in case-3. The line current or real power is used as input control signal (*Y*) for the SSR damping controller. Also, a phase imbalance series capacitive compensation is considered to explore its impact on SSR damping, whose damping is comparable with SSR damping controller.

In [30], an auxiliary damping controller using multi-input-multi-output (MIMO) state space methodology to damp sub-synchronous interactions (SSI) is designed for DFIG converters as shown in "Fig. 8". The auxiliary damping controller is implemented at RSC inner control loop with the locally available stator and rotor currents as input control signals. The effectiveness of RSC over GSC with auxiliary damping controller is clearly demonstrated as: 1) superior performance during high compensation levels, 2) the high controllability index of rotor voltage control on SSR mode and 3) directly alters the effective rotor resistance.

The authors in [82] developed a combined control with a Two Degree of Freedom (2DOF) control strategy in RSC and SSRDC at terminal voltage control loop of GSC. The 2DOF comprising derivative control is implemented at current control loops of RSC as shown in "Fig. 9". The purpose of the combined control is to enhance the mitigation of SSR and fault ride-through (FRT) capability of DFIG. In [83], an auxiliary damping controller is implemented on the active power control loop of RSC using the turbine generator speed as input control signal. A real power system of Argentinian consisting series compensated multiple transmission lines, wind power plants and various conventional plants with distributed loads is considered in [84]. To suppress the effect of SSCI, a Supplementary Damping Controller (SDC) is implemented at RSC to modulate the q-axis component of rotor voltage. The active power output of the wind farm is used as the input control signal to SDC.

An Optimal State Variable Feedback (SVFB) control based Linear Quadratic Regulator (LQR) to produce supplementary control signals for SDC is presented in [85]. The SDC utilizes the DFIG converter currents as input control signals. The output signals of SDC are used to modulate the reference signals of GSC and RSC current control loops. Also, the RSC and GSC are controlled with the centralized reactive power control scheme to enable SDC to damp SSI without deteriorating the DFIG's transient response. A nonlinear current controller based on Partial Feedback Linearization (PFL) technique to mitigate SSCI is presented in [86]. The PFL controller utilizes the transformed q-axis and d-axis components of voltage and current signals across the GSC filter. The output signals of PFL are given to the pulse width modulator to generate actuating pulses for GSC.

From the literature, we have summarized some of the selective papers in "Table 2" which have investigated the location and input control signal of SSRDC for DFIG converter controllers.

5.2. Mitigation of SSR through other methods

5.2.1. Series capacitor control method

A cost effective series capacitor control using an algorithm shown in "Fig. 10" is presented in [90]. The series capacitor is bypassed under SSR condition and reinserted automatically when the risk of SSR is low. The control algorithm monitors line current (i_{line}) and bus voltage (u_{line}) at the low voltage side of transmission line. From i_{SSR}, the magnitude of SSR current ($i_{SSR\ magn}$) is sampled and compared for two successive peaks to observe its variation. When the magnitude of SSR current ($i_{SSR\ magn}$) is greater than the pre-set threshold value and grows with time, the system control detects SSR condition. Subsequently, the bypass of series capacitor automatically takes place.

Table 2. Location and input control signals of SSRDC in DFIG converter controllers

Reference	Location of SSRDC examined	Input Control Signal(s) used
[73]	At the DC link voltage and terminal voltage control loop of GSC	Voltage across the series capacitor
[76]	At the reactive power control loop of GSC	Modal speeds
[77]	FLDC type of SSRDC at the reactive power control loop of GSC	Speed deviation of the rotor shaft
[81]	At the reactive power control loop of GSC/ MMC of HVDC link	Line current and real power
[79]	At the reactive power control loop of GSC	Voltage across the series capacitor
[80]	At the reactive power control loop of GSC	Voltage across the series capacitor
[30]	At the inner control loop of RSC	DFIG stator and rotor winding d-q axis currents
[83]	At the active power control loop of RSC	Turbine generator speed
[74]	At the voltage control loop of GSC	Locally available stator currents
[84]	At the reactive power control loop of RSC along with a band pass filter	Active power output of the wind farm
[85]	At the inner control loops of GSC and RSC	DFIG converter currents

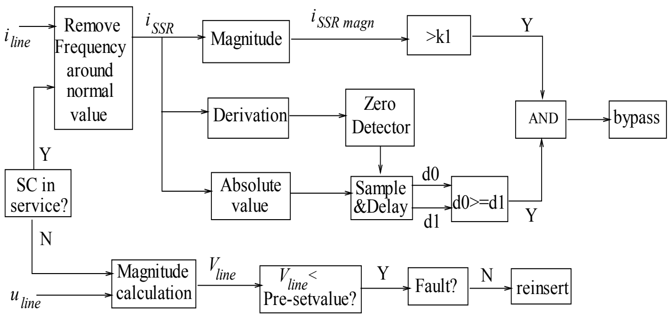

Figure 10. Series Capacitor bypass and reinsertion algorithm [90]

The reinsertion of the series capacitor automatically takes place on the basis of bus voltage (u_{line}) magnitude compared with a pre-set value. When the magnitude of u_{line} is less than the pre-set value, the control system checks for the cause of low voltage. If the low voltage is not due to fault, the system control sends reinsertion command.

5.2.2. Implementing filters at DFIG converters

In [87], the notch filters are inserted into RSC inner current control loops to suppress SSR and is tested with a practical system. In comparison to notch filter at the q-axis inner loop, embedding notch filter at the d-axis inner loop shown a strong impact on the damping of SSR. Similarly, in [88] and [89], the Subsynchronous Suppression Filters (SSF) is proposed for DFIG controllers to suppress SSR. Also, the best location for insertion of SSF in DFIG converters is determined using location dependent performance index in [88]. The inner current control loop of d-axis channel of RSC is found as the best location to insert SSF. In [89], a cost-effective solution is presented to implement SSF at an optimum number of DFIG's instead implementing at all DFIG's of a wind farm.

From the literature, we summarize the merits and demerits of various SSR damping methods in "Table 3". We observe that the use of FACTS devices with SSRDC show effective damping of SSR. It is noted that the FACTS devices dedicated only for SSR mitigation are not cost effective; however their applications are much significant in large power systems. It is worthwhile that the control capability of DFIG converters can be utilized to damp SSR through proper tuning of its controller parameters. The control capability of RSC controller is greater than GSC controller as its rating is higher. However, the improved damping of DFIG converters requires SSRDC. The literature shows that the SSRDC with an appropriate input control signal at suitable location in DFIG controllers can provide better damping. Also, the other methods such as series capacitor control and filter with DFIG show good response.

6. Conclusion and Future Perspectives

This paper reviews the analysis of SSR and its mitigation techniques in DFIG based wind farms. Some of the major findings of the review are:

- The eigenvalue, frequency scanning and electromagnetic transient analysis are most followed methods to analyze the SSR in DFIG based wind farms.

- The types of SSR in DFIG based wind farms are SSIGE, SSTI, and SSCI. In which the SSCI and SSIGE are most expected to occur than SSTI (probably does not occur).

Table 3. Merits and Demerits of various methods to damp SSR in DFIG based Wind Farms

Method of damping SSR	Merits	Demerits
GSC controller	• Built-in converter control	• Rating of GSC is low (25% to 30% of the generator rating) [84] • Less control capability on SSR damping [49]
RSC controller	• Built-in converter control • Direct control on the active and reactive powers of generator [82] • High rating than GSC [82] • Hence, higher control capability on SSR damping	• High gain RSC controller can destabilize SSR modes [45, 48-50] • Significant effect on SSR, mainly SSCI [30, 53] • Weakens the DFIG control bandwidth, and hence difficult to accomplish the FRT requirements [32] • Equivalent resistance of the aggregated impedance reduces with increase in RSC's current control gain which leads to prone SSR [51]
GSC and RSC Controllers	• Control capability of two converters	• High impact on SSCI [86] • The control interaction influences IGE [53]
GSC controller with SSRDC	• Utilization of reactive power control capability of GSC on SSR damping [76, 77]	• Restricted voltage control capability mainly at low wind speed and high compensation levels [82] • Less controllability index of reactive current control on SSR mode [30] • GSC needs greater damping control effort compared to RSC [30] • Supplementary controller requires careful tuning [88], extra work and cost [87, 89]
RSC controller with SSRDC	• High controllability index of rotor voltage control on SSR mode [30] • Superior performance during high compensation levels [30] • RSC control directly alters the effective rotor resistance [30] • RSC needs lesser damping control effort compared to GSC [30]	• High gain SSRDC required to move SSR mode into a stable region may destabilize other modes [79, 80] • Supplementary controller requires careful tuning [88], extra work and cost [87, 89]
SSRDC at both GSC and RSC controllers	• Enhances the FRT capability of DFIG during faults [85]	• Complicated approach [82]
FACTS devices with SSRDC	• Improves power system stability • Enhanced damping capability with SSRDC	• Supplementary controller requires careful tuning [88], extra work and cost [87, 89]

- The damping of SSR reduces with the increase in compensation level, rotor resistance, torque control loop gain of RSC, external line reactance and PI controller gain of RSC. However, the damping of SSR improves with the increase in wind speed, mutual inductance, and stator resistance.

- The SSCI is most sensitive to proportional gain of quadrature component current controller. Hence, an inappropriate gain of controller can cause SSCI even at low compensation levels.

- FACTS devices with SSRDC are used to damp SSR. The addition of FACTS devices can improve the stability and power transfer capability of transmission line.

- The implementation of SSRDC with GSC and/or RSC controller of DFIG is an economical solution to mitigate SSR. It is noted that, the SSRDC with RSC shows good performance for high levels of series compensation too.

- Participation factor and residue analysis are majorly used to find an appropriate input control signal to the SSRDC.

The high penetration of wind energy based generation into the existing power system can affect the damping characteristics of the overall system. Besides, the power converters of wind farm have significant effect on SSR. Hence, in future viewpoint, some of the investigations are significant with wind farms, such as:

- The damping characteristics of the power system with conventional turbine-generator and various types of wind farms to be investigated as which may encounter TI, IGE and SSCI. Hence, a suitable damping controller to be designed in this concern.

- The comparison of FACTS devices and DFIG converter controllers to mitigate SSR needs further research in the aspect of effectiveness, converter ratings and cost.

- Design and investigations on self-tuning and robust DFIG converter controllers along with SSR damping control need to be explored in order to meet grid code requirements.

- The dependency of control capability of converter on its rating is to be investigated extensively. Also, the coordination of RSC and GSC control of DFIG need to be investigated.

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