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Sub-synchronous resonance in wind energy integrated grid – problem and mitigation techniques – a review

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ABSTRACT

When wind energy conversion systems (WECS) are integrated with the Grid system then there are power quality issues arises. The fluctuation in the wind power delivery to the grid demands robust control for a better power quality. Therefore, voltage and frequency stability due to integration of wind to the grid is the primary concern to improve the overall grid integration capability for WECS. This paper reviews the power quality issues in the power grid due to introduction of WECS. The WECS integration with the grid introduces dynamic issues that include sub-synchronous resonance (SSR), low voltage ride through (LVRT), frequency support from wind generation, synchronization, and transients. Also, it focusses on the sub synchronous resonance introduced due to introduction of doubly-fed induction generator (DFIG) wind turbines to the transmission lines with capacitive series-compensation. The review of various power quality issues and methods used by the researcher's mitigations are discussed and detailed further research perspective.

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1. INTRODUCTION

Research on renewable energy resources exploration and integration to the grid is carried out in large with higher penetration of renewable energy in the power sector with the advantages like lower carbon imprint and lesser power production cost in the long run. One of the important power quality issues is that pops up while wind energy conversion system WECS is integrated to power system is the sub synchronous resonance. Oscillation that are less than the synchronous frequency that occurs while the WECS is connected to the series compensated power system is called the sub-synchronous resonance (SSR). SSR occurs while the Doubly fed induction generator (DFIG) is integrated with the series compensated power system. Discussion on DFIG integration to the grid and occurrence of SSR is discussed along with the different mitigation techniques that compensates SSR.

Kinetic energy of the wind while falling on the rotor converts it to mechanical energy. Rotor is coupled to the generator through the gear system. Generator which gets the mechanical input from the gear system would convert the mechanical energy into electrical energy as evident in Figure 1. Aerodynamic design of the rotor blades is articulated to enhance power conversion capability from kinetic energy in air to the rotor mechanical energy. The ratio of power that the rotor blades can convert from the air kinetic energy is defined as power efficiency coefficient. Construction of the wind turbine is categorized according to the few wind turbine-based parameter selection [1]. Different types of such wind turbines are as given in the following.

- Speed: Wind turbines that work near a specific rotor speed that is in a narrow range are called the fixed speed wind turbines. Maintaining better aerodynamic efficiency is the consideration where the rotational speed is adjusted according to the incoming wind speed in the variable speed wind turbine.
- Pitch angle: Both the fixed pitch angle and variable pitch angle setup for WECS.
- Direct or Indirect: Indirect drive doubly fed topology of squirrel cage induction motor with both gear system and the frequency converter, and direct drive synchronous generator with the frequency converter without gearbox. Pitch control in both these drives are relevant and also both are variable speed drives.

Wind turbine condition monitoring using the electrical parameters that are processed using the signal processing methods are detailed for different methods in the paper. Equations that govern the working of the WECS are important to understand the fault detection methods and parameters that are involved for detecting the faults. Input that drives the WECS is the wind speed that is the starting point of the energy conversion system. Kinetic energy of the wind falling on the turbine rotor is converted into electrical energy.

Conversion of the wind power to usable electrical power is defined by the term as power efficiency coefficient (C_p) that is dependent on the losses that are incurred due to gear and the generator and it's given by.

$$P_M = C_P P_W \tag{1.1}$$

$$P_W = \frac{1}{2}\pi R^2 V^3 \rho_{AIR} \tag{1.2}$$

In (1.1) defines the mechanical power generated from the wind P_M, which is the fraction of the wind power P_W. Power efficiency coefficient (C_p) depicts the amount of energy conversion from wind power to mechanical power. Wind power P_W is defined as given in (1.2) with rotor radius R, air density ρ_{AIR} and wind speed V.

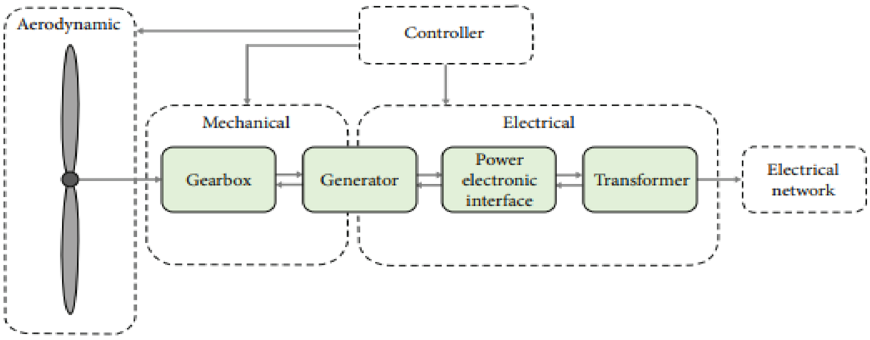

Figure 1. Wind turbine structure

Wind turbine is a complex electromechanical device with the components which combine the wind turbine, generator and the converter systems. The model in Figure 2 is utilized for understanding the mathematically constructed WECS [2]. Overall WECS as shown in Figure 1 illustrates the power conversion stages of the wind turbine. The only physical input to the WECS is the wind speed which is measured using Anemometer. Two modes of operation are set in the WECS according to the wind speed, one is the lower limit of speed at which the WECS starts the energy conversion stage. Wind turbine cut-out occurs when the wind speed is too high for conversion [3]. Braking is applied to the turbine in different ways which include applying a brake which is mechanical, electrical or hydraulic that is called parking brakes. Rotational speed of the wind turbine is increased by introducing the gear system hence producing the generator energy from the mechanical input. Produced energy is in terms of Megawatts in a typical wind turbine. Rotor side has the low-speed shaft while the generator side has the high-speed shaft for energy conversion. Rotor blades and the hub combine to make the wind turbine. Rotor blades are connected to the hub through the low-speed shafts. Wind turbine working is limited between two speed limits (lower and higher) between which the power production is stable for any wind turbine. Controlling the pitch of the blades helps in maximizing and minimizing the power conversion efficiency while in low winds and high winds respectively and also to protect from any structural damage of the wind turbine. Rotor is connected to the gearbox through the low-speed shaft [4]. An enclosure that contains gearbox, low and high-speed shafts, generators and the brakes on the top of the tower is called Nacelle. Rotor and the Nacelle is setup on the tower which is designed for observing more wind from the environment for obtaining more electrical energy. Direction of the wind is detected by the wind vane, which helps the yaw mechanism to maintain the wind turbine to be oriented perpendicular to the wind. Electrical motors are used to adjust the wind turbine with the yaw mechanism. Control technique of variable pitch variable speed wind turbines are discussed in the following section [5].

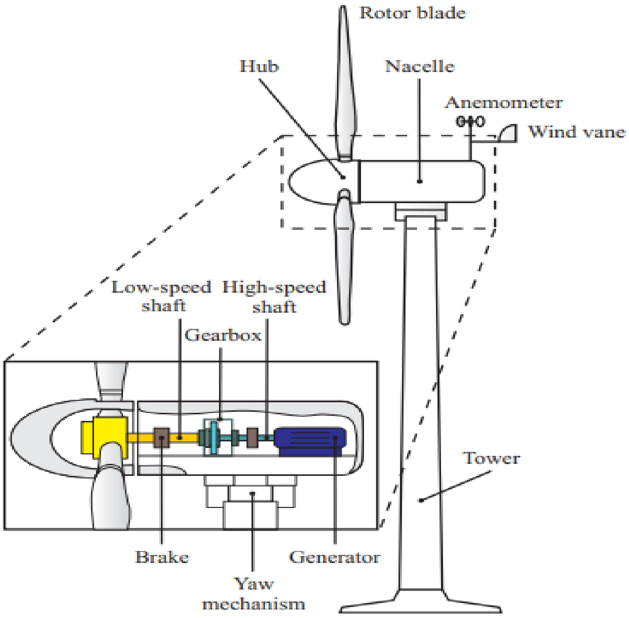

Figure 2. Main components of a horizontal-axis wind turbine

2. GENERAL CONTROL STRATEGY FOR WIND TURBINE

Operating trajectory of the wind turbine is maintained by the wind speed limits. Every control strategy of the wind turbine is to follow the best operating trajectory. Control of the wind turbine with the variable speed and variable pitch control is discussed in this section. Closed loop operation of the wind turbine needs the fault diagnosis and fault tolerant control to maximize the power generated and to minimize the shutdown time. Shutdown or curtailment of the wind turbine increases the cost of power production. Steady power production is possible if wind turbine operates on a certain trajectory depicted in Figure 3. Control strategy is coined as shown in Figure 4 to obtain the trajectory given in Figure 3. Power trajectory as depicted in Figure 4 has two portion I and II according to the wind speed variation. Income from the power generated below the cut-in speed, $V_{w,cut-in}$ is less than the operational costs and thus incurring loss if generated. Wind turbine can't produce useful power when made to work above the cut-out wind speed $V_{w,cut-out}$ since it is shutdown citing structural damages. Active power production is possible between cut-in speed, $V_{w,cut-in}$ and cut-out wind speed $V_{w,cut-out}$. The trajectory in Figure 3 is split into two portions, one being the partial load region I and second being the full load region II. In the benchmark model considered the full load is 4.8MW [6]. The pitch angle control for obtaining the desired output power is depicted in Figure 4. Pitch angle variation shown in green affects the torque generated and power generated depicted as red and blue waveforms. The input to the model wind speed V_w is used to obtain the torque and the power from the model. Power generated between rated wind speed $V_{w,N}$ and the cut-out wind speed $V_{w,cut-out}$ is the full load region. The control between the two modes of operation I and II is approached by shifting between different controllers for different speed range as shown in Figure 5. A reference controller that generates the torque and pitch reference value for the model to switch between the two modes of operation is shown. During mode I operation the generator torque reference and the optimum bitch reference is generated from the reference model and given to the wind turbine model [7]. Switching action between mode I and mode II is decided according the wind speed.

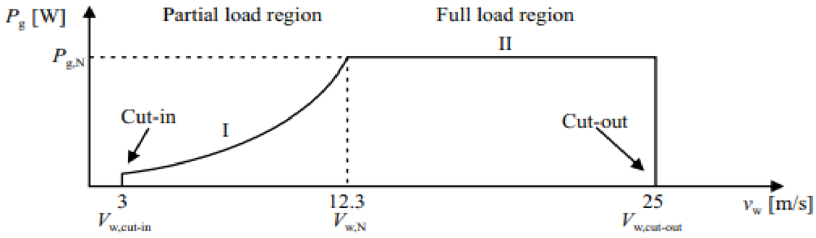

Figure 3. Ideal power curve for the wind turbine

During the mode II operation a constant generator torque is considered and pitch control action is applied on the wind turbine while maintaining a constant power from the wind turbine. Oscillations are damped in the drive train by using the drive train stress damper in both the modes. Trajectory shown in Figure 4 and control action Figure 5 is obtained by this reference controller. Reference controller is universally used for every model in the current research. The recent fault detection methods are recently developed and are presented in the following section. The complete benchmark model encompasses of the mathematical representation of the generator/converter, blade, pitch, drive train models in the WECS [6]. A random speed reference is applied on the mathematical model denoted by v_w which is the starting point of the bench mark model development. Considering the random values generated from the vector as the wind input to the mathematical bench mark model the dynamic torque generated from the rotor is approximated to in (1.1).

$$\tau_r(t) = \frac{\rho\pi R^3 C_q(\lambda(t).\beta(t))v_w(t)^2}{2} \tag{1.3}$$

For every instant 't' variation of wind speed is $v_w(t)$ instantaneous aerodynamic torque $\tau_r(t)$ defined in (1.3). Where $\rho$is Air density (kg/m^3) R is rotor radius, Cq is rotor torque coefficient λ is tip speed ratio and β is blade pitch angle.

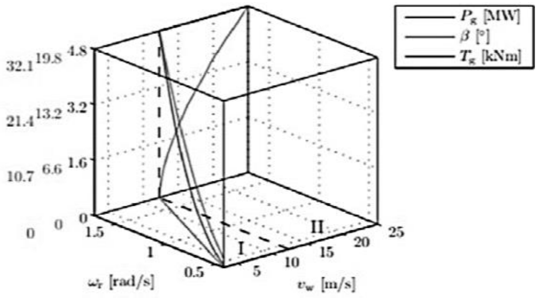

Figure 4. Typical control strategy for following the ideal power curve

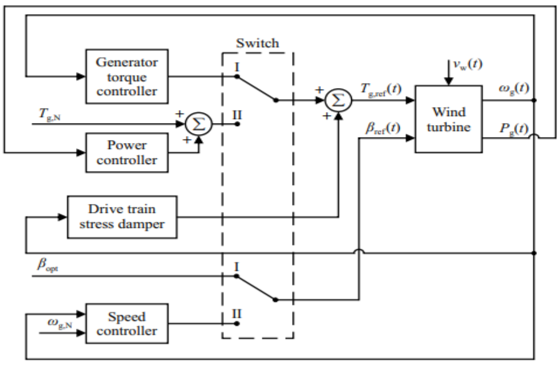

Figure 5. Structure of the reference controller
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Overall block diagram for the wind generator model is as given in Figure 6. Since the number of blades for any wind turbine is more than one usually the torque is a cumulative term that is the summation of torque generated in all the blades. Cumulative torque generated in the rotor is defined in the in (1.4). pitch angle for each blade is considered for the total torque generated in the rotor term.

$$\tau_w(t) = \sum_{1\le i\le 3} \frac{\rho\pi R^3 C_q(\lambda(t).\beta_i(t))v_w(t)^2}{6} \tag{1.4}$$

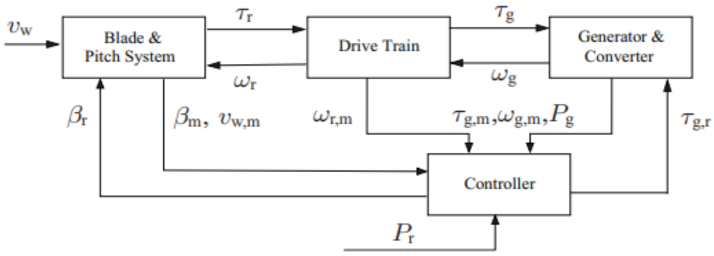

Figure 6. Overall block diagram of WECS bench mark model

In (1.4) denotes the pitch angle value β with a suffix 'i' which denotes the blade number. Three blades are considered in the bench mark model. The multiple Hydraulic cylinders are used for controlling the blade angle even without the electrical supply which is called as the "Hydraulic pitch system" and the equation governing the hydraulic pitch system is as defined as (1.5).

$$\frac{\beta(s)}{\beta_c(s)} = \frac{\omega_n^2}{s^2+2\varsigma\omega_n s+\omega_n^2} \tag{1.5}$$

It is defined as the second order system where ω_n is the natural frequency and ς is the damping factor. All blades have similar pitch model and if there is no disturbance in the pitch system there will be no occurrence of the damping factor in the system. A decrease in hydraulic power for increased air pressure will be observed if fault occurs in the system. Air pressure and the damping factor both would be the reason for the hydraulic power drop. Pitch sensor data are given to the actuators to control the blade movement. Sensor gain is bound to affect the actuators since the blade movement control will get affected. In order to reduce this effect, the pitch reference is calculated. The dynamics in the blade pitch gain value affects the actuators and the control of the blade movement is affected. Thus, to avoid this the average of the gradient value is used with the difference to the pitch reference value. In (1.6) defines the reference value of the pitch and $\beta_{r,f,i}[n]$ defined the sensor values and is given by.

$$\beta_{r,f,i}[n] = \beta_{r,i}[n] - \frac{\Delta\beta_{i,m1}[n]+\Delta\beta_{i,m2}[n]}{2} \tag{1.6}$$

During the disturbance in the sensor values the term $\beta_{r,f,i}[n]$ gets generated to avoid the actuator mismanagement. Here, i indicate the blade number $i \in \{1,2,3\}$.Pitch reference value gets shifted from $\beta_{r,i}[n]$ to $\beta_{r,f,i}[n]$ due to the irregular gain in the sensors. The rotor torque generated in (1.3) is converted to useful electrical power by using the drive train. The drive train comprises of both the gear box and the generator. Two mass mathematical model are used for this purpose and are given by in (1.7) and (1.8).

$$J_r\omega_r(t) = \tau_r\dot{(t)} - K_{dt}\theta_\Delta(t) - (B_{dt}+B_r)\omega_r(t) + \frac{B_{dt}}{N_g}\omega_g(t) \tag{1.7}$$

$$J_g\dot{\omega}_g(t) = \frac{\eta_{dt}K_{dt}}{N_g}\theta_\Delta(t) + \frac{\eta_{dt}B_{dt}}{N_g}w_r(t) - \left(\frac{\eta_{dt}B_{dt}}{N_g^2} + B_g\right)\omega_g(t) - \tau_g(t) \tag{1.8}$$

The in (1.5) and (1.6) are the torque equations for rotor and generator product of low-speed shaft moment of inertia J_r and angular velocity term ω_r. Drive train modeling of both the gear system and the generator system is defined in in (1.5) and (1.6). Where drive train's torsional stiffness is K_{dt} , torsional damping coefficient is B_{dt}, high speed shaft's viscous friction is B_g. Torsion angle of drive train is $\theta_\Delta(t)$ and efficiency is η_{dt} respectively. Efficiency deviation η_{dt2} act as the fault condition and not the efficiency η_{dt}. N_g is the gear ratio and J_g is the high-speed shaft's moment of inertia. Second Order Transfer function of the generator to converter model is defined as (1.9).

$$\frac{\tau_g(s)}{\tau_{g,r}(s)} = \frac{\alpha_{gc}}{s+\alpha_{gc}} \tag{1.9}$$

Measured generator torque and the reference generator torque are defined as τ_g and $\tau_{g,r}$ respectively. The gain parameter for converter conversion parameter α_{gc} is the transfer function parameter. In (2.0) defines the power generated in the generator.

$$P_g(t) = \eta_g \omega_g(t) \tau_g(t) \tag{2.0}$$

Where $\eta_g$the generator efficiency, generator angular velocity is $\omega_g(t)$, generator torque is $\tau_g(t)$. The offset fault detection in generator model is defined as given in (2.1). When the generator speed crosses the nominal speed set, the power generation will cross the reference power generation. The offset speed that would trigger the offset fault is defined as ω_Δ. The drive train damper is avoided to simplify the implementation of fault detection model.

$$P_g[n] \geq P_r[n] \vee \omega_g[n] \geq \omega_{nom} \tag{2.1}$$

There are two modes of operation in the WECS. One is when the generator speed is more than the nominal speed and another is when generator speed is less than the nominal speed. The decision between these two modes is set up by the offset value ω_Δ.

3. DOUBLY FED INDUCTION GENERATOR (DFIG)

DFIG is the variable speed wind turbine system that is most widely used since the start of the millennium. DFIG adopts the wound induction machine i.e., stator and the rotor with windings. Stator of the DFIG is connected directly to the grid while the rotor is connected through the back-to-back converter again connected to the grid. A partial scale converter is used with the capacity of 30% of power of the capacity of the wind turbine [8]. The purpose of the converter is to adjust the voltage and frequency of the wind turbine output integrated to the grid [9]. The bidirectional nature of the back-to-back converter proves to be useful for the control of voltage and frequency from the turbine to the grid.

In the Figure 7 there are two converters denoted as RSC and GSC. Rotor side converter (RSC) and grid side converter (GSC) are the converters that are used for the bidirectional power flow in from the WECS rotor and the main grid through the transformer [10]. The Wind farms are located at places where the wind speeds are higher and usually far from the consumption area. Long transmission line is inevitable in order to deliver the power generated from the WECS to reach the grid and consumption area. Series compensation is adopted in the long transmission to obtain the efficient power delivery in to the consumer area.

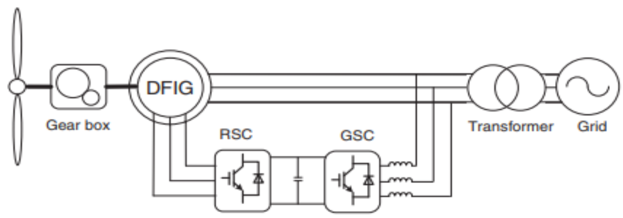

Figure 7. Doubly fed induction generator with partial scale converter

4. SUB SYNCHRONOUS RESONANCE IN DFIG INTEGRATED GRID

The oscillation introduced leads to instability when the series compensation in the line interacts with the DFIG topology [11]. Instability or oscillations are introduced in the converter section of the DFIG and reaches till the rotational speed of the DFIG. Negative resistance at lower frequency than the fundamental frequency causes this oscillation [12]. Occurrence of sub synchronous resonance (SSR) is recorded at different wind farms located in different places of the world [13]-[16]. An SSR phenomenon is modeled in order to understand the phenomena better to reduce the oscillations in the DFIG. Series compensated transmission line connected to the DFIG with LCL filter in the GSC is as shown in the Figure 8 [17].

Stability analysis of power systems usually uses the Eigen analysis using the linear state space matrix. The closed loop state space matrix is developed and stability analysis is carried out on the power system [18]-[24]. Parameters like the participation factor and sensitivity analysis confirms that the main factors for that defines the stability of the DFIG are control loop gains, series compensation levels and wind speed [19]-[24]. SSSRs can also be analyzed using different modeling techniques usually used by power electronics engineers like the impedance modeling discussed in [25], [26]. Complex vector method is also used for modeling [27]-[29]. Transfer function matrix-based modeling [30] is possible which can be rotated between different reference frames and used to model multiple input multiple output MIMO system either symmetrical or non-symmetrical without adding complexity unlike the complex transfer function [31], [32]. Combining independent models to form the complete model is possible [33]. Model with circuit representation combining the transfer functions can be developed for different wind turbine topology for which the stability analysis can be carried out drawing bode diagram. Resonance damping control also can be developed in the same manner [34].

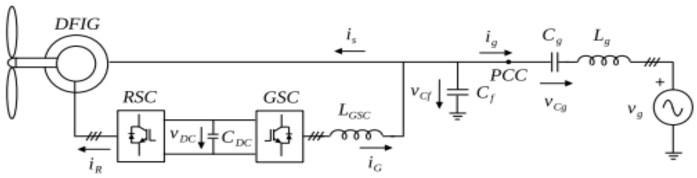

Figure 8. DFIG WECS connected to series compensated power system

5. POWER QUALITY ISSUES WITH GRID

Different power quality issues that get introduced due to the integration of the wind energy in the power system is discussed in the following section.

5.1. Reactive power/voltage support

Wind generators inherently use the induction generators for wind energy generation thus requiring reactive power injection for excitation. Unlike synchronous machines they cannot support reactive power to the grid [35]. Reactive power support is maintained within the limits of the wind integrated grid system by overloading the voltage source converter at the transient fault scenario [36]. Overloading of voltage source converter VSC avoids increase in DC link voltage. Reactive power compensation by checking the voltage within limits and improving the voltage profile is possible using the wind generator [37]. Wind generator exhibits the capability of observing and producing wind reactive power by coordinating among different reactive power sources [38]. Among the fixed and variable speed wind turbine generators fixed speed generators introduce more voltage variations while variable speed drive reduces about 75% of the voltage variations [39]. Another reason for voltage fluctuation is the short circuit impedance at the point of common coupling PCC. Also, it is observed that more the impedance more the fluctuation [40]. The Weak network includes FACTS devices with the Wind turbine to get rid of the voltage fluctuation and thus compensating the reactive power [41]. Voltage fluctuation is also dependent percentage of wind energy penetration in the grid. It is observed that voltage fluctuation is more pronounced when there is a penetration of power is more than 40% is seen in the grid [42].

5.2. Impact of the frequency

Apart from the voltage deviations discussed in the previous section the frequency deviation also affects the grid power. Introduction of wind energy to the grid affects the overall system inertia. In isolated systems this effect is substantial [43]. Torque set point is adjusted in the wind turbine control to adjust the grid frequency variation [44]. Wind turbine mechanical system is isolated from the electrical system to avoid network inertia problems in the grid [45]. Converter based wind turbine generator is utilized to regulate the frequency adapting to the power system variations [46]. The Kinetic energy extraction, energy storage systems and load control are other methods used for the frequency regulation while higher penetration of wind energy is expected [47].

5.3. Impact of the harmonics/power quality issues

Limitation in harmonic emissions is one the conditions to a fair power delivery from the wind turbine [48]. At different parts of the power network levels the harmonic is introduced. To understand how to mitigate the harmonics knowing from where the harmonics is introduced is necessary. Literatures [49]-[51] indicate that power electronic converters, filters, capacitors, turbine transformers, collector bus and power factor correcting devices introduce harmonics Type 1 to Type 4 of the wind turbine models have different harmonics models [52]-[54]. 5th, 7th, 11th, 13th, and 17^{th} are the most common harmonics injected from wind turbines [55]. PMSG based wind turbine generator with of 2 kHz to 150 kHz frequency range can lead to malfunctioning of communication in power lines [56]. Active Filter [57] and energy storage devices [58] are used to mitigate the harmonics from the wind turbine to the grid. Converter based wind turbine is combined with the filter that mitigates the current harmonics in the wind turbine integrated power system [59].

6. SUB SYNCHRONOUS RESONANCE MITIGATION TECHNIQUES

There are three major types of SSR damping available in the literatures published and they includes, flexible AC transmission system (FACTS) [60], [61], existing HVDC links [62] and modified DFIG controllers [63], [64]. Since economic SSR damping will be an important criterion for any power electronics engineer modification of DFIG controller is a better option for the SSR mitigation implementation. Both the RSC and GSC mentioned in Figure 1 can be used to control the SSR or damping SSR. Stability can be brought intact by tweaking the controllers meant for both RSC and GSC. GSC based SSR damping is implemented in [11], [14]. Both the implementation stressed on controlling the voltage across the series capacitor used for line compensation as used in Figure 2 'V_{cg}' for SSR damping. Estimators were used to obtain the series capacitor voltage to develop the SSR damping using the GSC. RSC based SSR damping is detailed in [15], [17], [21], [22]. RSC based SSR damping is the most preferred controller since the SSR damping can be implemented for higher dynamic conditions. GSC and RSC both are used in few of the literature [16], [63]. Pour and Santi [21] linear quadratic regulator (LQR) is used for adjusting the complex gains for damping the SSR. Instead of aligning with the stator voltage an observer is used to align the dq axis with the grid voltage vg thus reducing the SSR. Knowledge of grid impedance parameter knowledge is important for the estimation of grid voltage. Narendra *et al*. [15] RSC based damping controller is developed that controls the stator and rotor current to damp the SSRs. Although the control depends on the grid impedance parameters the RSC based controller has performed well compared to the reactive current reference based GSC controller. The phase compensation implementation [17] with the gain control is applied for damping action. Active power is phase compensated and filtered with the band pass filter to act on the desired range of frequencies. Leon and Solsona [22] virtual resistor in series with stator and virtual inductance in series with rotor winding. A proportional and derivative action is combined here that acts as a high pass filter thus damping the SSR. The notch filters at GSC DC-voltage control loop are adopted [63] or in RSC's inner current loop. A Line impedance compensation level if varied all the above methods may not respond and work for damping the SSR. A method that depends on the line impedance compensation level is adopted in [10]. Transfer function-based method is introduced with the phase locked loop (PLL) which affects the system stability. Frequency response analysis for open loop is used to obtain the dynamic of instability and apply the damping control.

7. MULTIFREQUENCY OSCILLATION -LARGE SCALE WIND POWER INTEGRATION

Apart from the SSR discussed in the previous section there are other oscillation issues which are evident when DFIG based WECS is introduced in the power system. Different oscillation issues that get introduced in the power system with the DFIG based WECS include high frequency resonance, super - synchronous oscillations, Shafting Torsional oscillations. The significant discussion is presented about SSR implementation in the previous section thus, this section will deal about the other oscillation issues.

7.1. Shafting torsional oscillations (STO)

Mass blocks of the turbine in the DFIG based WECS interact with each other to create the torsional vibrations. Tortional vibrations thus caused introduce a 1.4Hz oscillation components in the generator speed, torque generated from the turbine and electromagnetic torque generated from the generator. This process is called the STO. Drive shaft continues to tighten and relax because of which the damage is observed in the turbine mechanical shaft. Low frequency oscillations and the STO resonates between them to create even worse instability in the WECS system.

7.2. High frequency resonance (HFR)

The occurrence of the HFR is evident in a wind farm in Germany [65]. Interaction of power electronics involved in the voltage source converter (VSC)-high voltage DC (HVDC) system along with the AC grid introduced the HFR. The HFR is in the range between 250Hz to 350Hz. The LCL filters are used instead of the traditional L filter used in the GSC since its lower cost and better filtering capacity. Since LCL filter is a third order multivariate system where resonance is introduced to the GSC from the filter. Power system which is compensated using shunt capacitors for power factor enhancement when connected with the DFIG based WECS introduces HFRs. Condition of HFR usually occurs when the weak grid condition prevails which lacks the grid inertia. The range of this HFR frequency is found to be between 300Hz to 2000Hz discussed in the publication [66], [67]. Figure 9 shows the HFR evaluation using impedance analysis.

Analysis of the HFR is carried out using the impedance analysis as discussed in [68]. A shunt compensated grid system is modeled using the impedance modeling and defined as Z_{SYSTEM} and the DFIG WECS with both RSC and GSC is modeled using impedance modeling and defined as Z_{DFIG}. It is also discussed in [69] that when the LCL is decided unreasonably there is a HFR between the rotor part and the grid part of the DFIG. Phase frequency characteristics of the power system is affected when the hysteresis controller of the DFIG system is unstable and this analysis is found by discrete control action [70]. The Wide control bandwidth of the Wind turbine's GSC also introduces HFR as discussed in [71].

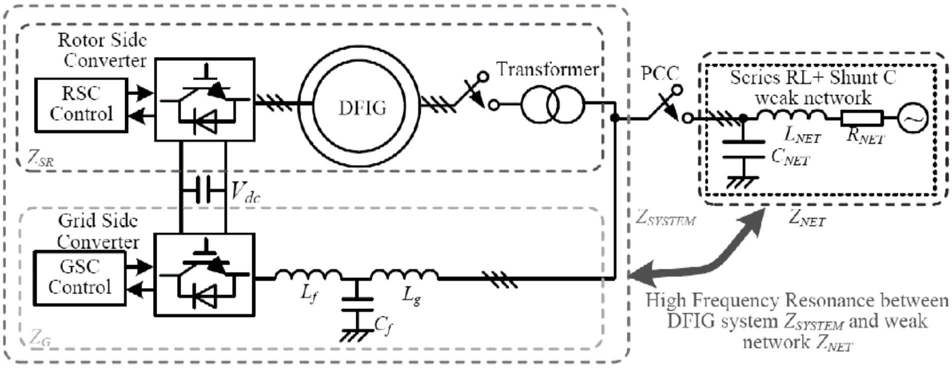

Figure 9. HFR evaluation using impedance analysis

8. MULTIFREQUENCY OSCILLATION -ANALYSIS METHODS

Linearized average models of the system is developed for the power system and the steady state values of all the state variables are gathered. Using the steady state values of the state variables the eigen analysis is carried out that clearly evaluates the stability or instability in the power system as discussed in [72]. The Real part of the eigen value mentions the describes the oscillation stability while the imaginary part of the eigen value evaluate the frequency of oscillations as discussed in [73], [74]. Eigen value sensitivity and participation factors [75] detects the parameters that affect the oscillation mode and also by checking the eigen values locus moving trend [76], [77]. For the eigen analysis process the complete modeling of both the electrical and mechanical blocks of the system must be included. Frequency scanning method is obtained by generating multiple frequency of current and injecting in the generator side and screen the resonance threat in the system. The method is discussed in [78]. Combination of both the Eigen value analysis and the frequency scanning method is termed as complex torque coefficient method. Both electrical and mechanical modeling of the wind turbine is utilized and separately analyzed complex torque coefficient is obtained for both the electrical and mechanical model by scanning the frequencies. This method is used primarily for finding the STO in the wind turbines and discussed in [79], [80]. Same method is used for developing the mitigation measures for the oscillations by developing the damping controller [81]. In few incidents it is also used for damping the sub-synchronous oscillation (SSO) [82]. Equivalent model has been developed for the different components of the wind turbine and are used to develop a single complete model for further analysis is the Time domain simulation analysis method. Wind turbines, power electronics involved and the grid components developed as equivalent model and then integrated to get the complete time domain model. Integrating the differential equations defining the complete power system time domain curves of different variables involved is observed in the analysis [83]. Impedance based models are utilized for analyzing the SSO and HFR due to the wind power integration with the grid in the system as discussed in [19], [84]. Harmonic linearizing [19] or state space method [85] is used to obtain the impedance model of the system in a static reference frame either using the positive or negative sequence impedances. After creating the impedance model, which is two order matrices, the stability is found by introducing the Gershgorin theorem, general Nyquist criteria, or evaluating zeros at certain range of the impedance matrix [86]. While at the same time if the impedance matrix is a decoupled expression, then an equivalent circuit is obtained and stability is analyzed using the damping stability criterion and also the intuitive physical meaning [84]. Although neglecting few control loops affect the accuracy of stability criteria by considering the actual operational conditions would improve the accuracy.

8.1. Mitigation of shafting torsional oscillations (STO)

Mitigating STO is dealt using two major methods, one is adding virtual inertia controller or the additional damping controller. A control loop that controls the active power to damp the oscillations and improves the STO damping is called the additional damping controller [87]. Two control loops one is electrical damping and the other is the electrical stiffness control is used for the shaft stabilizers [88]. Electrical stiffness coefficients and the electrical damping coefficients are used to control the damping characteristics in the STO situation. Virtual inertia controller uses the technique of controlling the electromagnetic torque generated from the turbine while a resonance occurring in the shaft. If found that the STO is due to resonance then the electromagnetic torque is adjusted to move the frequency to another value [89]. This change in frequency escapes the resonance and thus the STO. Inertia based control is discussed in damping the STO in [90]. Al though Sub-synchronous oscillations are applied using the control of both the GSC and RSC in the previous sections the SSO damping using the FACTS devices also is used extensively in the researchers.

8.2. FACTS based oscillation reduction

The stochastic nature of the power electronic converters is exploited to obtain higher performance in the transmission lines that can enable it to work near to its thermal limits. The switched converters are capable of producing different voltage amplitudes, with different phase delay, frequency and can also absorb or inject real and reactive from and to the transmission line while a DC input is either from a source or a storage unit. The stochastic nature of the voltage source converter is exploited to obtain the desired condition of power which makes up the flexible AC transmission systems (FACTS) Controllers. The SSO is damped by introducing the SVC [91] at the point of common coupling as shown in Figure 10. Wind generation and the series compensation levels is considered to be unchanged for the oscillation damping implementation. SVC is introduced with the damping controller that converts the shunt compensation into the oscillation damping controller.

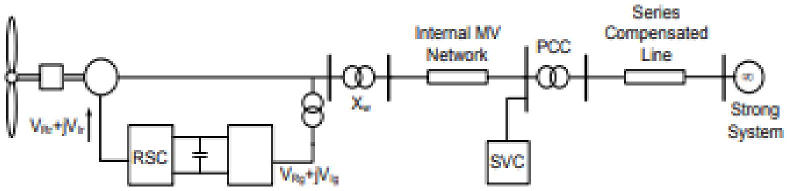

Figure 10. SSO Damping using SVC

The rating of the SVC is kept to very low power such that the purpose of the SVC is only to compensated for the SSO damping. Design of the damping controller needs to be carefully designed for this purpose. Performance comparison of two FACTS devices series static synchronous compensator (SSSC) and series vectorial compensator (SVC) are discussed in [92] with synchronous generator-based wind farm connected to the grid. Both Mechanical and the Exciter mode of the permanent magnet synchronous generator (PMSG) is tested for damping controller that is applied by properly designing the SSSC and SVC. Same complex plane is used for both the frequency domain eigen analysis and time domain based nonlinear model simulation. It is concluded that SVC offer a better damping action as compared both the mechanical and exciter mode. SSSC based damping controller in a multimachine system with WECS penetration is developed for damping observed in the system with short circuit occurrence in the system. Adaptive neural fuzzy inference system (ANFIS) based damping controller is used for a nonlinear system model with the time domain system model. SSSC controlled using the ANFIS controller proved to be effective in damping oscillations [93]. SSR or SSO reduction using the FACTS devices are discussed in the literature [94] which compares the performance of both SVC and thyristor-controlled series capacitor (TCSC) in damping. A self-excited induction generator based WECS connected to the grid is applied with each of the FACTS devices considered for comparison of damping performance. It is observed that TCSC is found to be bettered among the FACTS devices in damping SSR when a closed loop current control is applied on the device. Both normal and faulted conditions [94] are considered for checking the oscillation damping performance while SSSC is used in the WECS penetrated grid system. Inclusion of SSSC has shown a larger participation factor with the wind turbine generators in damping the oscillations.

8.3. Various controls in action

By using the appropriate controller, the wind turbine can be controlled to reduce the structural oscillations [95] the classical proportional integral and derivative controller (PID) is compared with full state feedback controller and input-output pole placement controller. The UPFC is one of the best devices used to damp the oscillation. The UPFC [96] is used for off-shore wind and seashore wave farms to damp the oscillations [97]. UPFC is used for mitigation of sub-synchronous resonances. And also, the damping performances are compared with dynamic simulations. The multi damping controller is proposed in [98], which uses the power system stabilizers (PSS), static var compensator and DFIG oscillation damper. The dynamic simulation results shown in [98] shows the performance comparison. The UPFC is used to enhance the damping with PI control, fuzzy control [99], robust finite time control [100], and add-on self-tuning control [101]. To maintain the supply and demand in power system, when the wind farm is highly penetrated by using the UPFC with adaptive fractional integral terminal sliding mode power controller [102] and a novel damping controller in DFIG [103], [104] are developed.

9. VARIOUS OPTIMIZATION IN POWER SYSTEM OSCILLATION DAMPING

To damp the low frequency oscillation the bacterial foraging algorithm (BFOA) is used in SSSC controller for single machine infinite bus system (SMIB) in [105]. The same technique is used for lead-lag compensator which uses the time-based objective function. Gravitational search algorithm (GSA) is used for same above said problem in [106], [107]. The hybrid algorithm of particle swarm optimization (PSO) with BFOA is used for the same problem in [108]. Here the lead lag structure and control gains are optimized. This hybrid PSO-BFOA is used in Lozi map based chaotic optimization algorithm is discussed in [109]. Then the multi-objective genetic algorithm is used in [110], [111] in SSSC controller for minimization of power angle, voltage and power flow time deviations. The Table 1 shows the various optimization techniques and objective functions used in the literatures.

All FACTS devices are meant for different parameter control which is defined in Table 1. The voltage, angle, real power and reactive power are controlled by using the different controllers in order to get an oscillation damping in all parameters. Other oscillation damping algorithms that are similar to the previously discussed methods are published in different publications [112]-[132] which has similar methodologies that are discussed in the previous sections.

Table 1. Comparison of various optimization and objective function for power oscillation damping

Paper	Technique	Objective function	Description
[105]	BFA	$J = \int_{t=0}^{t=t_1} [\lvert\Delta\omega(t,X)\rvert]t.dt$	Δω (t, X) denotes the rotor speed deviation for a set of controller parameters X (note that here X represents the parameters to be optimized, i.e., the parameters of the SSSC controller), and t1 is the time range of the simulation. With the variation of the parameters X, the Δω (t, X) will also be changed.
[106]	GSA	$J = \int_{0}^{t_1} t\lvert e(t)\rvert dt$	Where, 'e' is the error signal (⊗) and 1t is the time range of simulation.
[107]	GSA	$J = \int_{t=0}^{t=t_1} (\sum \Delta\omega_L + \sum \Delta\omega_1)\, t.dt$	where, $\Delta\omega_L$ and $\Delta\omega_1$ are the speed deviations of inter-area and local modes of oscillations respectively and t_{sim} is the time range of the simulation.
[108]	Hybrid PSO+BFOA	$J = \int_{t=0}^{t=t_1} [\lvert\Delta\omega(t,X)\rvert]t.dt$	Δω (t, X) denotes the rotor speed deviation for a set of controller parameters X (note that here X represents the parameters to be optimized, i.e., the parameters of the SSSC controller), and t1 is the time range of the simulation. With the variation of the parameters X, the Δω (t, X) will also be changed.
[109]	Hybrid PSO+BFOA	$J = \int_{t=0}^{t=t_1} (\sum \Delta\omega_L + \sum \Delta\omega_1)\, t.dt$	where, $\Delta\omega_L$ and Δω1 are the speed deviations of inter-area and local modes of oscillations respectively and t_{sim} is the time range of the simulation.
[110]	ILCOA $J = \int_{t=0}^{t_{sim}} t.\lvert\Delta\omega\rvert.$	$J = \int_{t=0}^{t_{sim}} t.\lvert\Delta\omega\rvert.dt$	where Δω denotes the rotor speed deviation of the generator and t_{sim} is the time range of the simulation
[111]	GA	$F = (F_1, F_2, F_3)$ Where $F_{1=} \int_{t=0}^{t=t_{sim}} (\Delta\delta.t)dt$ $F_{2=} \int_{t=0}^{t=t_{sim}} (\Delta V_T.t)dt$ $F_{3=} \int_{t=0}^{t=t_{sim}} (\Delta P_L.t)dt$	Δδ, ΔVT and ΔPL denote the rotor angle, terminal voltage and tie-line power flow deviations with respect to time, and t_{sim} is the time range of the simulation.

To Mitigate sub synchronous integration (SSI) in DFIG based wind farms, supplementary modulating control signal, is added in GSC, full scale frequency converter (FFC) and the HVDC onshore MMC [112]. The detailed model used [112] captured SSI at 50%,60% and 70%. The efficacy of the different supplementary regulation methods is checked by time domain studies. The Stability of the wind energy conversion based on DFIG connected to a series compensated line is analyzed [113], [114] considering the dynamics of the components of DFIG and Wind turbine. The rotor side current control methods show the most substantial impact on the system stability. The sub synchronous control interaction (SSCI) and torsional interaction (TI) have discussed [116] frequency scanning method, calculation of electrical damping by test signal method, electromagnetic transient (EMT) analysis. The presence of SSCI is confirmed by collectively using the first and third methods. The different risks of SSTI are identified using EMT analysis. The analysis and mitigation of Sub synchronous interaction is presented in [118]. Where the state variables are identified by using participation factors which involved in interaction, mitigation method is determined by controllability indices.

Damping oscillations, inner turbine oscillations in grid connected wind power generation system are reviewed [119]. Wind turbine torsional dynamics interaction with the active, reactive power modulation in Wind energy conversion system based on DFIG is analyzed [120]. Implementation of static and dynamic performance at different operating conditions for the optimization of controller parameters of MSC and GSC are explained [121]. Eigen structure assignment method [122] is designed and implemented with the controller of Wind energy conversion system based on DFIG which works for the purpose of power system stabilization, active damping controller. Supplemental damping controller is implemented in order to incorporate and to compensate for the phase lag caused by the rotor voltage input. To enhance the damping in the system, Power oscillation damping controller is also designed and implemented [123]. Coordinated control of wind farms based on DFIG for power oscillation damping is highlighted [124]. The consequence of changing synchronous generator combined with the power system stabilizer by a DFIG on different modes and mode shapes are also investigated. Modified small signal stability analysis SSSA [125] is incorporated in order to handle the probability density function of wind power output. Optimization problem is solved and damping controller parameters is found out by using particle swarm optimization (PSO) method. The effect of SSR [128] in DFIG based wind energy conversion system is studied using simple model and stability of the system is analyzed using bifurcation method [126]. Power system sub synchronous oscillation damper is designed and implemented [127] for the mitigation of SSCI.

To improve the operating range and to damp sub synchronous oscillations (SSO) of wind farms with series compensator is studied with supplementary damping control [128], [129]. SSR is mitigated using novel auxiliary damping controller (ADC) [100]. The performance of the ADC is effective with minimal additional cost under different operating conditions. Voltage source converter based HVDC line is implemented as a closed loop interconnected model and remaining part of the power systems are demonstrated as two open loop system. Sub synchronous oscillation [129] in the power systems caused due to the open loop modal coupling. The Sub synchronous interactions in AC power system with multi terminal DC network is examined using open loop modal analysis [130] which reveals that strong SSI is introduced by the selected Voltage source converter in an open loop condition in turn reduce the damping of SSOs. Sub synchronous interactions induced by wind power system based on DFIG without series compensated transmission lines is studied [131] using closed loop interconnected dynamic model and two open loop subsystems. When Open loop modal resonance is strong, generator causes the poorly damped SSO's in power system. Wind farms with series compensation protected against unstable Sub synchronous control interactions is analyzed [132] which consists of centralized protection coordinator and distributed protection relays. Different oscillation reduction techniques are also detailed in survey carried out and the inferences from those publications are discussed.

10. CONCLUSION

The method of wind power generation and the problem associated with the grid when integration is done has been presented in detail. Oscillation is generally introduced in wind integrated system and found they are found to be more severe when the connected to grid system. The detailed analysis of various methods that are used for detecting the different oscillation parameters from different researchers have been presented. The problems due to this are found to be severe, When the mitigation techniques that are need to be adopted for damping the oscillation problems are discussed from recently published research work. The overall power quality issues depend on disturbances that get introduced while the wind energy system integrated to the grid is discussed in the paper with the issues like the sub-synchronous resonance and the oscillations in the line. Few literatures have implemented the methods through which we can mitigate the power quality disturbances with the WECS integrated to the grid. The series compensation techniques that can reduce this voltage and SSR is discussed in detail. The detailed literature survey is carried out on the topics of power system oscillation and damping using the FACTS devices for wind power generation. The advantages and shortcomings are presented in this paper. This paper able to provide better insight to focuses the reader to have an overview of the power system oscillation damping control in wind power generation. Also, the paper shows that there is a gap between the usage of recent new mathematical controller and the optimization techniques. The UPFC is costlier than SSSC since it requires two converters. The SSSC is found to be capable of solving the problem like oscillation using only one converter. Which implies the advantage of the controller as compared to other existing controlled.

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