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Determination of Sub Synchronous Control Interaction between Wind Turbines and Series Compensated Transmission Lines

Anitha Sarah Subburaj*‡, Sandeep Nimmagadda**, Islam Atiqul***, Stephen B. Bayne****

* School of Engineering, Computer Science & Mathematics, West Texas A&M University, Canyon, TX-79016, USA
** Department of Electrical & Computer Engineering, Texas Tech University, Lubbock, TX-79409, USA
*** Department of Electrical & Computer Engineering, Texas Tech University, Lubbock, TX-79409, USA
**** Department of Electrical & Computer Engineering, Texas Tech University, Lubbock, TX-79409, USA

(asubburaj@wtamu.edu, sandeep.windenergy@gmail.com, atiqulwindenergy@outlook.com, stephen.bayne@ttu.edu)

‡Corresponding Author; Anitha Sarah Subburaj, School of Engineering, Computer Science & Mathematics, West Texas A&M University, Canyon, TX-79016, USA, Tel: +91 806651 5246, asubburaj@wtamu.edu

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Abstract- In this paper, a modified frequency impedance scanning tool is developed to scan wind turbine side impedance at various frequencies. Voltage harmonic injection technique by retaining the fundamental frequency is used to determine the impedances at any given subsynchronous frequencies. Additionally, the tool is designed to incorporate the entire frequency range of interest in a single simulation rather than the traditional multi-run or looped frequency scanning techniques. The principle of frequency scanning analysis is used to determine the risk of sub-synchronous control interaction (SSCI) before an interconnection of wind farm. The tool measures the impedance of non-linear models containing power electronic devices (such as wind turbines) at sub-synchronous frequencies (SSF). The tool is validated with a passive RLC circuit at a known resonance frequency in PSCAD and also for non-linear systems consisting of representative Doubly Fed Induction Generator (DFIG) wind turbine model and a designed SSCI test grid. The tool developed is used to determine the behaviour of a representative DFIG wind turbine at sub-synchronous frequencies and its susceptibility to SSCI events under various operating conditions. Sensitivity of various wind parameters at wind farm level on the impedance exhibited by the wind generation plant is studied.

Keywords: Sub-synchronous control interaction; series compensation; wind turbine; frequency impedance scanning tool.

1. Introduction

Series compensation is widely used in today's transmission system to improve the stability and voltage controllability of the network. Some of the well-known problems with series capacitors are sub-synchronous resonance (SSR) issues and induction generator effects (IGE). The electrical properties of the machine resonating with the system at sub synchronous frequencies are called Induction Generator Effects (IGE). The effects are solely due to the electrical phenomenon with no mechanical components. They affect wind and fossil generators. They cause self-excitation because the synchronous motor circuit acts like an induction generator at subsynchronous frequencies. The effective slip can cause negative resistance, hence negative damping. The effects can result in rapidly growing currents or voltages. In order to minimize such effects, it is recommended that wind turbine generator suppliers be required to provide the impedance characteristics (frequency range of 0 Hz to 120 Hz in 1 Hz) of their machines when looking into the wind farm from the system. Higher frequencies may be needed for other types of harmonic impedance calculation studies and should also be provided up to approximately 1 kHz [1- 2].

The first SSR event occurred in Mohave generating plant in 1970 when the multi-mass synchronous generator interacted with 50% series compensated transmission line leading a hole burnt in the generator shaft due to increasing torque oscillations. Recently, in 2009 similar interactions were found to occur between the devices with power electronic controls in wind turbines and series compensated transmission lines at sub-synchronous frequencies and is called as sub synchronous control interactions (SSCI) leading to instability. The interactions occurred in two wind farms in Electric Reliability Council of Texas (ERCOT). Both the wind farms suffered numerous crowbar failures due to increased current oscillations.

The resonant conditions can lead to severe system over-voltages, un-damped oscillations, and instability, all of which have the potential to cause cascading outages and equipment damage. The power electronic equipment connected in a radial series-compensated configuration is particularly susceptible to stability issues due to self-excitation of induction generator with increased level of series compensation. Following a static wire initiated fault, the two wind farms at ERCOT with a capacity of 485 MW were left in radial connection with a 50% compensated transmission line. Within 200 milliseconds, sub synchronous oscillations grew and the voltage reached 195% of the nominal value causing damage to the crowbar circuit in the wind turbine and tripping of additional transmission facilities. Finally, the Sub synchronous oscillation was cleared by bypassing the series capacitors after 1.5 seconds. SSCI is a highly technical issue that has been found due to grid integration of wind turbines, and has gained high importance particularly in ERCOT since 2009 [1-8]. The details of the event are discussed in reference [9-10].

Wind turbines are connected to the grid through power electronic devices making it a controllable power source which can be represented as a constant power source in series with controllable impedance. The value of the impedance depends on various parameters such as controller constants, induction generator parameters etc. Therefore, the resonant frequency of a wind turbine varies with the physical parameters of the turbine, controller parameters and operating conditions such as active and reactive power output (thereby making SSCI a highly manufacturer dependent issue), and wind speed. The resonant frequency exhibited by the turbine under certain conditions might match with the resonant frequency of the series compensated transmission line leading to SSCI.

The first and foremost step to prevent SSCI is to perform a resonant frequency scan for the wind turbines. The study should include a set of all possible operating scenarios of the turbine and mitigation techniques should be implemented if an interaction is found to occur in the detailed study.

In this paper, a modified frequency impedance scanning tool is developed to scan wind turbine side impedance at various frequencies. Voltage harmonic injection technique by retaining the fundamental frequency is used to determine the impedances at any given Sub-synchronous frequencies. Secondly, the tool is designed to incorporate the entire frequency range of interest in a single simulation rather than the traditional multi-run or looped frequency scanning techniques. Finally, the tool is optimized and validated for non-linear systems consisting of representative DFIG wind turbine model and a designed SSCI test grid.

2. Background and Literature Review on Existing Frequency Impedance Scanning Tools

Two common techniques that are used to perform resonance studies are Eigen value analysis or by injecting harmonic frequencies in the system to measure the impedance. As wind turbines are highly non-linear, Eigen value analysis is not applicable to study SSCI. Turbine side and grid side impedance frequency scans are required to be conducted in order to check if a resonance condition is leading to an unstable system [1-8]. Currently available software's in the market are limited to perform frequency impedance scans for linear devices such as transmission systems that can be represented with passive elements. The software's do not possess the capability to run frequency impedance scans for non-linear equipment and systems [10, 11]. The nonlinear equipment's include power electronic devices with controls such as Flexible Alternating Current Transmission System (FACTS) devices, High Voltage Direct Current (HVDC) transmission systems and wind turbines. Several methods to develop frequency impedance scanning tool using harmonic injections are proposed in the literature.

The analyses related to the effects caused when synchronous generators are placed near a series capacitor when the mechanical mass resonates with the effective impedance of the system are called Sub-Synchronous Resonance (SSR) studies. Nath et al conducted a SSCI study in reference [12] using an IEEE second benchmark model for SSR studies with wind farms consisting of Type 3 and Type 4 wind turbines.

The Type 3 turbine is known commonly as the Doubly Fed Induction Generator (DFIG) or Doubly Fed Asynchronous Generator (DFAG), which has the variable frequency ac excitation added to the rotor circuit. The excitation is supplied through the slip rings by a current regulated, voltage-source converter that has instantaneous rotor currents' magnitude and phase adjustment. The rotor-side converter is connected with a grid side converter back-to-back, to exchange power directly with the grid. Some of the characteristics of Type 3 turbine are as follows:

- A small amount power injected into the rotor circuit can affect a large control of power in the stator circuit.
- It offers the benefits of separate real and reactive power control, similar to a traditional synchronous generator, while being able to run asynchronously.
- Even under significant grid disturbances, the torque producing components of the rotor flux can be made to respond fast enough that the machine remains under relative control.

The Type 4 turbine offers a great flexibility in design and operation as the output of the rotating machine is sent to the grid through a full-scale back to-back frequency converter. The rotating machines of this type have been constructed as wound rotor synchronous machines, with control of the field current and high pole numbers. Some of the characteristics of Type 4 turbine are as follows:

- Turbine is allowed to rotate at its optimal aerodynamic speed. The gearbox may be eliminated, such that the machine spins at the slow turbine speed and generates an electrical frequency well below that of the grid.
- The inverters convert the power, and offer the possibility of reactive power supply to the grid [11].

Frequency impedance scan was used to perform the SSCI study in reference [12] but the details of the scanning tool were not discussed. It was shown that type 3 wind turbines are more vulnerable to SSCI and type 4 wind turbines are immune to SSCI even at high series compensation levels [12]. Sahni et al provided screening guidelines for potential SSCI scenarios in reference [13]. This is done by identifying the critical system conditions which are assessed using frequency impedance scanning technique. Current harmonic injection technique is used to perform the frequency impedance scan [13]. In [14], Suriyaarachchi et al provides a comprehensive approach to detect SSCI using both frequency scanning analysis and detailed Eigen value analysis. However, in reference [14] a linearized model of DFIG wind turbine is used for both the methods. This might impact the generalization of results obtained in the paper as the linearization is heavily dependent on the converter controls which is different for each wind turbine manufacturer. Cheng et al presents reactance cross over technique in reference [15] to detect SSCI for wind farms involving DFIG wind turbines. A mathematical formulation for the frequency impedance relationship of the network and the wind plant is provided in reference [15]. Current harmonic injection technique is used for obtaining frequency impedance scans considering the non-linearity of the wind turbine.

In most cases, the harmonic current injection technique is used without considering the fundamental frequency component. The controllers in the wind turbine are designed for a narrow bandwidth around the fundamental frequency. Hence, the wind turbine impedance scanned in the absence of fundamental frequency [16] might not represent a real time SSCI scenario, in which both Subsynchronous and fundamental frequency components are present. Moreover, current injection techniques are not preferred for all wind turbines as voltage oriented reference frame is used in the vector control for machine side and line side converter.

Secondly, the turbine model is simulated several times in a loop by increasing the frequency in small steps for the range of SSF of interest. This requires a lot of computation and time, in addition to the large number of scenarios considered for the wind turbine, which is unavoidable.

3. Proposed Frequency Tool

The algorithm and the implementation of the frequency tool are discussed in this section. The tool is optimized to conduct frequency vs impedance scans for wind farms and wind turbines [17-21]. Harmonic current injection technique might lead to stability issues or convergence problems in the simulator as discussed in the previous section. Hence, the first requirement is to retain the fundamental voltage component and add the sub-synchronous component as a small deviation or harmonic to the existing fundamental frequency. The deviation in output from the fundamental is calculated from the measured signal (has both fundamental and SSF component) thereby estimating the impedance for the corresponding SSF. The second requirement is to build a source which can output the range of SSF of interest in a single simulation by increasing the phase angle of the signals at regular time intervals. The algorithm developed with the above requirements and the software implementation of the tool is discussed in the following sub-sections.

3.1. Algorithm of the frequency impedance scanning tool

The frequency impedance scanning tool developed is based on voltage harmonic injection to the existing fundamental frequency input. The overall block diagram and simulation set up to connect the frequency tool to the system (such as wind farm) whose impedance (Z) at various sub-synchronous frequencies (SSF) needs to be measured is shown in Fig.1.

The tool mainly consists of two parts which include:

1. Building a three phase harmonic signal generator with amplitude A, frequencies ranging from f0 to fn increasing in steps of fstep, and with each frequency for a time period of Tp. The major challenge in building this source is to maintain the phase continuity when the frequency increases from one time step to next.

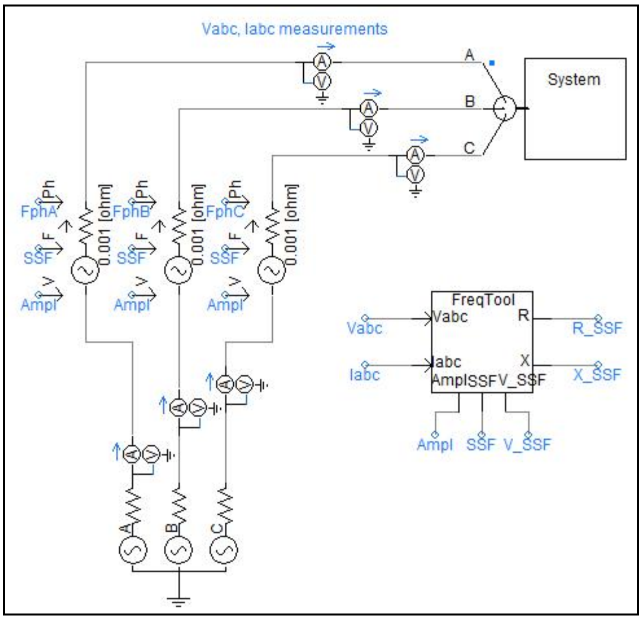


Fig.1. Simulation set up to connect the tool to the system to perform Z Vs F scan

2. Extracting the SSF component of current from the measured current signal at wind turbine bus, to calculate the impedance at respective frequency. The block diagram of three phase harmonic generator and the impedance calculation block is shown in Fig. 2 and is discussed in more detail in the following sub-sections.

3.1.1 Three phase harmonic signal generator

The algorithm for three phase harmonic generator is briefly described as follows:

Step 1: Start frequency (freq_start) , stop frequency (freq_stop), step increase in frequency (freq_step), amplitude of the harmonic wave generated (Amplitude) and time period in between two frequency steps (Time period) are given as an input to the generator.

Step 2: If variable frequency voltage source is not available in the software library, a step increase in frequency might lead to a phase discontinuity in the injected harmonics. Hence, the following three rules must be satisfied by the given input in order to maintain phase continuity before and after step increase in frequency.

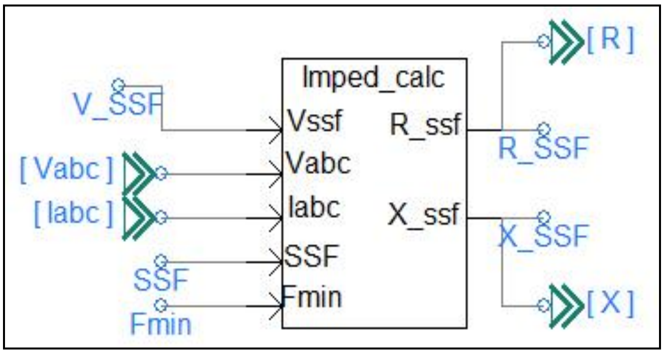


Fig. 2.a. Block diagram of harmonic signal generator

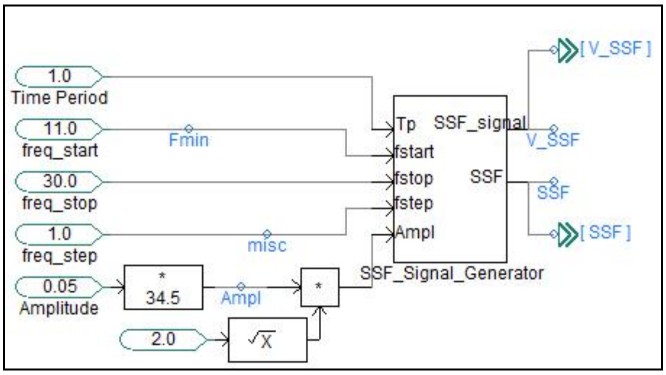


Fig. 2.b. Block diagram of impedance calculation block

Freq_inital = (n* fstep), where n is a whole number

Time period = (k / fstep), where k is a natural number

Freq_final = (c * fstep), where c is a whole number and c > n

Building the three phase signal harmonic generator is very simple in PSCAD compared to SIMULINK due to the availability of "amplitude/frequency/phase modulator" built in block in PSCAD master library. Therefore, the step increase in frequency after a certain time period is directly given to the each block to generate a three phase variable frequency harmonic signal.

Step 3: The frequency is determined at every time instant given the time period for each SSF, initial frequency and frequency step. The frequency remains constant in a given time period and does not vary linearly as in the case of chirp signal available in SIMULINK.

$$F_{calc} = f_{inital} + \frac{T_s - mod(T_s, T_{step})}{T_{step}} \qquad (1)$$

The frequency is reset to its initial value once F_calc is greater than Freq_final using a comparator. The output signal in each phase is shown in Fig. 3.

Step 4: The three phase voltages of amplitude A are calculated for the given frequency as given by equations (2) to (4).

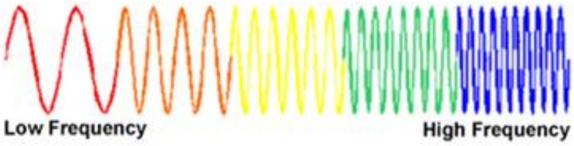


Fig.3. Variable Frequency signal

Step 5: The 3 phase output signal is given to a controlled voltage source which is connected in series to the fundamental voltage source as shown in Fig. 1.

$$ph\ A = A * \sin(\ 2\pi F_{calc} T_s - \ 0) \qquad (2)$$

$$ph\ B = A * \sin(\ 2\pi F_{calc} T_s - \frac{2\pi}{3}) \qquad (3)$$

$$ph\ C = A * \sin(\ 2\pi F_{calc} T_s + \frac{2\pi}{3}) \qquad (4)$$

Step 6: The amplitude of the harmonic signals is usually limited to 10% - 20% of the phase to neutral voltage of the grid in order to avoid exceeding the voltage and current limits of the wind turbine. Further, the output is found to be too noisy if the harmonic signal is too small compared to fundamental voltage.

3.1.2 SSF impedance calculation algorithm

The algorithm for impedance calculation from measured voltage and current signals at wind turbine bus is given below:

Step 1: Three phase harmonic voltage (Vssf), voltage (Vabc) and current (Iabc) measured at bus of interest, sub synchronous frequency (SSF) and starting frequency (fmin) are given as an input to the block a shown in Fig. 2.b. The voltage and current measurements will contain both fundamental and sub-harmonic frequency components.

Step 2: Sub-synchronous voltage angle is calculated using the abc2ab and ab2_M_ang blocks as shown in Fig. 4. Using the reference angle, the measured voltage and current is rotated into DQ at SSF using abc2dq block. The resultant DQ component will have the SSF voltage and currents as DC and fundamental frequency components at (SSF – fundamental frequency).

Step 3: The dc component of the voltage and current signals in DQ reference frame is extracted using DCfilt block. The algorithm used in DCfilt block is a slight deviation from the conventional Fourier transform that is used to detect the harmonics with order greater than one and is shown in Fig. 5.

The first modification is that, (SSF – fund freq) is provided as the frequency input (freq) in Fig. 5 for DCfilt block instead of the fixed fundamental frequency in Fourier transform. Secondly, as (SSF- fund freq) varies with simulation time, the fixed time delay block used in Fourier transform is replaced with variable time delay block in DCfilt. The dc component of the signal in each cycle is obtained by subtracting the signal, with the same signal delayed by one cycle using the variable time delay block.

The variable time delay block does not exist in PSCAD. Hence a user built model for variable time delay block was developed in PSCAD using FOTRAN. Moreover, SIMULINK has a variable time step solver whereas PSCAD has a fixed time step solver. As a result, the difference between signals with and without time delay was not very accurate, particularly for the marginal (R/X around zero) cases and included considerable amount of noise. An algorithm was written (provided in appendix A) to minimize the error to less than 0.5% as shown in Fig. 6.

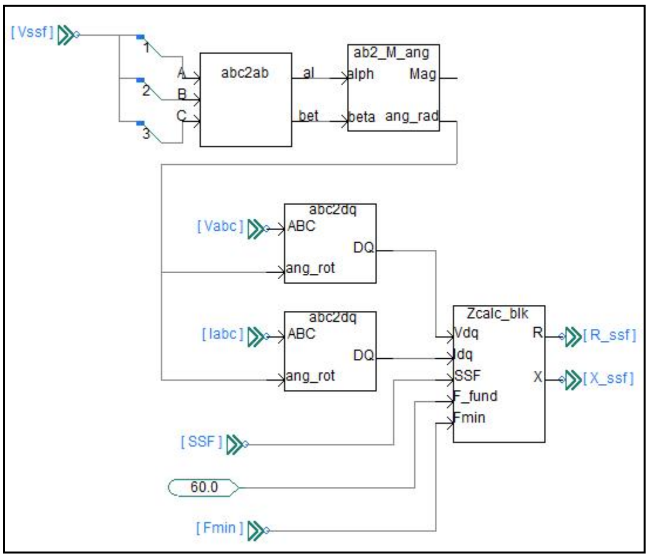
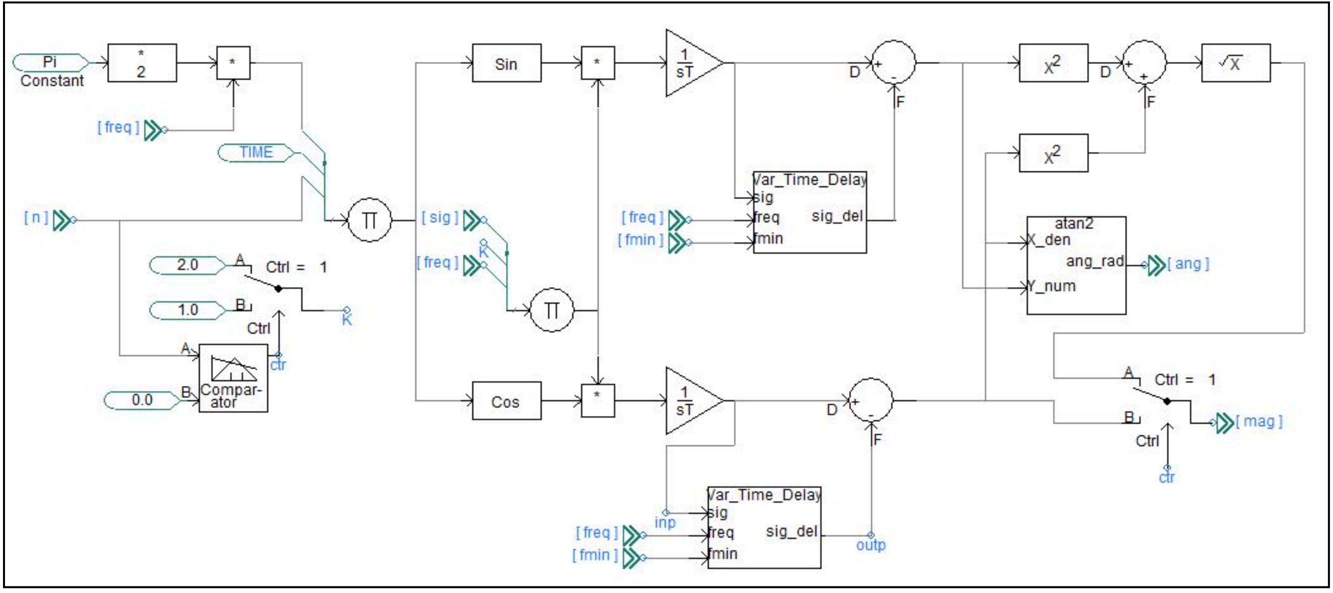


Fig.4. ABC to DQ conversion of measured signals (Imped_calc)

Step 4: The obtained SSF voltage and currents are converted to phasor representation.



Step 5: Resistance and reactance values are calculated using imped block from the obtained voltage and current phasor.

4. Validation of Frequency Impedance scanning tool

4.1. Preliminary Validation with build in model output for a linear RLC circuit

The developed tool is validated with the built in frequency impedance scan model. A simple RLC series circuit with a known sub-synchronous resonance frequency at 20Hz is considered. The harmonic voltage source is connected in series with grid represented by an ideal three phase voltage source.

The resistance and reactance estimation of both the built in model and the developed tool are found to be the same up to the fourth decimal place as shown in the Fig. 7. The built in model uses current harmonic injection technique and the frequency tool developed used voltage harmonic injection technique.

4.2. Validation with a designed SSCI scenario between Wind turbine and test grid

In order to determine the risk of SSCI when a wind farm is connected to a grid, frequency vs impedance scans are required to be conducted at the Point of interconnection (POI) of the wind farm to the grid. The impedance at various frequencies needs to be determined at the POI, for both the wind farm side and grid side.

4.2.1. Wind farm set up

A 30 MW wind farm connected to 110 kV transmission grid is modelled to study SSCI. The wind farm consists of 10 DFIG (type 3) 3 MW wind turbines. An aggregate representation of the wind farm into a single wind turbine is considered as shown in Fig. 8. An equivalent representation of collection system and pad mount transformer is included in the model.

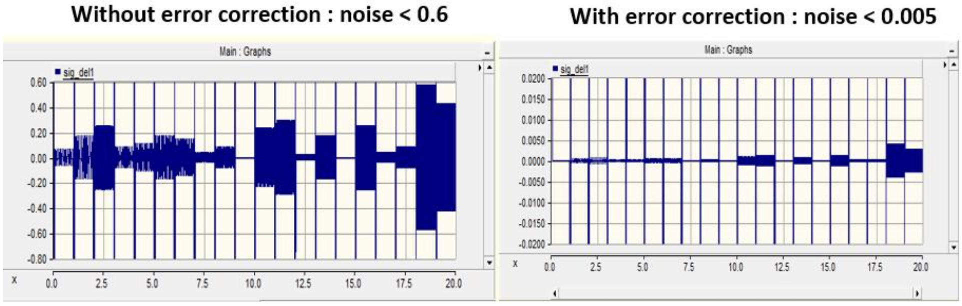


Fig.5. Block to extract the dc component of the measured signal (DCfilt)

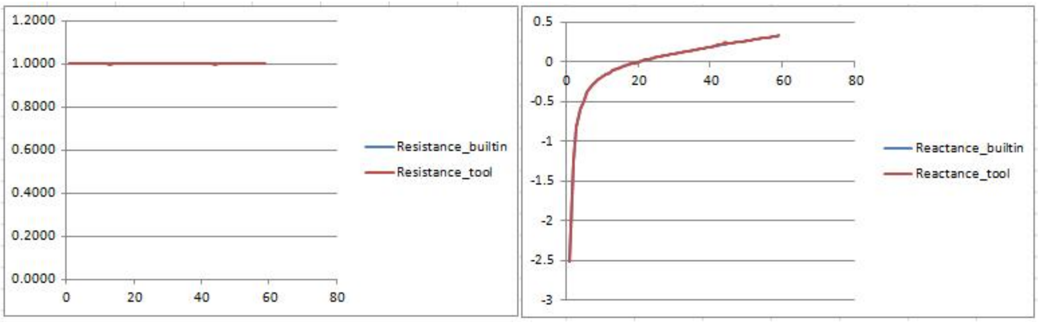


Fig.6. Variable Time Delay with and without block error correction

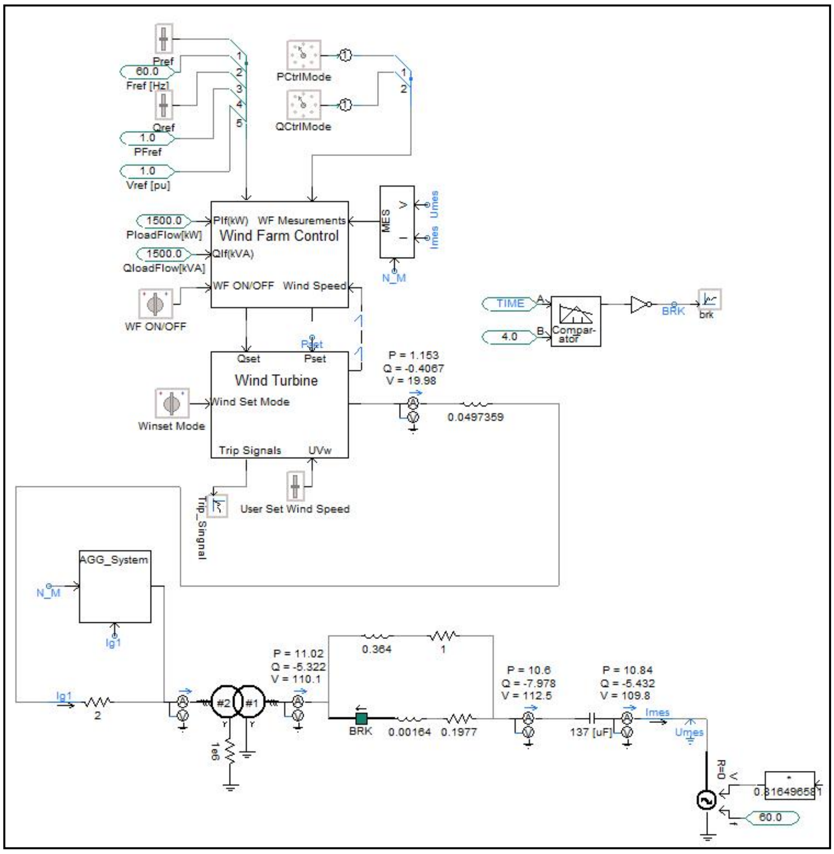


Fig.7. Results from validation of tools with built-in frequency impedance scanning block in SIMULINK

Fig.8. SSCI test grid connected to Frequency impedance scanning tool

The model includes a central controller for active and reactive power control. These controllers send P and Q set-points to the wind turbine depending on substation measurements and the mode of control selected.

For the active power controller there are three possible control modes (parameterPCtrlMode,) as shown in Fig. 8:

Mode 1: No control. Active power control is not active.
Mode 2:Direct active power control. Setting for the desired active power reference in the parameter "Pref" in p.u. as seen in Fig. 8.
Mode 3: Frequency control. Setting for the desired frequency reference in the parameter "Fref [Hz]" in Hz.

For the reactive power controller there are four control modes available (parameter QctrlMode) as shown in Fig. 8:

Mode 1: No control. Reactive power control is not active. In this case, the value introduced in "QloadFlow" will be used in the model.
Mode 2: Direct reactive power control. Setting for the desired reactive power reference in the parameter "Qref" in p.u. (Fig. 8).
Mode 3: Power factor control. Setting for the desired power factor reference in the parameter "PFref".
Mode 4: Voltage control

Setting for the desired voltage reference in the parameter "Vref [pu]" in p.u. The frequency tool connected to the detailed wind turbine model is shown in Fig. 8. The tool is connected to the low voltage side of the substation transformer.

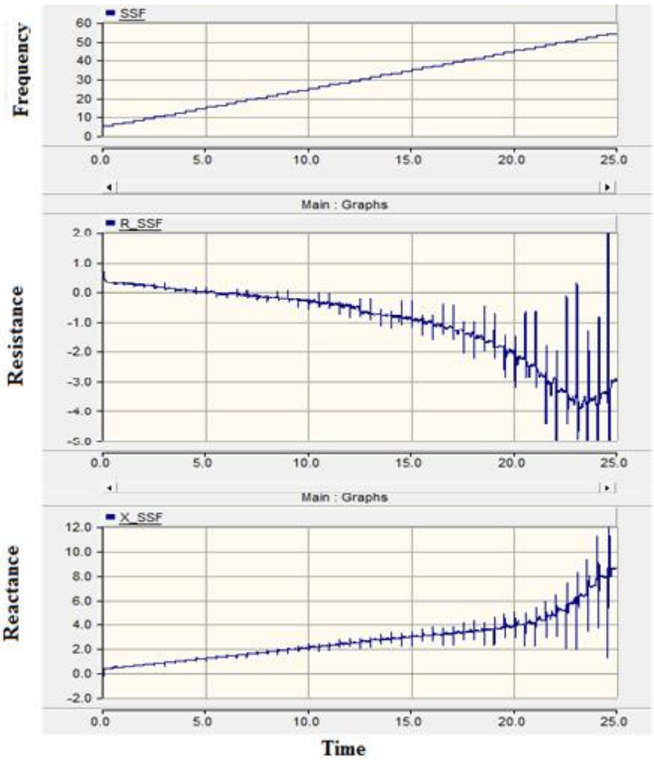


Fig.9. Wind turbine Frequency impedance sweep

Impedance vs Frequency scanning is conducted for the wind turbine. The magnitude of harmonic voltage injected was equal to 5% of the nominal voltage of the bus at which the tool is connected. Frequency impedance sweep from 5Hz to 55Hz for the wind turbine model along with the model settings is shown in the Fig. 9. The sweep is considered for a wind speed of 7.7m/s along with fixed active and reactive power wind farm control. The active power limit provided by the wind farm controller was 1pu and the reactive power reference was set at 0 pu. The grid voltage is set at 1pu. As seen in the Fig. 9, the wind turbine exhibits an inductive reactance characteristic for all the frequencies. The negative resistance is seen for frequencies above 20Hz.

4.2.2 SSCI Test Grid

A test grid with series compensated transmission line is developed as shown in Fig. 8 in order to perform sub synchronous studies. The impedance at various frequencies can be varied by changing the parameters of the grid. The grid consists of two transmission lines with a circuit breaker connected to one of the lines. The second transmission line can be removed by opening the circuit breaker at any time. The resistance and inductance parameters of the transmission line and the series compensated capacitor are configured in such a way that the grid exhibits an opposing reactance to the turbine when the breaker is closed. The reactance is set to be significantly lower when the breaker is closed compared to the reactance when the breaker is open. The frequency tool is connected to the grid on the low side of the generator step up transformer of the wind farm as shown in Fig. 8.

4.2.3 SSCI between wind turbine and grid at 20.5Hz

The SSCI test grid is designed in such a way that SSCI occurs at 20.5Hz. The magnitude of the reactance of the grid at 20.5Hz is same as the turbine but capacitive in nature (inductive for wind turbine). The primary condition for a resonance to occur is to have zero reactance at a frequency below fundamental frequency. In an electrical circuit, the condition exists when the inductive reactance and the capacitive reactance are of equal magnitude, causing electrical energy to oscillate between the magnetic field of the inductor and the electric field of the capacitor. The second necessary condition for SSCI to occur is to have a net negative resistance. The active elements such as batteries, generators and operational amplifiers generate energy. The passive elements such as resistor, capacitor and inductor cannot generate energy, but have energy drop because they take energy from the circuit. Also negative resistance is a property of the electrical circuits in which an increase in voltage across the device's terminals results in a decrease in electric current through it. Since the grid has passive components such as conducting cables and transmission lines that does not have the ability to supply voltage or current and thereby cannot exhibit negative resistance. But wind generator on the other hand is called as an active source as it delivers power in the circuit with its power electronics and control system components and hence can be seen as a negative resistance. If the resistance offered by the collection system is significantly large, then the resistance offered by the wind farm will be smaller in magnitude compared to the grid. Therefore SSCI will not occur in such cases as the net resistance offered by turbine and the grid is positive. The close look into the turbine and the grid side scanning between 18 to 21Hz is shown in the Fig. 10.

Fig.10. Turbine and Grid side F Vs Z scanning between 18 to 21Hz

Finally, the resistance and reactance of turbine and grid are designed in such a way that SSCI is proposed to occur at 20.5Hz. The negative resistance offered by the turbine is greater in magnitude than the positive resistance offered by the grid. The reactance of the grid is opposite to that of the turbine but equal in magnitude creating a resonance condition. The SSCI test grid designed for resonance (when the breaker is closed) at 20.5 Hz, is connected to the wind turbine as shown in the Fig. 9. It should be noted that the frequency impedance sweep is conducted from the same point (low voltage side of generator step up transformer) for both wind turbine and the grid.

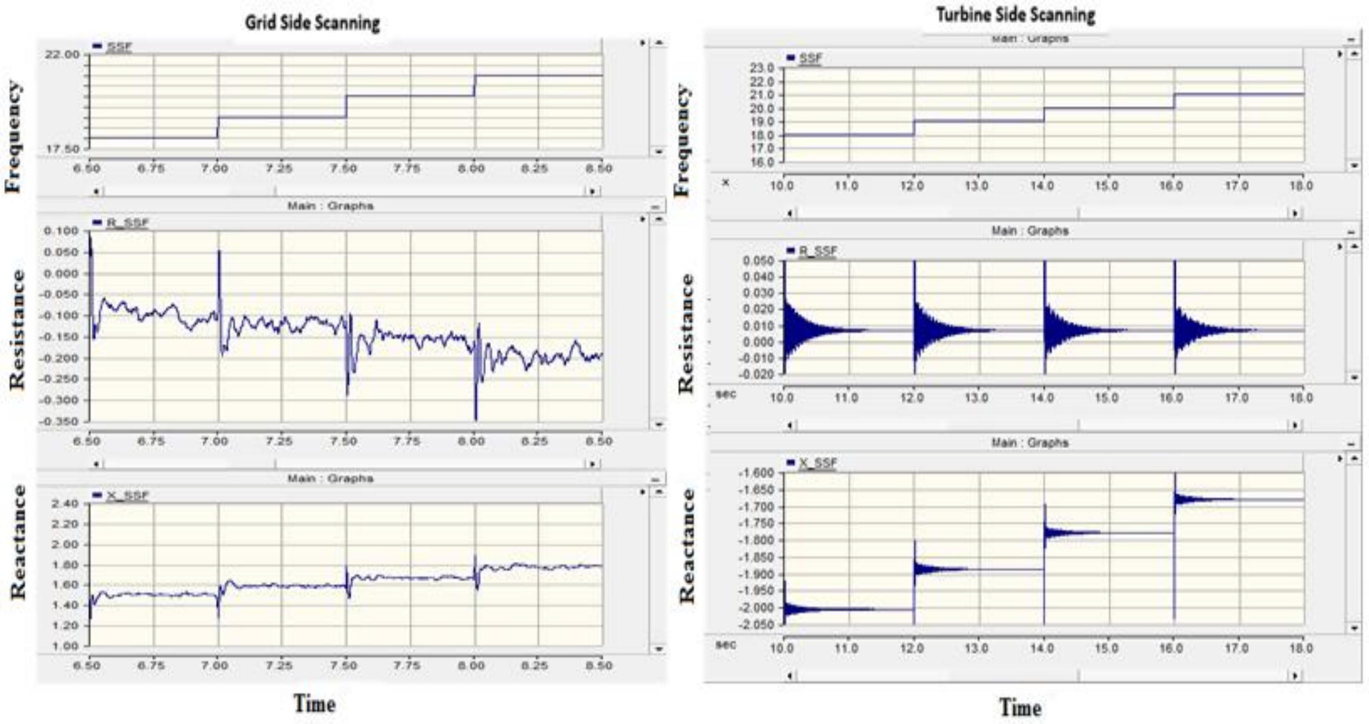
The circuit breaker is closed at 3s, as a result of which net zero reactance or resonance and negative resistance is seen by the system. Therefore growing sub synchronous oscillations are found to occur as shown in the Fig. 11. The frequencies of oscillations are found to be 20.5Hz on stationary reference frame or 39.5Hz (60 – 20.5Hz) in synchronous reference frame.

This ensures that the impedances of the wind turbine identified by the frequency tool developed is accurate as the SSCI occurs at the designed resonance frequency (20.5Hz) thereby validating the tool for non-linear systems.

5. Sensitivity analysis using developed tool with DFIG wind turbines

The frequency tool developed is connected to a 30MW wind farm (WF) consisting of 3MW DFIG wind turbines. Sensitivity of various parameters at wind farm level on impedance exhibited by the turbine is studied.

The wind farm model set up is same as explained in section 4. Each case is simulated for two wind speeds: 7.7m/s and 11.5m/s. Wind speeds are chosen in region 2 at medium wind speed and region 3 to cover all possible WT operations. The cases simulated are shown in Table 1.



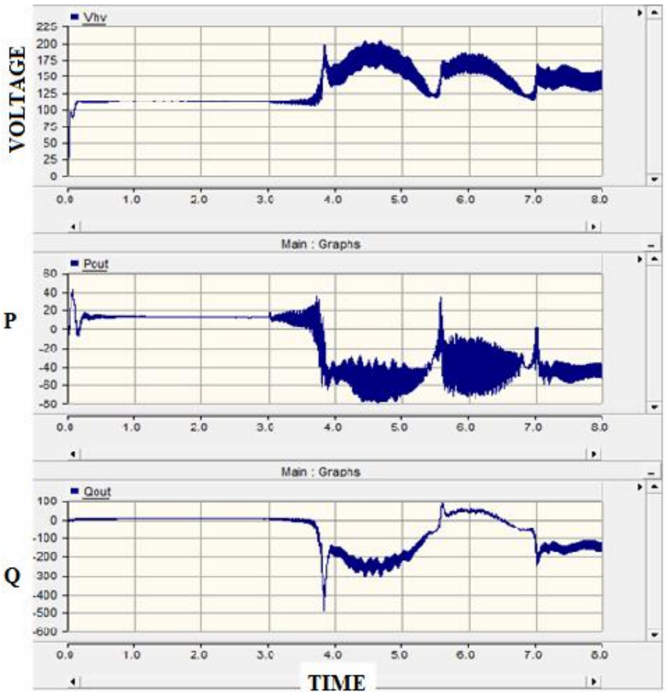


Fig.11. SSCI between wind turbine and grid at t > 3s

5.1. Results: Impedance (Z) Vs frequency (SSF) scans

The impedance vs frequency plots showing the sensitivity of parameters shown in the Table 1 at various wind speeds and inference from various results are discussed in this section.

Table 1. Cases considered to study impedance vs frequency sweep for wind farm consisting of DFIG wind turbines

No	**Description**	**Cases Studied**
1.a	WF P control mode	(2 & 3)
1.b	WF Q control mode	(2, 3 & 4)
2.a	WF P set point	(1, 0.6 & 0.2) pu
2.b	WF Q set point	(-0.5, 1 & 0.5) pu
3.a	WF P controller Kp/Ki	Original Kp = 0.8/ Ki = 2 (1, 5, 10, 100) Kp/Ki
3.b	WF Q controller Kp/Ki	Original Kp = 1e-6/ Ki = 0.7 (1, 5, 10, 100) Kp/Ki
4	Number of Turbines	Original N = 10 (0.6, 0.8, 1, 1.2, 1.4) N
5.a	Collection system R	Original R = 3.75 ohm (0.6, 0.8, 1) R
5.b	Collection system L	Original L = 49.73 mH (0.6, 0.8, 1, 1.2, 1.4) L

Case.1.a. WF P Control modes

No deviation in R or X is observed until 30Hz. For frequencies above 30Hz, a slight increase in resistance and reactance magnitude is found for frequency dependent active power control option (option 3) compared to fixed active power control option (option 2) at 7.7m/s wind speed. No significant deviation in R and X is found between two options at above rated wind speeds. The variation of impedances for different active power control modes at the three wind speeds 7.7m/s and 11.5m/s are shown in Fig. 12.a and 12.b respectively. The wind farm Q control is set in mode 2 and the P and Q reference set points are provided as 1pu and 0pu respectively.

Case.1.b. WF Q Control modes

The impedance variation for various Q control options at various wind speeds is analysed. The Wind farm P control is set in mode 3. The wind farm P and Q reference set points are fixed at 1pu and 0pu respectively. No deviation in impedance is found between the three reactive power control options. However for low wind speeds, the magnitude of negative resistance is less for voltage dependent reactive power control (option 3) compared to the rated wind speed condition.

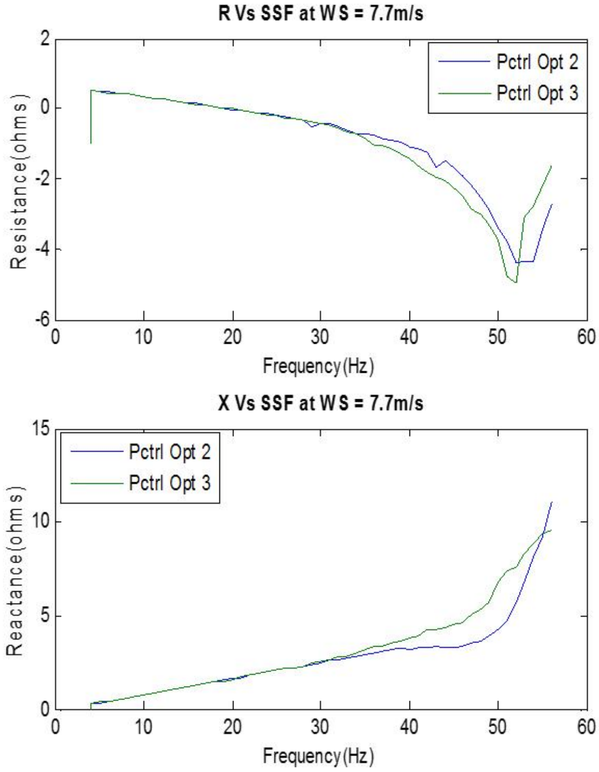


Fig.12. a. Z vs SSF scan for various WF P control modes at WS = 7.7 m/s

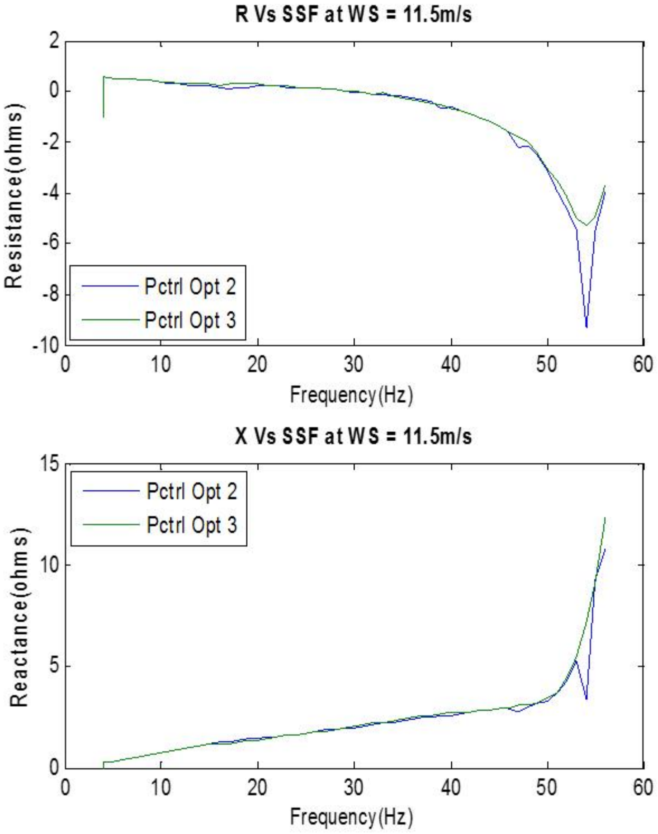


Fig.12.b. Z vs SSF scan for various WF P control modes at WS = 11.5 m/s

Case.2.a. WF P set point

The impedance variation for various wind farm active power set points (Pref) at various wind speeds is shown in Fig. 13.a and 13.b. Both the wind farm P and Q control are set in mode 2. The wind farm Q reference set points are fixed at 0pu. Deviation in impedance is observed only when the P set point is reduced to values as low as 0.2pu compared to the base case of 1pu. This will significantly affect the active power output of the turbine and hence cannot be considered as an option for SSCI mitigation. It should be noted that the wind farm P set point acts only as a limit to the wind turbine controls.

Case 2.b. WF Q set point

The impedance variation for various wind farm reactive power set points (Qref) at various wind speeds is analyzed. Both the wind farm P and Q control is set in mode 2. The wind farm P reference set points are fixed at 1pu. No change in impedance was found with various reactive power set points. It should be noted that the reactive power set point for fundamental frequency need not have an impact on the impedances at the sub synchronous frequencies.

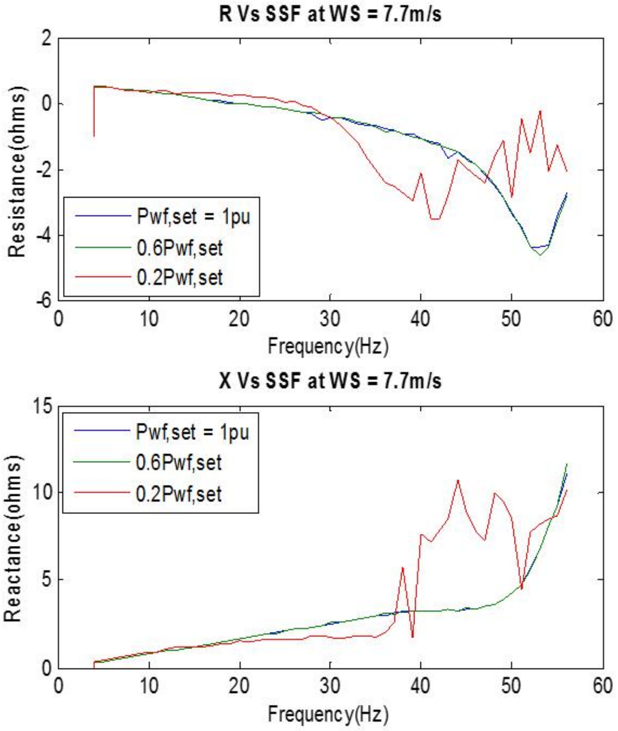


Fig.13.a. Z vs SSF scan for various WF P set point at WS = 7.7 m/s

But, varying any parameter in the system which has an impact on reactive power should have an effect on impedances at all frequencies.

Case.3.a. WF P control Kp and Ki constants

Simulations to observe the effect on impedance for various wind farm active power PI control set points at different wind speeds is conducted. Both the wind farm P and Q control is set in mode 2. The wind farm P and Q reference set points are fixed at 1pu and 0pu respectively. No change in impedance with wind farm P control PI controller constants is observed.

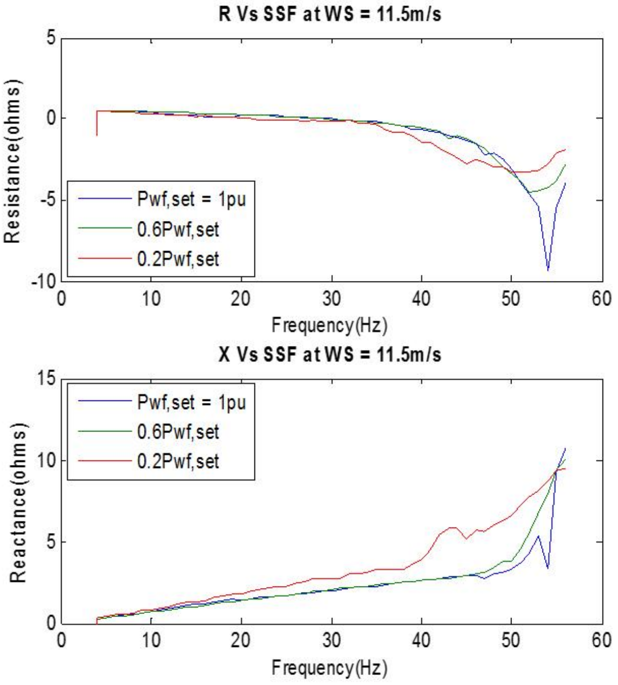


Fig.13.b. Z vs SSF scan for various WF P set point at WS = 11.5 m/s

Case.3.b. WF Q control Kp and Ki constants

The effect of various WF reactive power PI controller constants on impedance with simulation settings similar to case 3.a is conducted. No change in impedance was observed.

Case.4. Number of turbines

Simulations to observe the effect on impedance for various number of wind turbines at different wind speeds is conducted and the impedance vs frequency curves are shown in Fig. 14.a and 14.b. Both the Wind farm P and Q control are set in mode 2. The wind farm P and Q reference set points are fixed at 1pu and 0pu respectively. The magnitude of resistance and reactance decreases with increase in number of turbines. However the frequency at which the resistance crosses zero does not change with number of turbines.

Case 5.a. Collection system R

The resistance exhibited by the turbine moves towards the positive direction with an increase in the collection system resistance. Moreover, frequency range for the wind farm exhibits positive resistance increases with increase in collection system resistance. Hence, increasing the collection system resistance would be the simplest way to mitigate SSCI especially for resonance frequencies below 30Hz.

The wind farm control inputs are same as in the previous case and the impedance vs frequency plots for various wind speeds is shown in Fig. 15.a and 15.b.

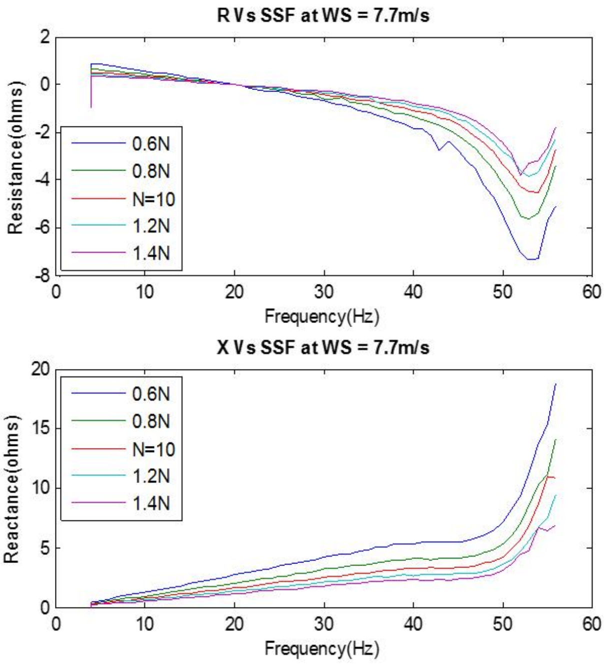


Fig.14.a. Z vs SSF scan for varying number of turbines at WS = 7.7 m/s

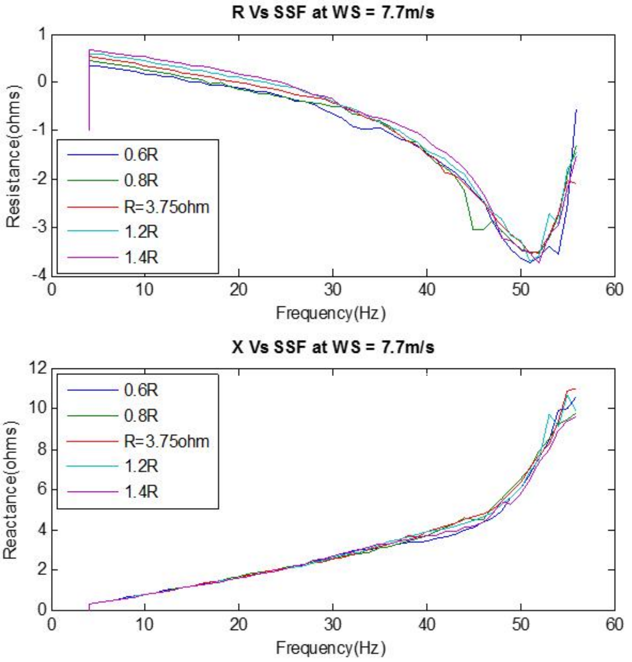


Fig.15. a. Z vs SSF scan for varying collection system R at WS = 7.7 m/s

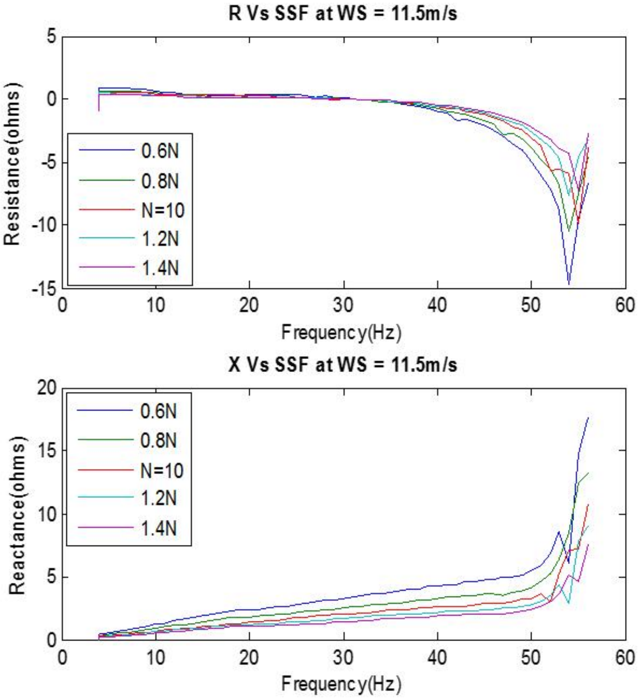


Fig. 14. b. Z vs SSF scan for varying number of turbines at WS = 11.5 m/s

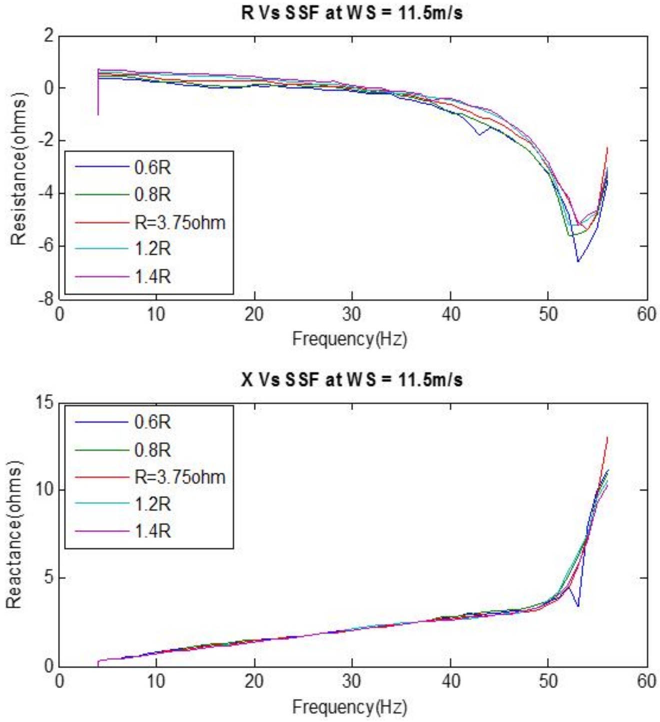


Fig.15. b. Z vs SSF scan for varying collection system R at WS = 11.5 m/s

Case 5.b. Collection system L

Similar results as in the previous case was observed for varying collection system reactance. The magnitude of positive reactance increases with increase in collection system inductance as shown in Fig. 16.a and 16.b.

5.2. Overall Observations

Following are the overall observations obtained from the above results:

a. For low wind speed conditions, the turbine exhibits negative resistance for a small range of frequencies between 25Hz to 35Hz. The resistance remains positive for the rest of the frequencies and hence there is no risk of SSCI at these frequencies.

b. The wind turbine exhibits inductive reactance at all frequencies (positive reactance shown in all figures is inductive and negative reactance is capacitive).

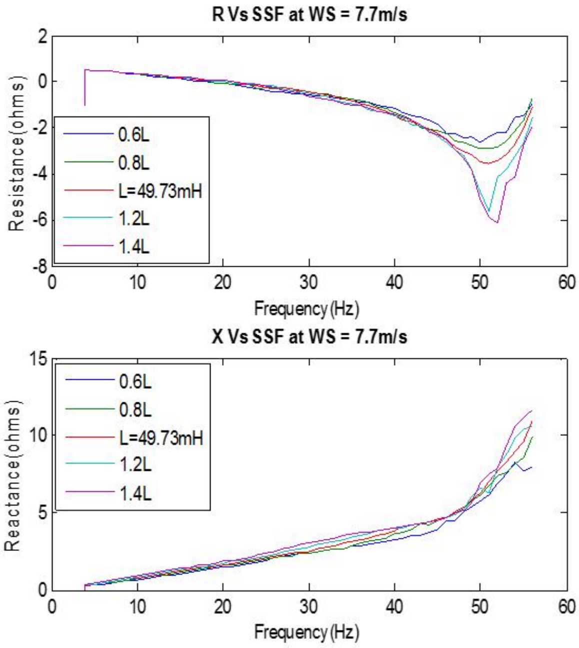


Fig.16. a. Z vs SSF scan for varying collection system L at WS = 7.7 m/s

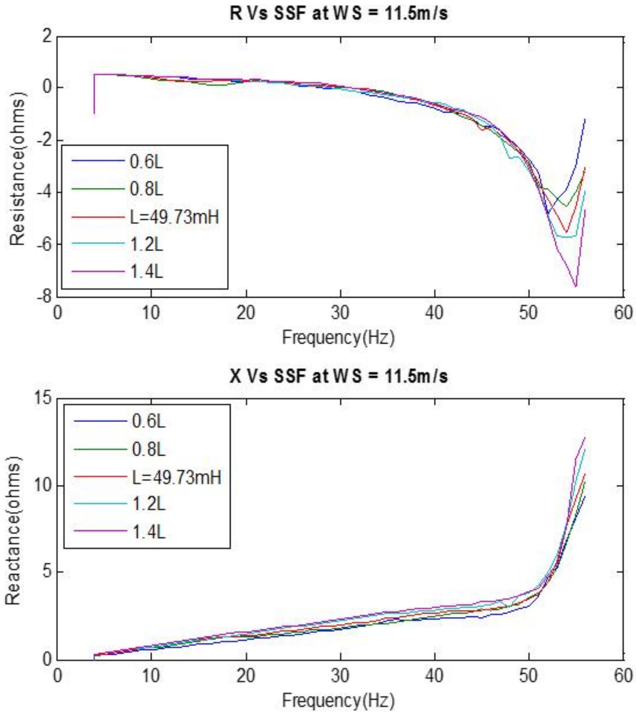


Fig.16. b. Z vs SSF scan for varying collection system L at WS = 11.5 m/s

c. Sub-synchronous frequency (SSF) impedance is based on the operating point at which the WF operates. This means the impedance is highly dependent on the active power generated by the WF.

d. Varying Parameters which impact the currents or active powers and direct passive elements such as collection system Z contribute to impedance shifting.

e. The amplitude of SSCI oscillations is higher for higher wind speed and active power.

f. Other parameters which do not have an impact on powers have no effect on impedance at any SSF.

g. Using WF P control mode 3 and WF Q control mode 4 have positive effects on SSCI as it enables wider time to respond although it does not damp oscillations.

h. Following cases have an impact on SSF impedance
- WF P set point (variation when Pset< 0.5pu)
- Number of turbines
- Collection system impedance

i. Following cases do not have any impact on SSF impedance
- WF P & Q control mode
- Q set points
- WF P & Q controller constants

6. Conclusion

The process to develop a frequency impedance scanning tool that can be used for non-linear systems such as wind turbines was discussed. The tool was based on voltage harmonic injection technique capable of injecting a frequency band in a single simulation. The tool was validated for a linear RLC circuit with the output of the built in tool. Few blocks used in the tool such as variable time delay block were not available in the master library of PSCAD and hence user written components were built in FOTRAN. As PSCAD is a fixed time step solver, an error correction algorithm was developed to reduce the error between the signals with and without time delay. It was shown that the error between a signal with and without time delay was reduced from 0.6% to 0.05% with the error correction. The tool was then used to scan the impedances of a 30MW wind farm consisting of ten 3MW wind turbines connected to 110kV grid. The wind farm exhibited an inductive reactance for all frequencies and negative resistances for frequencies above 10Hz. A SSCI test grid with series compensation was designed to have an opposing reactance and the magnitude of resistance lower than the turbine at 20.5Hz. The test grid was connected to the wind turbine and SSCI between the wind farm and the transmission grid was observed. The increasing sub synchronous current oscillations were found to occur at the designed frequency of 20.5 Hz in stationary reference frame. This validates the tool for nonlinear systems including wind farms. The tool developed was used to perform sensitivity analysis to determine the impact of various parameters at wind farm level on impedance at sub-synchronous frequencies. Valuable inferences were drawn from the study which provides a basis to investigate solutions to mitigate SSCI in the future. Finally, the developed tool can be used to study the risk of SSCI for potential projects at a particular point of interconnection.

The cost effective solution to prevent SSCI is by changing the wind turbine controls such that the wind farm exhibits a different reactance compared to the grid. From the studies conducted in this project, the solutions to mitigate SSCI can be investigated in the following lines:

a. Choosing the right number of turbines during the design phase of the project such that SSCI does not occur between grid and the wind farm.

b. Modifying collection system resistance such that the wind farm exhibits positive resistance at the sub synchronous frequency where the resonance or interaction occurs.
c. Modifying the collection system reactance such that the wind farm reactance does not match the grid reactance.
d. Add a STATCOM/SVC with custom controls to mitigate SSCI at wind farm level [23].
e. Adding an extra control loop in the turbine to exhibit infinite resistance (ideally) at sub-synchronous frequency where resonance occurs. This is done by forcing the d axis current to zero corresponding to any voltage oscillations at SSF. This might require modification of power converter controls. This would be the best and least cost solution to mitigate SSCI.
f. Control system damping controllers: Adding sub synchronous damping controllers to the existing vector control loops which include low pass filters, changing proportional gains and additional lead lag controllers will help mitigate the SSCI issue and should be studied further. Such methods are presented in [22-27] by Lean et al. In [16], the author reduces the wind farm dynamics into a state space model and SSCI damping controller is designed to mitigate sub-synchronous oscillations. Further investigation is required to be performed which removes the need for linearizing the wind turbine and wind farm model, shifting the impedance by varying a wind turbine parameter. The sensitivity of turbine impedance with respect to wind turbine or power converter parameters should be studied in more detail. The wind turbine parameters include MSC current loop PI parameters, LSC current loop PI parameters, DC link PI controller and Phased locked loop (PLL) controller constants.

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