ANALYSIS OF SUB-SYNCHRONOUS OSCILLATIONS IN WIND POWER PLANTS

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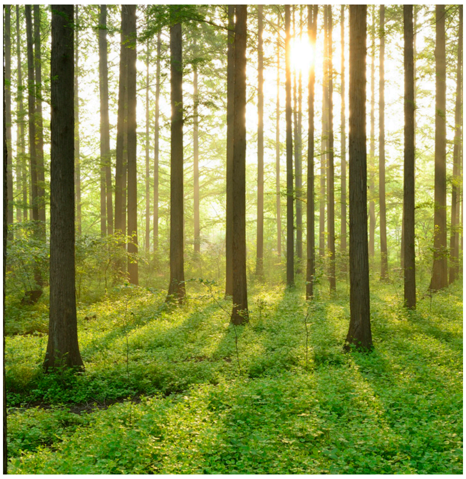


VINDFORSK


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Analysis of Sub-Synchronous Oscillations in Wind Power Plants

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Foreword

Vindkraften utgör en av de viktigaste förnybara energikällornan som också innebär stora fördelar för elsystem i form av ekonomi, genomförbarhet och miljöhänsyn.

Det finns också utmaningar som följer med integrationen av vindkraft i elsystemet. En av de största är odämpade kraftoscillationer, SSCI, som har studerats i detta projekt som är finansierat av Energiforsk och Energimyndigheten genom programmet Vindforsk.

Man har konstaterat att det kan uppstå elektriska pendlingar i nätet när vindkraftverk av viss typ kopplas upp i radiella nät. Dessa pendlingar kan skapa svängningar i nätet som i sin tur kan ge skador på vindkraftverken.

Projektet har kartlagt förutsättningarna för att dessa pendlingar ska kunna uppstå samt föreslagit åtgärder för att förhindra desamma. Projektet är ett bra exempel på hur man snabbt kan analysera och förstå ett fenomen samt hur man kan åtgärda problemet.

Projektet har utförts av KTH med Muhammad Taha Ali som forskarstuderande och Mehrdad Ghandhari som projektledare.

Göran Dalén

Ordförande i Vindforsk

Sammanfattning

Vindkraft, som utgör en av de viktigaste förnybara energikällorna, ger upphov till betydande fördelar för elsystem i termer av ekonomi, genomförbarhet och miljöhänsyn och lockar därför investerare, forskare och ingenjörer. Förutom fördelarna finns även utmaningar som följer med integrationen av vindkraft i elsystemet. En av de största utmaningarna som integrationen av vindkraft har medfört är odämpade kraftoscillationer.

Sedan slutet av 2009 undersöks en ny typ av oscillationer som har uppmärksammats av forskare. Denna typ av svängning uppträder när en dubbel inducerad induktionsgenerator (DFIG) vindturbin är ansluten radiellt till en seriekompenserad transmissionsledning. Under sådan radiell anslutning växlar styrkretsarna för omvandlare av DFIG med seriekompensationskondensatorn. Denna interaktion är känd som subsynkron kontroll-interaktion (SSCI), som i sin tur triggar tillståndet för spänning och skapar oscillationer som fortsätter att växa snabbt.

Då detta är ett nytt fenomen finns ett betydande behov av att denna interaktion ska undersökas. Projektet går ut på att studera och utreda SSCI. Målet är att analysera och förstå vad som orsakar sådana svängningar och att designa en kontrollteknik som kan minska dem. Projektet är uppdelat i två delar. I den första delen fokuseras på analysen av SSCI-fenomenen och bestämning av kontrollparametrarna för energi-elektroniska omvandlare som spelar en väsentlig roll i interaktionens trigger. Den andra delen gäller design och undersökning av kontrollteknik som, utan att det behövs en extra kraftig elektronisk enhet, kan förhindra uppkomsten av SSCI och göra systemet mer robust.

Summary

Wind energy, being one of the vital sources of energy among the renewable energy sources, brings with itself an appreciable number of benefits for power systems in terms of economical, feasible, and environmental concerns which have magnificently attracted investors, researchers, and engineers. Along with the benefits, there come some challenges which accompany the integration of wind power in the electric power system. One of the main challenges which the integration of wind power has come across recently is of undamped power oscillations.

Since late 2009, a new type of oscillation is being researched upon and it has gotten the attention of researchers. This type of oscillation comes into existence when a doubly-fed induction generator (DFIG) wind turbine is connected radially to a series compensated transmission line. During such radial connection, the control circuitry of converters of DFIG interacts with the series compensation capacitor. This interaction is known as subsynchronous control interaction (SSCI) which in return triggers the condition for voltage and current oscillations and these oscillations keep on growing rapidly.

Being a recent challenge, there is a significant need for this interaction to be examined. This project deals with the study and investigation of SSCI. The objective of this project is to analyze and understand the reasons and causes which inflict such oscillations and to design a control technique which can mitigate the oscillations. This project is divided in to two parts. In first part the main focus is to analyze the phenomenon of SSCI and to pinpoint the control parameters of power electronic converters which play an essential role in triggering the interaction. The second part deals which the design and implementation of control technique, without using any additional power electronic device, which can make the power system immune to SSCI and which can make the system more robust.

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1 Introduction

1.1 BACKGROUND

Integration of wind energy in the power system is one of the main focuses nowadays. Since most of the wind turbine farms are located far away from the load side so there is a need to transfer a large amount of electrical power from the generation side to the load side. In order to make the power transfer effective over the long distances, a technique of series compensation is used. The series compensation technique adds up a series capacitor in transmission line which decreases the effective reactance of line and increases the power transfer through it.

However, in 2009 in Texas an incident of undamped power oscillation occurred because of the interaction between doubly-fed induction generator (DFIG) wind turbine and series compensation capacitor. There was a fault in the transmission system, the fault was cleared by a circuit breaker operation which led the DFIG wind farms in a radial connection with series compensated transmission line. As a result of this radial connection the growing oscillations in voltage and current of the system were observed which damaged the converters of the wind turbines. The oscillation grew rapidly and in a short period of time the peak value of voltage reached up to 195% of its nominal value. This oscillation condition was damped when the series capacitor was bypassed 1.5 s after the initial event.

Initial research on this incident showed that these oscillations occurred because of the interaction between converter controllers of DFIG and the series compensation capacitor and the phenomenon is named as sub-synchronous control interaction (SSCI). The frequency of these oscillations falls in sub-synchronous range, i.e., below 50Hz. The occurrence of SSCI in DFIG wind farms did not stop after the Texas' incident; there are few other incidents of similar nature which happened in south-western Minnesota and in many parts of China including Hebei. The frequent repetition of SSCI in DFIG wind farms raises many questions regarding the stability and reliability issues of wind energy. There is a dire need to understand the causes of this problem and to provide a solution for it.

1.2 PROBLEM STATEMENT

Research is being done to investigate SSCI. In few research works it is shown that the control parameters of power electronic converter play main role in triggering the conditions for interaction. Research also shows that proportional parameters of controllers are involved in making the system unstable. However, there is a need to analyze the matter further to pinpoint the particular control parameters which are sensitive to SSCI so that the values of such parameters can be selected carefully.

Along with the analysis of SSCI, a mitigation technique is also required to overcome the challenge. Some techniques are introduced, in the literature, which use flexible AC transmission system (FACTS) to damp the oscillations, and there are other techniques which use supplementary control signal in the converters of DFIG to mitigate SSCI. Although these technique contribute in damping the oscillations in the system up to a specific compensation level but using any additional FACTS devices is an expensive solution and supplementary control based on remote signals would require some complex computations and is risky to be erroneous.

1.3 OBJECTIVES & IMPLEMENTATION

This project aims to analytically investigate and study the phenomenon of SSCI in order to figure out the components or the control parameters of the system, which are responsible in inflicting the SSCI condition. Also, the objective of this project is to design a control technique which can make the DFIG system robust and stable for any realistic value of series compensation, without using any additional FACTS device and without using any remote signal for the supplementary control.

The project is divided and carried out into two parts. The first part is the analysis of SSCI. For this part of the project a technique of eigenvalue analysis is used. A mathematical model of DFIG system is designed using MATLAB. Ordinary differential equations are used to represent the dynamics of the system. The system is then linearized and the eigenvalues of the system are calculated and analyzed for different circumstances. This analysis helped to find out the control parameters which are sensitive in making the conditions for interaction.

The second part of project is to design a mitigation technique for damping the oscillations. For this part, the designed DFIG system is simulated for different circumstances to observe SSCI. Based on the analysis and understanding of SSCI, a power oscillation damper (POD) is designed. The POD is then tuned using residue technique. The optimal place for the addition of POD in DFIG's converters is found, and appropriate input signals to POD are tested.

2 Analysis of SSCI

The SSCI is studied by applying the eigenvalue analysis on the linearized mathematical model of DFIG based power system. Through the eigenvalue analysis, the sub-synchronous modes are identified which are responsible of the occurrence of control interaction in the system. The identification of such modes helps further to study the phenomenon of SSCI and to pinpoint the components and control parameters of the system which are sensitive to SSCI condition.

2.1 MATHEMATICAL MODELING OF DFIG-BASED SYSTEM

Research shows that the DFIG is the only type of wind turbine generator which is vulnerable to SSCI. In order to investigate the SSCI phenomenon thoroughly, a detailed mathematical model of DFIG is designed. Ordinary differential equations are used to represent the dynamics of all the parts of DFIG and external network. The block diagram of the test system which is designed to for carrying out the analysis of SSCI is shown in figure below:

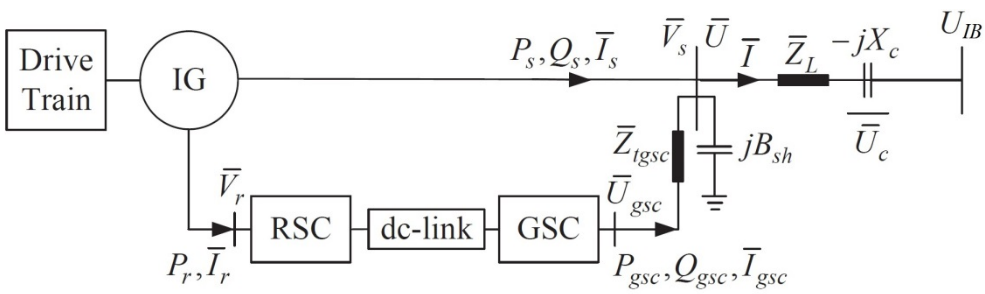

Figure 1: Block diagram of DFIG-based power system.

The DFIG consists of an induction generator whose stator is connected directly to the grid through a transformer while the rotor is connected through a back-to-back converter. DFIG is capable of operating at the speed which can be below or above certain the synchronous speed to a certain limit. The back-to-back converter is further classified into two parts. The voltage source converter (VSC) close to the rotor of the generator is called rotor-side converter (RSC) and the converter close to the grid is called grid-side converter (GSC). There is a dc-link between RSC and GSC with a purpose of storing the energy to enable the proper operation of both the converters. The converters being used in DFIG are of ratings lower than the rated power of DFIG, as the converters only deal with the fraction of total power. The ordinary differential equations are used to model drive train, induction generator, RSC, GSC, dc-link, and grid-side transformer.

In order to observe the control interaction in the designed DFIG system, the control parameter of the DFIG converters are selected such that the system can with stand the series compensation level, of the transmission line, upto 60%. The DFIG system experiences SSCI when the compensation level is increased beyond 60%. The figure below shows the infliction of sub-synchronous oscillations, in the active power of DFIG, as a result of SSCI when the compensation level is inscreased to 65%.

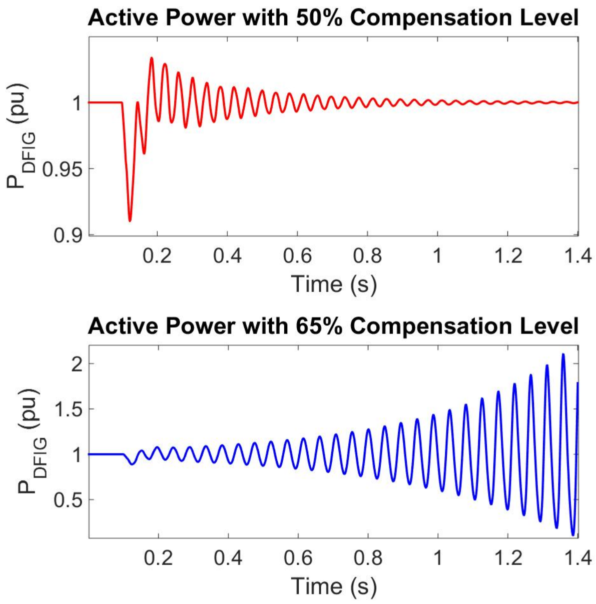

Figure 2: Observation of SSCI in the designed system

2.2 EIGENVALUE ANALYSIS OF DFIG-BASED SYSTEM

Eigenvalue analysis is an analytical tool which is capable of computing the characteristics of the oscillation in terms of frequencies and the damping at each frequency. Such characteristics play an essential in the investigation of SSCI. The stability of the system is measured through the damping ratio. For a system to be stable, the damping ratio should be positive.

The eigenvalues of the system for both the circumstances (50% and 65% compensation levels) are analyzed. Figure 3 shows the scattered plot of the calculated eigenvalues of the system with 50% series compensation level (with blue crosses) and with 65% series compensation level (with red crosses).

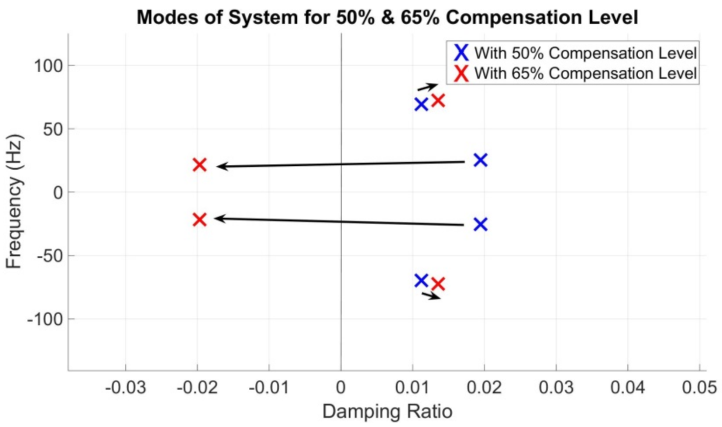

Figure 3: Eigenvalues corresponding to modes of interest

It can be analyzed that the increase in series compensation level significantly affects the modes of sub-synchronous frequency (frequency below 50Hz) in an adverse way. The movement of eigenvalues corresponding to both the modes of interest is shown with arrows. As the compensation level increased from 50% to 65%, the sub-synchronous modes move towards the left plane having the negative damping ratio, hence making the system unstable.

On the other hand, the increase in compensation level slightly affects the super-synchronous frequency modes, but in a positive way, as it can be seen from Figure 3 that the damping of mode with super-synchronous frequency is improved slightly.

Hence, it can be said that the observed oscillation in the designed system, as shown in figure 2, is the sub-synchronous oscillation as the mode of the system which is responsible for the undamped oscillation is of sub-synchronous frequency.

2.2.1 Sensitivity Analysis of Control Parameters

The term control parameter is referred to the proportional and integral parameters of the PI controllers of VSC. The designed DFIG system uses 8 PI regulators, 4 in RSC and 4 in GSC, and a total of 16 control parameters. The block diagrams of RSC and GSC are shown below:

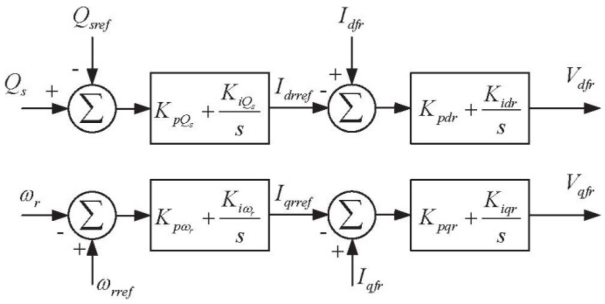

Figure 4: Block diagram of RSC

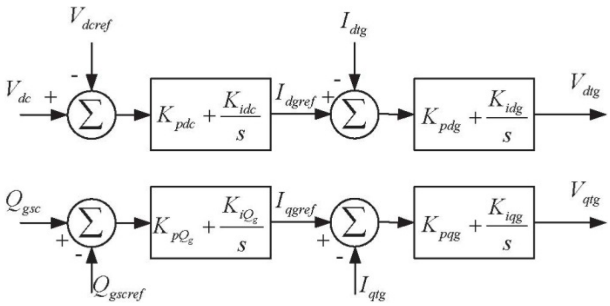

Figure 5: Block diagram of GSC

In order to find out the control parameters to which the modes of interest are sensitive, the eigenvalue sensitivity analysis is performed. This analysis is performed by changing the value of each parameter, turn by turn, and observing the movement of eigenvalues corresponding to the modes of interest. The series compensation level of the system is kept to be 55% so that the sub-synchronous modes becomes poorly damped but the system stays in stable region. The value of each control parameter is increased from 0 to a certain value to see the impact of each parameter. Broadly, all the 16 control parameters of the system are classified in to 4 groups based on their effect on the modes of the system. The classification of control parameters is shown in the table below.

TABLE I
Classification of Control Parameters

Type	Parameters	Property
A	K_{iQs}, K_{pwr}, K_{iwr}, K_{idr}, K_{idc}, K_{pQg}, K_{iQg}, K_{pqg}, and K_{iqg}	No significant effect on sub-synchronous mode
B	K_{iqr}, K_{pdc}, and K_{idg}	Increase in value decreases the damping ratio of sub-synchronous mode
C	K_{pQs} and K_{pdr}	Increase in value increases the damping ratio of sub-synchronous modes but deteriorate super-synchronous modes
D	K_{pqr} and K_{pdg}	Affect the sub-synchronous mode significantly

It can be seen from the table above that the type-D parameters (K_{pqr} and K_{pdg}) are the most sensitive parameters for the infliction of SSCI. Both parameters are the proportional parameters of the inner current controller of active power control loop.

K_{pqr} is the parameter in RSC controller and K_{pdg} is the parameter in GSC controller. While keeping the compensation level to 55%, the value of K_{pqr} is varied from 0 to 0.2. Although the variation in K_{pqr} is notably small, as compared to the variations made for other parameters, both the sub and super-synchronous modes show significant movement as a result of this variation. It can be seen in Figure 6 that the net change in the damping ratio of sub-synchronous mode is around 0.1 for the small change in K_{pqr}. The behaviour of modes of interest in response to small alteration in K_{pqr} implies that the sub-synchronous mode is very sensitive to this parameter and it is of great importance to choose the value of K_{pqr} properly so that the system can with stand the series compensation level as high as possible.

The other parameter which is found sensitive to sub-synchronous mode is K_{pdg}. The response of modes is observed while changing the values of K_{pdg} from 0 to 2. The resultant movement of eigenvalues shows that the increase in K_{pdg} has a beneficial impact on SUP mode, but for SUB mode there is a very small range of values of K_{pdg} for which the damping ratio is positive.

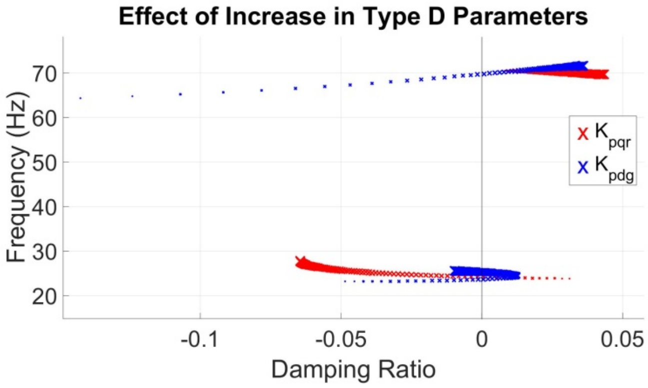

Figure 6: Effect of Type-D parameters on modes of interest.

The effect of series compensation level on the range of type-D parameters, to which the system can remain stable, is shown in Figure 7. The range of type-D parameters is evaluated for 10%, 30%, 50%, and 70% compensation level separately. In the figure, the blue surface shows the area of the values of type-D parameters where the least damping ratio (ζ_{least}) of the system is positive and the system operates in stable region. The green surface shows the values of type-D parameters for which the system gets unstable. The red surface is for zero damping ratio which divides stable and unstable ranges and the white dots show the value of K_{pqr} and K_{pdg} which are chosen in the designed model.

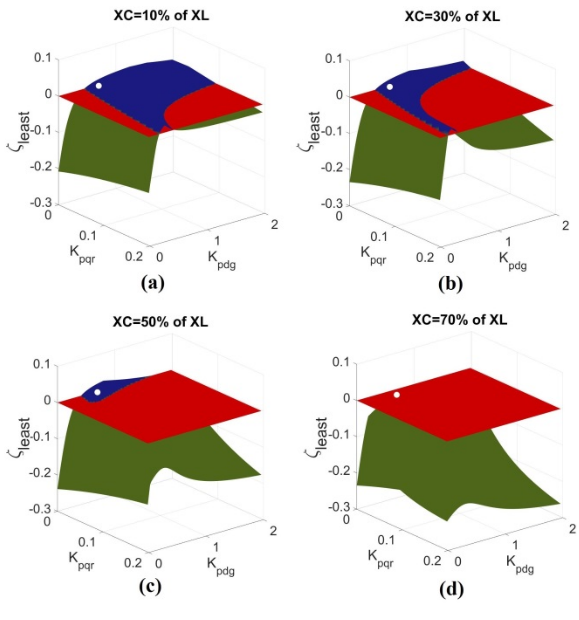

Figure 7: 3D illustration for the effect of Type-D parameters on modes of interest.

It can be seen in figure that the stable range of the parameters gets smaller as the compensation level is increased. In figure (c), the stable range of both the parameters is very small. For the higher compensation levels the proper tuning of the two mentioned control parameters is essential. As the compensation level is increased to 70%, the system gets unstable for any value of the parameters and it shows that the solution to mitigate SSCI through proper tuning of control parameters is limited to certain level of series compensation.

3 Mitigation of SSCI

3.1 DESIGN AND IMPLEMENTATION OF POD

A power oscillation damper (POD) is designed to prevent the infliction of SSCI in DFIG-based power system. POD is basically a controller which takes in an input from the system and provides a supplementary control signal to the system as its output. In order to use POD for the mitigation of SSCI, the output signal of the POD is added to the controllers of VSCs of DFIG as a supplementary control signal. The block diagram of POD is shown in figure below.

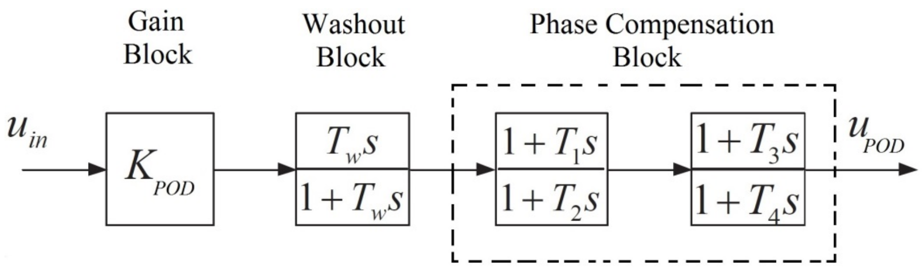

Figure 8: Block diagram of POD.

A POD consists of 3 blocks which are gain block, washout block, and phase compensation block. The gain block multiplies the input signal with selected value of gain. This selected gain determines the damping provided by the POD. The gain of the POD is required to be selected optimally as the increasing gain of POD would possibly increase the damping of mode of interest but it might has an adverse effect on the damping of other system modes.

The washout block is a high pass filter which filters out the noises of low frequencies. This block eliminates the effects of any steady-state value of the input signal.

The phase compensation block consists of a lead-lag filter and adds phase to the signal. The extent of phase added is dependent upon the selected values of filter parameters. The appropriate phase-lag or phase-lead characteristics, for providing high damping to the system, can be obtained by tuning the lead-lag filter properly.

The supplementary control signal from POD is added in the summation junctions of the RSC and GSC controllers, one by one. The active power and apparent power generated by the DFIG, and the current through transmission line are used as the input signals to the POD. All the parameters of POD are tuned separately for different input signals and for different placements of POD in the VSC controllers of DFIG. For every placement of POD in to the system and for every input signal to POD, the gain of POD is selected by observing the root-locus plot of the closed loop system.

After the detailed study, it was found that the POD works best, for all the input signals, when it is added in to the inner current controller of dc-voltage control loop, in GSC (V_{dc}-3 junction).

3.2 SIMULATION RESULTS

After analyzing all the input signals and after selecting the optimal placement of POD in the DFIG converter controller, the simulations are performed for different compensation levels to observe the occurrence of SSCI and its mitigation.

3.2.1 Simulation of linearized system

The simulations are performed to see the effect of the POD on the DFIG system for different levels of series compensation and for different values of rotor speed. In figure 9, the 3D surfaces are plotted with the percentage compensation level along the x-axis, the rotor speed in p.u. along the y-axis, and the damping ratio of system's least damp mode along the z-axis. The POD with all the input signals is added to the inner current controller of dc-link voltage control loop in GSC, one by one. It can be seen that the addition of POD significantly increases the damping of the system as compared to the damping of the system without POD. It can be observed that when there was no POD in the system, the system gets unstable when the compensation level is increased beyond 60%. But, after the addition of POD, the system can with stand the compensation level of 90% and beyond. It can also be seen in the figure that the POD helps the damping of the system to increase when the compensation level is increased.

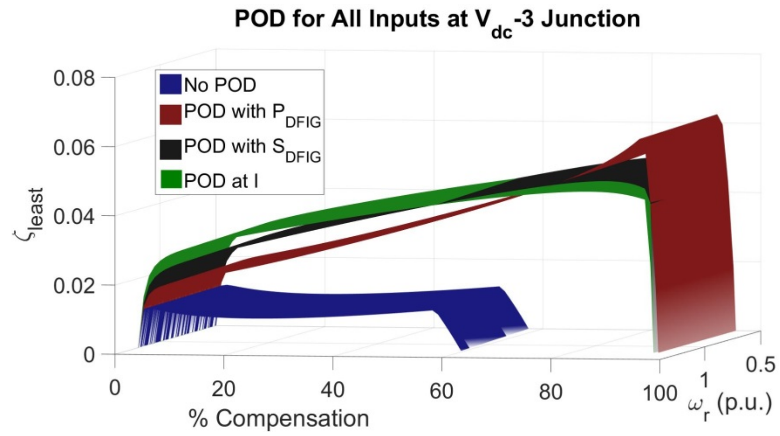

Figure 9: Effect of POD on the DFIG-based system.

To compare the stability of system with and without POD in terms of range of type-D parameters, the 3D surfaces are plotted in figure 10, similar to ones plotted in figure 7 for the system without the POD. Here, the POD with DFIG active power as an input is added to the V_{dc}-3 junction of GSC, and the simulations are done for 30%, 50%, 70%, and 85% series compensation level, respectively. Here it is obvious that, unlike in figure 7, there is an appreciable range of values for type-D parameters even when the compensation level is higher than 70%. Addition of POD not only the increases stability region of system but also improves the damping ratio of the least damped mode.

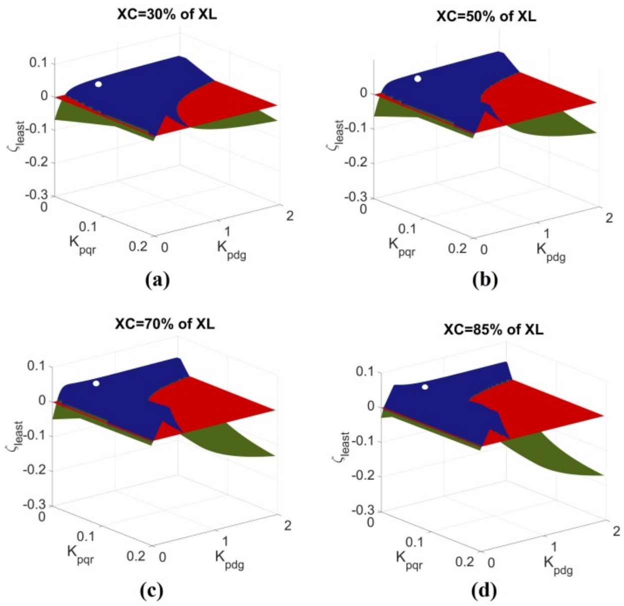

Figure 10: 3D illustration for the effect of Type-D parameters with POD on modes of interest.

3.2.2 Simulation of non-linear system

The non-linear system is also simulated to observe the effect of POD on the DFIG system. The POD for all the inputs is added at V_{dc}-3 junction for the compensation level of 65%. The figure 11 shows the simulation of system for the POD with different inputs. It is evident from the figure that all the PODs successfully mitigate the infliction of SSCI in the system and adds high damping to it, while the system without POD proceeds towards instability. This simulation result corresponds well to the result obtained from the linearized system as shown in figure 9.

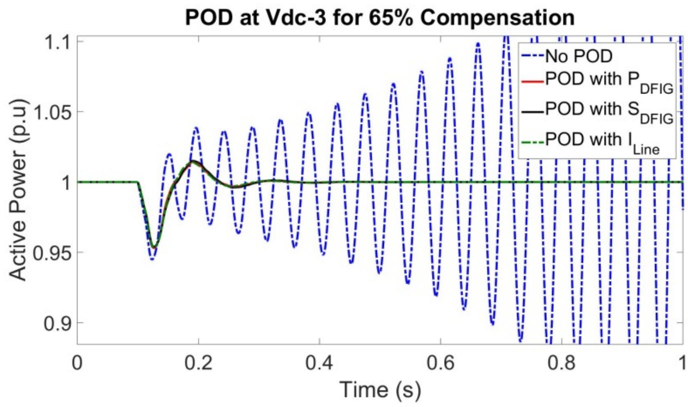

Figure 11: Simulation of DFIG-based system at 65% compensation level

In order to test the strength of POD for mitigating SSCI at higher compensation level, the POD is placed in the system with 85% compensation level. The simulation result for this highly compensated system is shown in figure 12. The figure shows that the performance of all the PODs is improved with the increase in the compensation level unlike the performance of the system without POD. By looking at figure 11 and 12, it can be concluded that the designed and tuned POD adds more damping to the system for higher compensation level.

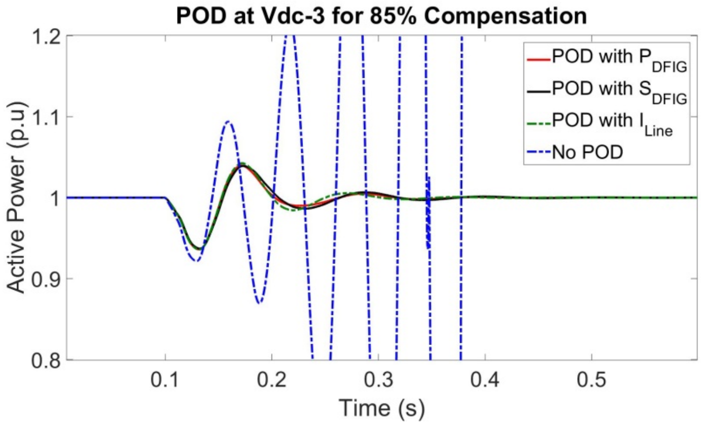

Figure 12: Simulation of DFIG-based system at 85% compensation level

4 Conclusion

The designed mathematical model of DFIG system is simulated and tested for different circumstances of system and for conditions of SSCI. The system's parameters are selected such that it can with stand series compensation level of 60%. The simulation results show that SSCI occurs in system when the compensation level is increased beyond 60% compensation level.

The eigenvalue of the linearized system are calculated to analyze the behavior of modes of the system corresponding to the subsynchronous frequency. For identifying the sensitive control parameters of DFIG, the eigenvalues sensitivity analysis is carried out. The value of each control parameter is changed from 0 to a certain value and the movement of eigenvalues of subsynchronous frequency is observed. Based on the movement of eigenvalues, two control parameters are identified to be the most sensitive ones. For the both rotor-side and grid-side converters, the proportional parameters of the inner current controller are observed to be affecting the eigenvalue of interest, significantly. It is shown that if the values of these parameters are chosen appropriately, then the SSCI condition can be avoided up to a certain level of series compensation.

For the mitigation of SSCI, a POD is designed. Three different signals are selected and tested as the input to POD, these signals are active power of DFIG, magnitude of apparent power of DFIG, and current through transmission lines. All of these signals are local signals; this removes the hassles of additional calculations and the risk of being erroneous. The POD for all the input signals is tested for all the placements in converter controllers. It is found that the POD works best when is tuned properly and is placed in the grid-side converter controller.

The results obtained by the proper placement of POD in converter controller clearly show that the sub-synchronous oscillations in DFIG system can be damped. The POD is tested for different levels of series compensation and it was seen that POD can successfully make the DFIG system immune to SSCI for any realistic level of series compensation. The designed POD not only mitigated SSCI but it also added significant damping in the system, hence, making it more stable.

5 Contribution of the Project

The main contribution of this project can be summarized as follows:

1. A detailed mathematical model is designed and verified in MATLAB/Simulink. The dynamics of the system, containing a DFIG connected radially to series compensated line, are represented by ordinary differential equations. The system is tested under different circumstances to observe the occurrence of SSCI.

2. Eigenvalue sensitivity analysis is performed on all the proportional and integral control parameters of the converter of DFIG. The movements of eigenvalues are plotted to visualize the effect of parameters on sub and super-synchronous modes of the system. The grouping of control parameters straightforwardly explains the different effects of control parameters on the modes of sub and super-synchronous frequencies. The parameters which are significantly sensitive to SSCI are also identified. The relation between the series compensation level and the range of values of sensitive control parameters is discussed. This analysis can be significant for carefully selecting the values of control parameters. Proper tuning of control parameters can avoid the SSCI condition up to a certain level of series compensation without using any additional control strategy.

3. A supplementary controller is designed and tested by adding it to all the junctions of RSC and GSC controllers. The control strategy does not use any additional FACTS device. Only the local signals are tested as the input to the supplementary controller therefore the need to estimate remote signal is excluded, and it also reduces the risk of the input signal being erroneous.

6 List of Publications

1. ***C1:*** Muhammad Taha Ali, Mehrdad Ghandhari, and Lennart Harnefors, "Effect of control parameters on infliction of sub-synchronous control interaction in DFIGs," *2016 IEEE International Conference on Power and Renewable Energy (ICPRE)*, Shanghai, 2016, pp. 72–78.

2. ***C2:*** Muhammad Taha Ali, Mehrdad Ghandhari, and Lennart Harnefors, "Mitigation of sub-synchronous control interaction in DFIGs using a power oscillation damper," *2017 IEEE Manchester PowerTech*, Manchester, United Kingdom, 2017, pp. 1-6.

3. ***J1:*** Muhammad Taha Ali, Mehrdad Ghandhari, and Lennart Harnefors, "Analysis and Mitigation of Sub-Synchronous Control Interaction in a Grid Connected DFIG," Submitted.

ANALYSIS OF SUB-SYNCHRONOUS OSCILLATIONS IN WIND POWER PLANTS

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Along with the benefits, there come some challenges which accompany the integration of wind power in the electric power system. One of the main challenges which the integration of wind power has come across recently is of undamped power oscillations.

The main focus here has been to analyze the phenomenon of subsynchronous control interaction and to pinpoint the control parameters of power electronic converters which play an essential role in triggering the interaction. The report also deals which the design and implementation of control technique, without using any additional power electronic device, which can make the power system immune to subsynchronous control interaction and which can make the system more robust.

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