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DYNAMIC IMPACT OF DFIG WIND TURBINE ON POWER SYSTEM STABILITY- A REVIEW

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ABSTRACT: With increasing population and pollution the wind turbine as specially DFIG (Doubly Fed Induction Generator) is become most popular as an electrical energy source. This paper addresses the short review on stability withdetail SSR (Sub Synchronous Oscillation) issues of DFIG wind turbine connected to grid and finally suggested the research gap in this area.
Keywords: DFIG, small signal stability, transient stability, sub-synchronous resonance.

1. Introduction:

The future expansion of wind energy is targeted 230 GW in 2020 and 300GW in 2030. Most wind farms in Europe and North America use Doubly Fed Induction Generators (DFIG). [1] In India the total potential of wind energy is 49130MW and it is target to achieve 35000MW in 2017 with DFIG wind turbine[2]. The market growth is roughly 30%. Due to whethercondition, generally wind turbine is located far away from the load center and connected to relatively weak grid [3]With increasing the high penetration of wind farm in the recent scenario will create large system stability problem.

The wind turbine generation is generally classified with following different types.1. Fixed speed type induction generator.2. Variable speed type induction generator/synchronous generator. Amongthe above classification DFIG (Doubly fed Induction Generator with gear),CDSG (Converter Driven Synchronous Generator without gear) and GFC (Brushless Generator with gear) becomes most attention in power system stability study for their different mode of operations. Until 1998 generally constant speed wind generator of 1MW is used and between 1998 to 2008 mainly DFIG of 1MW to 3MW is used. In current paper the dynamic behavior ofDFIG based WTG is being studied with specially focus on SSR. InDFIG, stator winding is directly connected to grid and rotor winding is connected via RSC and GSC convertor through dc-link. With its reactive power capability, it can be treated as PV/PQ bus for steady state analysis [4] the dynamic behavior of DFIG is highlighted below.

1.Aerodynamics Model 2. Two-Mass Model 3. Generator is modeled in d-q axis.
4. RSC controller model. 5. GSC controller Model 6. DC-link model.7. Pitch controller model

2. Small Signal Stability.

Small signal stability problem normally occurs due to insufficient damping torque and results in rotor oscillations of increasing amplitude [5]. Linearized model of matrix A and its Eigenvalueidentify the small signal stability. Low frequency oscillation modes with approximate frequency of 0.1 to2 HZ were observed and depend mainly on number of generators involved. The time-domain simulation also confirmed the frequency of oscillation up to 2HZ suggested by Eigen-value analysis. In [6] the complete eigenvalue analysis of DFIG connected to infinite bus is presented without controller. The analysis is also carried out with changing the different system parameters. The nonlinear Matlab-Simulink model is developing which satisfy the eigenvalue results. This is very good basic paper for small signal stability analysis. The eigenvalue analysis of DFIG connected to infinite bus with and without controller is develop in [7]. The small signal stability analysis of DFIG based wind power system with and without controller under different modes of operation is carried out in [8]and the additional damping controller is designed for reduced the oscillation for three mode of operation. In [9] Hops-bifurcation technique is presented for computing the boundary for analysis of small signal stability of DFIG connected to grid under the varying wind speed with and without controller. The complete Jacobin matrix is derived for linearized the full order model. A novel parameter tuning method based on PSO was proposed to optimize the parameter of the controller with SMIB and multimachine system. It shows the dynamic performance of WT has been improved with controller and it further improves with optimization of parameters and therefore the capability of fault ride through can be enhanced. [10] .The small signal stability of a distribution system is investigated with penetration of wind and solar and show that wind generator dynamics are very significant in the system oscillation compare to solar generation[11].Optimized control of DFIG-based wind generation sensitivity analysis and PSO optimization is proposed in [12].In this paper the key idea is used to first identify the critical parameters using eigenvalue sensitivity and then optimized that parameters to improve dynamic behavior of DFIG. The PSS for a DFIG is similar to PSS of synchronous machines is shown in [13]. A PSS with and without supplementary controller is proposed to improve the damping performance DFIG and show that PSS with supplementary controller gives better response.In [14], the application of eigenvalue sensitivities damping controllers is designed for DFIG to damp the electro-mechanical oscillations which has been successfully applied to the controller design of PSS and FACTS devices. The impact of STATCOM is studied with SMIB and the supplementary controller is designed to improve the small signal stability for large wind farm with DFIG. The simulation is carried out in Digsilent /Power factory [15]. Thevar coordinate control is proposed to improve the small signal stability for economic reason compared with SVC and STATCOM. The eigenvale analysis is carried out and simulation is built in Digsilent /Power factory [16].

3. Transient Stability.

Wind turbines connected to the grid are frequently subjected to grid faults. Various gridfaults can occur in the electrical networks and most of them are related with the networkvoltage. They are usually characterized by a change in the magnitude of the voltage andby time duration. [17].The IEEE-9 bus system is tested for transient stability (3-phase fault) analysis with different penetration level of DFIG wind farmswith GSC control strategy in[18] . It shows that initially the wind farms support to the transient stability but as penetration level is increased the system is stability margin is reduced. The comparison of transient stability between synchronous generator and DFIG generator is carried out with different cases and shows that at higher penetration of DFIG require the reactive power compensative device to maintain the terminal voltage of PCC ant nominal level[19].The transient characteristics DFIG and SCIG is compared and show that when the DFIG rating is increased compare to SCIG the system becomes stable but is SCIG rating is increased than DFIG , system will lost its stability. If DFIG penetration is continuously increased than voltage recovers after the fault is more rapidly but voltage-drop is greater. So to achieve good terminal voltage, RSC control scheme designed which improve the results. The simulation is built in PSCAD/EMTDC [20]. An uninterrupted control scheme of RSC and GSC is shown in IEEE-10 machine and 39-machine with DFIG wind turbine. Withsuitablearrangement of RSC and GSC the transient stability is improved. Few SG is equipped with PSS to damp the oscillation and system is simulated in PSCAD/EMTDC. [21]. The PSO based controller gainhas been implemented in DFIG to improve the transient stability. The DAEs have been solved using simultaneous Implicit (SI) method and simulation is carried out for three 8 bus power system networks with DFIG and infinite bus with only synchronous machine and DFIG and synchronous machine in the network [22]. The STATCOM based modified P/Q control scheme of transient stability is studied for DFIG wind turbine. With the suggested scheme critical clearing time was increased by two cycle and stability is enhanced. [23] The STATCOM with mechanically switchable capacitor bank is proposed to mitigation of disturbances of DFIG based wind farm subjected to three phase fault. It shows the performance is improved and switch is reducing the cost. Simulation is carried out with MATLAB. [24]. The cooperative control strategy is developed for STATCOM for improving the dynamic performance of DFIG wind farm under three phase fault. The control parameter is optimized and simulation is carried out in PSCAD/EMTDC. [25]. Many solutions have been suggested in the literature to improve system transient stability such as SVC [39], TCSC [40], and battery energy storage system [41].

4. Sub Synchronous Oscillation

The increase of power transfer capability of long transmission lines can be achieved by reducing the line inductance. Series capacitors are one of the conventional series compensators in power systems which are used for compensation of the inductive reactance of the transmission line. However, if a resonant frequency of the transmission system is complementary to any of the torsional oscillating frequencies of the turbine generator mass-spring system, sub synchronous resonance (SSR) will develop where electric resonance of the transmission system and the torsional oscillations of the mass-spring system of the turbine generator set will be mutually excited causing serious shaft oscillations and other damages to the system [26].

4.1Introduction to SSR with DFIG.

Sub synchronous resonance is an electrical power system condition where the electricnetwork exchanges energy with a turbine generator at one or more of the naturalfrequencies of the combined system below the synchronous frequency of the system [42] Series compensation in the line results in excitation of sub synchronous currents at an electrical frequencyfergiven by

$$fer = f0 * \sqrt{Xl/Xe}$$

where, Xcis the reactance of the series capacitor, Xe is the reactance of the lineincluding that of the generator and transformer, and f0is the nominal frequency of thepower system. Generally,Xc can be varied up-to 60-70% of Xe. Therefore,fer< f0. The sub synchronous currents result in rotor torques and currents at the complementaryfrequency as fr (fr= f0-fer).These rotor currents result in sub synchronous armature voltage components that mayenhance sub synchronous armature currents to produce SSR. SSR is divided into two significant parts: Self-excitation (called as steady state SSR) and transient torques (called as transient SSR). Self-excitation is partitioned into two major parts: Induction Generator Effect (IGE), and torsional interaction (TI)

4.2. Induction Generator Effect

Induction generator effect involves only electric system dynamics. Generator armaturecurrents at sub synchronousfrequency fer produce a component of rotating mmf in thearmature air gap of angular velocity 2*pi*fer. This mmf interacts with the main field air gapmmf to produce torques at sub synchronousfrequency fer-f0and at super synchronousfrequency fer+f0. If the generator rotor torsional mode frequency fnisdifferent from the sub synchronous torque frequency f0-ferthen relatively littletorsional interaction takes place. However, because the rotor circuits are turning morerapidly than the rotating mmf, the resistance to the sub synchronous current viewed fromthe armature terminal is negative due to the commonly understood induction machinetheory. When this negative resistance exceeds the sum of the armature and networkresistance at the resonant frequencyfer, the armature currents can be sustained or grow.This phenomenon is called induction generator effect [42], [58]. Wind farm comprising squirrel cage induction generators are also susceptible to theinduction generator effect.

4.3 Torsional Interaction

Torsional interaction involves both the electrical and mechanical system dynamics. Whenthe frequency of the sub synchronous component of the armature voltage is close to oraligns with the electrical system natural frequency, the resultant sub synchronous currentwill produce a rotor torque that is phased to sustain rotor oscillation. The torques at rotortorsional frequencies may then be amplified and potentially lead to shaft failure. Thisinterplay between the electrical and mechanical system is known as torsional interaction[42], [58].

4.4 Torque Amplification

System disturbance such as fault and switching of lines in the network may excite theoscillatory torque in the shaft of the generator. The shaft torque response is not sinusoidalwith a single frequency, but contains contributions from many components includingunidirectional, exponentially decaying, and oscillatory torques from sub synchronous tomultiples of network frequency. Due to SSR, the sub synchronous frequency componentmay have large amplitude immediately following the disturbance that may be damped outsubsequently. Each occurrence of the high amplitude transient torques may lead to cyclicfatigue in the shaft system [42], [58].

4.5 Techniques for Study of SSR.

There are several techniques available for the study of sub synchronous resonance in power systems. The most common techniques are:

(a) Frequency scanning

(b) Eigenvalue analysis

(c) Electromagnetic transient simulation

In 2003, the impact of a large-scale integration of wind farms into a utility grid wasstudied [43], which focused on major interconnection issues. In this paper, bothconventional IG based wind farms and DFIG wind farms are considered. Wind farminteraction with series compensated transmission line was discussed for the first time inthis paper.In December 2005, Xc Energy released a report on the study of a series capacitor in theWilmarth-Lakefield transmission system [44]. This report specifically discussed theimpact of the series capacitor on the interconnected network and turbine generatorsconnected at various points in the network. Series compensation of 65% was consideredfor the analysis according to this report. A 107 MVA wind farm based on 100 DFIGs wasproposed at the Lakefield system. Induction generator effect and torsional interactionwere studied thoroughly using the frequency scanning method. Induction generator effectwas found to be dependent on the rotor circuit parameter and operating slip of the DFIG.For the analysis, the slip was varied between -30% to +30%. From the frequencyscanning, unstable SSR induction generation effect was detected at 10Hz. Statorimpedance and rotor impedance were found to be responsible for the resonant frequencyand equivalent negative resistance, respectively. This study suggested that when a largenumber of wind turbines are aggregated, the SSR issue might become more prominent.Different sizes of wind farms and their impact on the SSR were a major contribution ofthe work. However, no small signal analysis or electromagnetic transient studies wereperformed. However, no eigenvalueanalysis was provided to illustrate the improved stability in a closed loop system.Modeling of DFIG based wind farm connected to a series compensated transmission linewas presented in [45]. Small signal analysis and time domain simulations were carriedout in this paper. Impact of a series capacitor and control parameters on the SSRoscillation were reported. Further studies of SSR with DFIG based wind farms werereported in [46]- [49]. A detailed modeling of the DFIG based wind farm connected to aseries compensated transmission line was reported in these papers. Small signal analysisfollowed by a time-domain simulation was performed to examine the SSR conditions.DFIG converter controller design and its interactions with series capacitor were studied.Through participation factor analysis, authors established a criterion to detect andmitigate the SSR by choosing suitable controller parameters. There are two events related to SSR that have already occurred in the wind farmsconnected to a series compensated transmission line. In October 2009 a single line toground fault occurred on a 345 kV series compensated line connected to two large windfarms in Texas, of capacity ≈485 MW. After the fault, once the faulted line was cleared,the wind farm continued to operate radially with a single 345 kV line with 50% seriescompensation. Then, the SSR interaction between the wind turbine generator control andseries capacitor initiated and grew sufficiently large to damage the wind turbines asvoltage exceeded 2 pu before the series capacitor was bypassed. From the preliminary analysis it was found that the control interaction of the DFIG based wind turbinecontroller and series capacitor caused the undamped voltage oscillations [50].Another incident was witnessed in the Buffalo Ridge area of Minnesota. Many windfarms are planned and connected to the 345 kV series compensated transmission line in11southwestern Minnesota. In one case, the series compensation level was chosen to be60% in a 54-mile line. One end of the line was connected to a 150 MW wind farm. This was later confirmed as the sub synchronousresonance that was caused due to the interaction of the DFIG controller and the seriescompensated transmission line [60], [71].Other literatures used thyristor controlled series capacitor (TCSC) and static var compensator (SVC) to damp SSR in such a series compensated wind farm [31-32]. An eigenvalue analysis is presented to damp the SSR with STATCOM with IEEE second benchmark. A PI controller is designed to damp the SSR and to improve system transient stability. The robust optimization method Nelder and Mead is used to select the optimal values of the PI parameters. The study is carried out with and without STATCOM in PSCAD/EMTDC software. [33]. A SVC based damping controller is designed in [34] to mitigate the SSR of series compensated line. The SSSC and STATCOM based control strategy is in shown with IEEE-first benchmark [35] to damp the oscillation of SSR and it shows that SSSC give good performance than STATCOM. The damping controller performance of SVC and TCSC is shown in[36-37] to mitigate the SSR oscillation equipped with wind farm and simulation is carried out in PSCAD/EMTDC.A supplementary controller on the grid-side converter (GSC) control loop is designed to mitigate SSR for wind power systems based on doubly fed induction generators (DFIGs) with back-to-back converters. Different supplementary controller feedback signals and modulated-voltage injecting points are proposed and compared based on modal analysis and verified through root locus analysis to identify the optimal feedback signal and the most effective control location for SSR damping. [38]. More recently the utilizing the DFIG wind farm to mitigate the small signal oscillations and SSR in FBM is highlighted in [39,40,41,42]

4.6 SSRin Wind Farms Connected to HVDC Lines

As the application of HVDC for the wind farm interconnection grows, the threat of SSRinteraction between the wind turbines and HVDC controllers also increases. Fromprevious research it has been found that the torsional interaction of HVDC controller isless dangerous than the series compensated transmission line [59], when connected to alarge synchronous generator [53], [54], [55]. However, impact study on the IGbased wind farm has not been done thoroughly. The potential of SSR in wind farmsconnected to HVDC line was first indicated in [56]. In [57], a study of torsionalinteraction of wind turbine and HVDC controller is presented. This is demonstrated onlythrough the transient simulations. In addition, the impact of various parameters was notstudied. In this thesis, a systematic study of the potential SSR in an induction generatorbased wind farm connected to series compensated line and HVDC system is presented. Aparallel AC-DC system configuration used for the analysis of SSR with synchronousgenerator is utilized in this paper [55].

5. Conclusion

The market growth of wind generator is roughly 30%. Because of such a large penetration, the DFIG based wind generator should not be disconnected from the system. Generally, DFIG suffering from high transient current, oscillation in rotating mass of the shaft, rotor over speed, grid voltage and frequency when subjected to disturbance. There following research scope is available to maintain the grid stability from above survey.

- Small signal stability should be carried out on the base of eigenvalue sensitivity.
- It is possible that the PI controller may have a large range of parameters under different system situation. It would be interesting to develop the wide range of control parameter variations for large signal stability.
- A typical system curve for multiple DFIGs trajectory sensitivity analysis will be needed to handle large-scale wind farms.
- Generally, people has represented multiple DFIGs as one WT in modeling and simulation, it would be more important to consider more close –to –reality multiple DFIG mode.
- There should be need to coordinated controller to enhance the overall performance of the distribution.
- Required to computation of small signal stability boundaries for large wind farm and connectFACTS devices to damp oscillation or damping controller should be designed.
- It is observed that DFIG is generally operated at constant power factor, so more VAR compensating equipment is necessary.
- Under fixed voltage strategy, DFIG will support against the transient fault. But as the penetration (more than 12%) isincreased, the voltage and speedboth are reduce will requireFACTS devices and damping controller.
- In case of serious disturbances, very heavy current will flow through its own RSC and GSC converter, so they must have to disconnect and to regain the stable system there is requirement to co-ordinate the FACTS and damping controller or proper co-ordination of RSC and GSC converter is required with external signal.
- Generally, the authors have to concentrate on symmetrical fault, so there is wide scope on analysis of unsymmetrical fault with wind farms.
- STATCOM is most popular FACT device for enhance the transient stability, but as the rating of STATCOM is increased it produce harmonics so there is a scope to analysis the harmonics phenomenon with stability.
- To reduce the cost of FACT device, they must be connected at different points not at only one point, to do so, more co-ordination of FACT device is required.
- Some interesting issue to improve the stability with economic cost is co-ordinate the SMES or Battery storage device with STATCOM.
- Since wind farms are spread over a large geographical area, the specific generator speed that was used for the damping of SSR oscillation was not discussed

* A detailed sub synchronous resonance analysis should be performed with other types of wind farms connected to LCC HVDC lines and series compensated transmission lines
* Scope to design the new strategy of damping controller to mitigate SSR.
* A new approach on STATCOM is DSTATCOM is now highlighted, so there is a wide scope to mitigate SSR with this new concept.
* DFIG inbuilt converter controller do have potential to mitigate the small signal oscillations which may reduce the cost of FACTS devices.

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