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DOI: 10.1109/JSYST.2013.2297180

A Combined Approach of using SDBR and STATCOM to Enhance the Stability of Wind Farm

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Abstract: **This paper presents a method to enhance the stability of grid connected wind farm composed of fixed speed wind turbine generator system (WTGS) using a combination of small size series dynamic breaking resistor (SDBR) and static synchronous compensator (STATCOM). SDBR and STATCOM have the active and reactive power control abilities, respectively, and a combination of these units pave the way to stabilize well the fixed speed wind farm. In this study, centralized control scheme of using SDBR and STATCOM in together is focused, which can be easily integrated with wind farm. Different types of symmetrical and unsymmetrical faults are considered to evaluate the transient performance of the proposed control scheme, applicable to grid connected wind farm. The effect of multi-mass drive train of fixed speed WTGS in fault analysis along with its importance in determining the size of SDBR to augment the transient stability of wind farm is investigated. Extensive simulation analyses are performed to determine the approximate sizes of both SDBR and STATCOM units. Dynamic analysis is performed using real wind speed data. A salient feature of this work is that the effectiveness of the proposed system to minimize the blade-shaft torsional oscillation of fixed speed WTGS is also analyzed. Simulation results show that a combination of small size SDBR and STATCOM is an effective means to stabilize the wind farm composed of fixed speed WTGS.**

I. INTRODUCTION

The industry worldwide is turning increasingly to renewable sources of energy to generate electricity. Wind is the fastest growing and most widely utilized of the emerging renewable energy technologies in electricity systems at present, with a total of 194.4 GW installed worldwide at the end of 2010 [1]. Variable speed wind turbine generator system (WTGS) is getting more attraction than the fixed speed nowadays. However, fixed speed WTGS technology still retaining a sizeable share on the wind power market due to their superior characteristics such as brushless and rugged construction, low cost, maintenance free, and operational simplicity. The lifetime of wind turbine is expected more than 20 years. Therefore, it is still a matter of interest to investigate the interaction of fixed speed WTGS with power system [2].

The fixed speed WTGS that uses induction machine as wind generator has the stability problem similar to synchronous generator [3-6]. This study focuses on both transient and dynamic stability improvement issues of fixed speed WTGS. Due to the huge penetration of wind power to the grid, wind farm grid codes have been developed recently in many countries in which Fault ride through (FRT) is an important constraints to adopt with [7-11].

There are different techniques and compensating tools reported in power system literatures to augment the stability of fixe speed WTGS [6, 12-32]. Energy capacitor system (ECS) [12-13], battery energy storage system (BESS) [14-16], superconducting magnetic energy storage system (SMES) [17-19], and flywheel energy storage system (FESS) [20] are very effective tools as having both active and reactive power control abilities. STATCOM is also found to be a potential candidate to stabilize fixed speed WTGS [21-23]. The transient response of pitch controller is comparatively slow as reported in [24-25] compared to the FACTS devices used in [12-23]. Besides these, dynamic braking resistor (DBR) can be used for wind generator stabilization [26-32]. As DBR has only the active power control ability, it is good idea to incorporate reactive power compensating device along with DBR. For stability augmentation of fixed speed WTGS, series dynamic braking resistor (SDBR) [29-31] is more effective than DBR with shunt-connected topology [26-28]. In [29-30], a simulation analysis is performed using only one fixed speed WTGS that connects the grid. That study is symmetrical to distributed topology where each SDBR is connected close to the individual wind generators and differs significantly from the centralized topology using only one SDBR installed at the wind farm terminal. Incorporation of SDBR with dynamic voltage restorer (DVR) increases the system cost due to the presence of transformer and LC filter [31]. In the earlier works with SDBR [29-31], the effect of other synchronous generators that exist in a realistic power system is not evident. This study focuses on transient and dynamic stability augmentation of grid connected wind farm composed of fixed speed WTGSs using a combination of SDBR and STATCOM, the purpose of which lies to reduce the overall cost of the compensating devices.

Therefore, centralized SDBR and STATCOM are considered to be connected at the terminal of wind farm that connects the power system to observe the effectiveness of the proposed system during normal and grid fault conditions, in this study. Instead of representative wind farm model used in [29-30], where the components are expressed using simple transfer function, a realistic component modeling is considered in this study, using laboratory standard power system software package PSCAD/EMTDC [33]. The detailed six-mass drive train model is considered in fixed speed WTGS for the sake of

Manuscript Receipt Date: 1/20/2013, Revised Date: 12/6/2013.

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precise analysis. The effect of multi-mass drive train of fixed speed WTGS for fault analysis and its importance to determine the size of SDBR unit that sufficiently augments the FRT capability of wind farm are investigated in detail.

Power generation using wind energy deals with systems from engineering and science disciplines, e.g., mechanical, electrical, electronics, computer, and aerospace engineering. This study particularly focuses on two electrical systems i.e., SDBR and STATCOM including their control aspects to improve stability of wind energy conversion system along with the improvement of turbine blade-shaft torsional damping. Therefore, the study is essentially important for researchers working in systems-level and systems engineering.

To determine the minimum size required for both SDBR and STATCOM units to withstand against grid fault and to maintain constant terminal voltage during randomly varying wind speed condition, extensive simulation studies are performed. Real wind speed data measured in Hokkaido Island of Japan is used in the dynamic analysis. Both symmetrical and unsymmetrical faults are considered as network disturbances, in the analysis. One of the novel features of the study is that the effect of blade-shaft torsional oscillations of fixed speed WTGS during grid fault is analyzed and it is reported how much the oscillation can be minimized using the determined small size of SDBR and STATCOM. It is also reported how much the proposed scheme can enhance the stability of synchronous generator available in the power system. Simulation results show that the proposed scheme, which combines small size SDBR and STATCOM units can enhance the transient and dynamic stabilities of wind farm composed of fixed speed WTGSs, as well as entire power system.

II. MODEL SYSTEM

Figure 1 shows a model system used for the simulation analyses. One synchronous generator (SG) representing the main power plant is connected to an infinite bus through transformers and transmission lines respectively. Twenty wind generators in a wind farm are connected to the grid through individual transformer and a common transmission line. A capacitor bank, C, has been used for reactive power compensation of each induction generator (IG) at steady state. The value of capacitor C is chosen so that power factor of the wind generator during the rated operation becomes unity [6]. The AVR (Automatic Voltage Regulator) and GOV (Governor) control system models for SG used in this study are available in [6]. Generator parameters are shown in Table I. Centrally controlled SDBR is considered to be connected at wind farm terminal. The STATCOM is connected to point K of Fig. 1. The system base power is 100MVA.

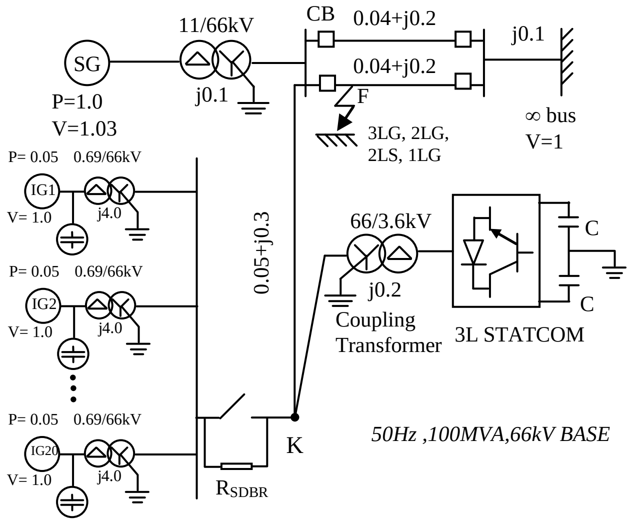


Fig. 1. Model system

TABLE I
GENERATOR PARAMETERS

SG		IG	
MVA	100	MVA	2.5
Ra (pu)	0.003	r1 (pu)	0.01
Xa (pu)	0.13	x1 (pu)	0.1
Xd (pu)	1.2	Xmu (pu)	3.5
Xq (pu)	0.7	r21 (pu)	0.035
X_d' (pu)	0.3	x21 (pu)	0.030
X_q' (pu)	0.22	r22 (pu)	0.014
X_d'' (pu)	0.22	x22 (pu)	0.098
X_q'' (pu)	0.25	H (sec)	3.3
T_{do}' (sec)	5.0		
T_{do}'' (sec)	0.04		
T_{qo}'' (sec)	0.05		
H (sec)	2.5		

III. MODELING OF WIND TURBINE

Mathematical relation for mechanical power extraction from the wind can be expressed as follows [34].

$$P_W = 0.5\,\rho\,\pi\,R^2\,V_W{}^3\,C_P(\lambda,\beta) \qquad (1)$$

Where, P_w is extracted power from the wind, ρ is the air density [kg/m^3], R is blade radius [m], V_w is wind speed [m/s] and C_p is the power coefficient which is a function of both tip speed ratio, λ, and blade pitch angle, β [deg]. The wind turbine characteristic used in this study is shown in Fig. 2 for different values of β [35]. In this study, the conventional pitch controller is considered in the simulation [34].

In this paper, the six-mass drive train model is considered for the precise analysis of WTGS as shown in Fig. 3, the details of which are available in [6, 36]. The parameters used in this study are given in Appendix. Due to the high and low stiffness of the high and low speed shafts of wind turbine the torsional oscillation analysis of wind turbine drive train is important.

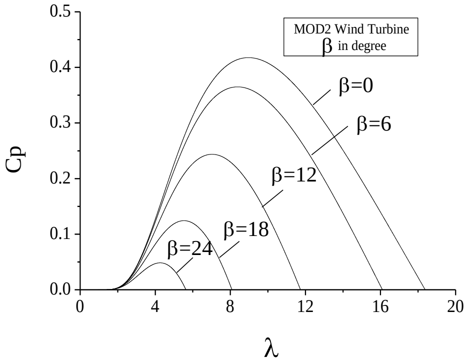


Fig. 2 C_P- λ curves for different pitch angles

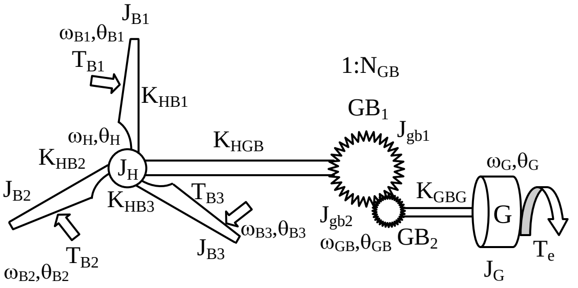


Fig. 3 The six-mass drive train wind turbine generator system

IV. MODELING AND CONTROL SCHEME

In this study, a coordinated control scheme is adopted among SDBR, STATCOM, and pitch controller to stabilize the wind farm under dynamic and network fault conditions. The coordinated control scheme is shown schematically in Fig. 4.

- In normal operation, wind farm terminal voltage deviates a lot due to the rapid wind speed fluctuations as the capacitor banks placed at the terminals of individual wind generators are designed to maintain unity power factor under rated power conditions when the wind speeds are at rated values. STATCOM will work during normal operation to maintain constant voltage at wind farm terminal and hence, terminal voltage is set as the control input of the STATCOM, in the coordinated control scheme. The STATCOM will also works during grid fault condition when the terminal voltage falls below a threshold value.
- The SDBR works only during the grid fault condition along with the STATCOM to enhance the fault ride through capability of wind farm when the terminal voltage falls below the threshold value.
- The pitch controllers are attached with individual wind generators and activate when the power exceeds the rated values of the generators. Therefore, wind generator output power is set as the input of the pitch controller. During the grid fault condition, the pitch controller will also activates when the wind generator power exceeds the rated values, especially when the fault occurs at high wind conditions.

A. SDBR

The concept of SDBR to augment the fault ride through capability of electric generator was first reported in 2004 [37]. Series dynamic braking resistor is used to balance the active power during network disturbance through electrical dissipation. A resistor is dynamically inserted in the generation circuit for short time during the grid fault, which increases the voltage at generating end and thus helps balancing power and electromagnetic torque as well.

In this study, SDRB is placed centrally to augment the FRT capability of wind farm composed of fixed speed WTGSs, as shown in Fig. 4. There are few ways to implement the switching of SDBR during fault condition. In this study, SDBR is switched on-off using standard circuit breaker, which is simple to implement but on-off conditions may lead to a limit cycle. However, soft switching scheme can easily be adopted using IGBT or GTO devices where the limit cycle issue can be resolved. Wind farm terminal voltage is reasonably chosen as the control input of the centrally placed SDBR as shown in Fig. 4. During the network fault condition, the wind farm terminal voltage as well as the voltages at individual wind generators reduces suddenly. The wind farm voltage is compared with the Reference voltage, V_{Ref} (0.9pu value is considered as reference, in this study), and SDBR is switched on instantly. The essence of SDBR is that it has current-squared relationship to dissipation the electrical power and it quickly restores the wind farm voltage that eventually helps the wind farm to be connected with the power system, fulfilling the FRT requirement of wind farm grid code.

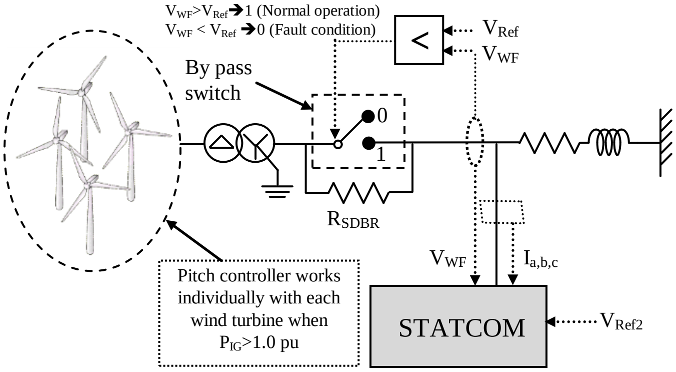


Fig. 4. Proposed co-ordinated control scheme for wind farm

B. STATCOM

Due to the limitation of state-of-the-art semiconductor switch technology, the power voltage rating is generally around 6.0 kV, with mainstream switch voltage rating at 4.5 kV. Therefore, in this work, three-level inverter based STATCOM is used to increase the output voltage for suitable connectivity with wind farm. The STATCOM total rating is considered as 50 MVA. Considering the practical viewpoints and suitability of the simulation analysis, the overall solid-state power circuit combines four three-phase inverter modules, each with nominal rating of 12.5 MVA as shown in Fig. 5.

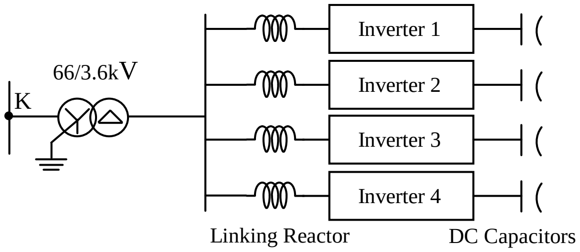
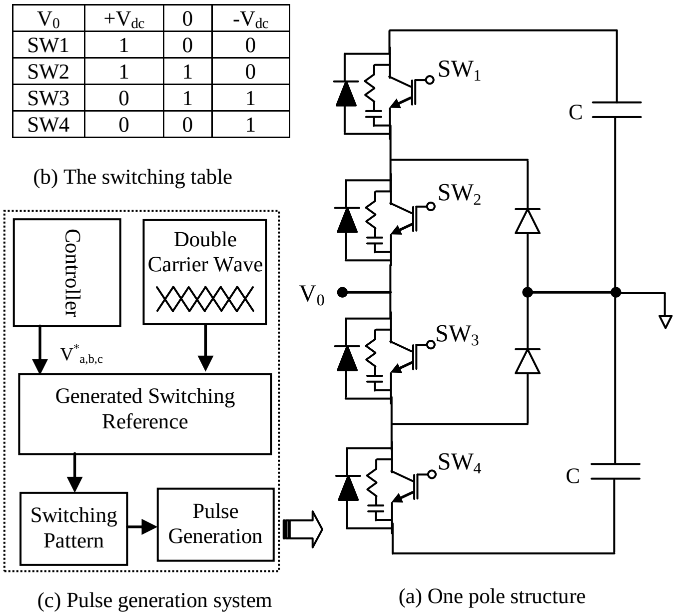


Fig. 5. Schematic diagram of STATCOM design

The one pole structure of three level IGBT inverter is shown in Fig. 6(a). The IGBT switching table and control methodology of STATCOM are shown in Fig. 6(b) and Fig. 6(c) respectively. The aim of the control is to maintain desired voltage magnitude, (V_{Ref2} in Fig. 4) at the wind farm terminal. For the control of voltage source inverter (VSI), the well-known cascaded vector control scheme is used as shown in Fig. 7.

C. Pitch Controller

The conventional pitch controller is considered in this study which progress the error signal between wind generator output power and the reference (1.0pu) through a PI controller [6]. The time delay of the servo system is considered as 5 sec and rate limiter value is chosen as 10°/sec.



V$_0$	+V$_{dc}$	0	-V$_{dc}$
SW1	1	0	0
SW2	1	1	0
SW3	0	1	1
SW4	0	0	1

(b) The switching table

(c) Pulse generation system

(a) One pole structure

Fig. 6. Schematic diagram of STATCOM switching circuit.

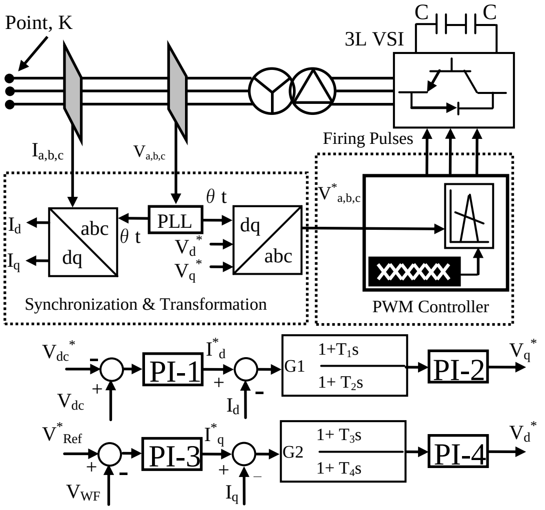


Fig. 7. Control block diagram of 3L VSI based STATCOM

D. *Sizing of SDBR and STATCOM Considered*

One of the objectives of this study is to get some approximate idea about the size of SDBR and STATCOM required to augment the fault ride through of a grid-connected wind farm. Earlier study shows that the size of STATCOM required to stabilize a grid-connected wind farm is almost close to the MVA rating of wind farm itself [22], when only STATCOM is the compensating device used at the generation side. On the other hand, a 1.0 pu breaking resistor might be sufficient to stabilize the system when only SDBR is used.

When both STATCOM and SDBR are used in the system for stabilizing the wind farm during grid fault condition, the optimum sizing of the devices also depends on the types and duration of faults and grid code requirements. Therefore, analytical method may not be appropriate to determine the optimum sizing, in this case. In the following section, a detailed simulation study is carried out considering different types of faults, fault duration, wind farm recent grid codes, etc, which will give an idea about the approximate sizing of SDBR and STATCOM required to stabilize the system.

V. SIMULATION ANALYSES

The system shown in Fig. 1 is simulated using laboratory standard power system simulator PSCAD/EMTDC [33]. FORTRAN program is incorporated with PSCAD to implement the six-mass drive train model of WTGS. The time step is chosen 0.00002 sec. The simulation time is chosen 5.0 sec and 600 sec for transient and dynamic stability analyses, respectively.

In the simulation study, it is assumed that wind speed is constant and equivalent to the rated speed during transient analysis. This is because it may be considered that wind speed does not change dramatically during the short time interval of the simulation for the transient characteristic analysis. Wind farm grid code is fairly important to analyze the transient characteristics of WTGS. Fault ride through (FRT) or low voltage ride through (LVRT) is now required to be considered for connection of large scale wind farms in power systems. The FRT complaint wind farm must remain connected to the system during network disturbance, because a shutdown of large wind farm can have a serious effect on the power system normal operation. In this study, the simulation results are described in light of the recent grid code, set by E.On Netz, recently known as TenneT TSO GmbH, shown briefly in Fig. 8 [10-11]. Symmetrical three-line-to-ground (3LG), and unsymmetrical double-line-to-ground (2LG), double-line-to-line (2LS), and single-line-to-ground (1LG) faults are considered for transient analysis. Simulation analyses are described in the following sections.

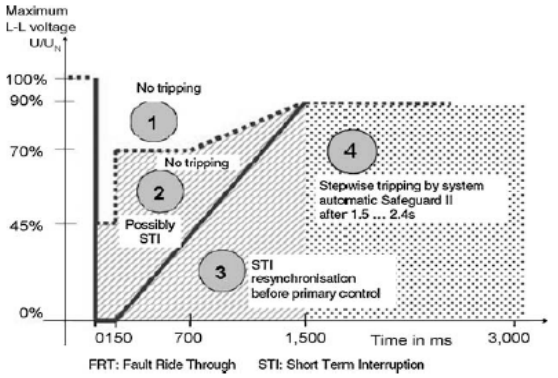


Fig. 8. Low voltage ride-through standard set by E.On Netz

A. *Transient Analysis using Lumped Model of WTGS Considering only SDBR*

In this case, one mass lumped model is used as the drive train of fixed speed WTGS and the transient effect of SDBR are demonstrated considering a 100msec 3LG fault. At first, a 1.0pu (based on system base) SDBR is inserted at the wind farm terminal and responses of voltages at different wind generators and wind farm terminal are shown in Fig. 9. Figure 9 presents the expected result that FRT is not possible unless SDBR or other compensative tools are considered. Voltage responses with 1.0pu SDBR and reduced value of SDBR are shown in Fig. 10. Using the same values the real power and IG rotor speed responses for WTGS-1 are shown in Figs. 11 and 12, respectively. From Fig. 11, it is seen that too large value of SDBR may cause overloading of wind generator and too small value delays the voltage recovery shown in Fig. 10. In this analysis, a 0.25pu SDBR found to be optimum to augment the FRT of wind generator considering one mass lump model. However, for longer duration fault (150msec), the system is found to be unstable even with a 1.0pu SDBR as can be seen in Fig. 13. One possible reason might be that GOV control of synchronous generator is not sufficient enough to survive against longer duration fault without additional compensating device which may have some impact on the overall system. In addition, the IG may require some reactive power support to re-establish its electromagnetic torque quickly during longer fault condition.

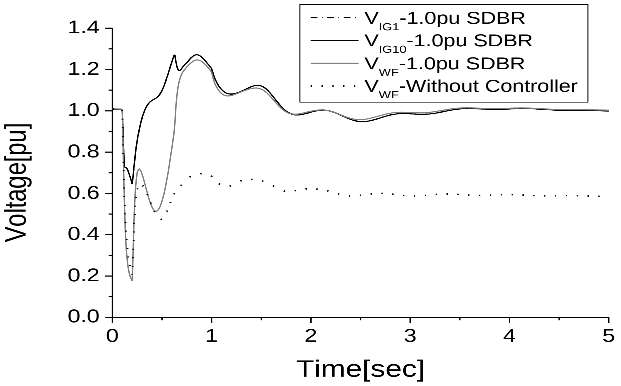


Fig. 9. Voltage responses (100msec fault, one-mass, 3LG)

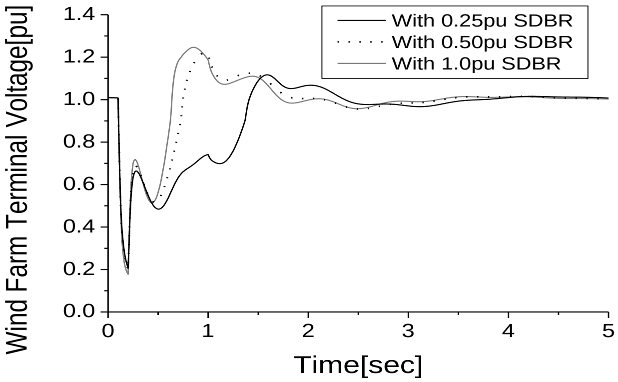


Fig. 10. Voltage responses with different values of SDBR (100msec fault, one-mass 3LG)

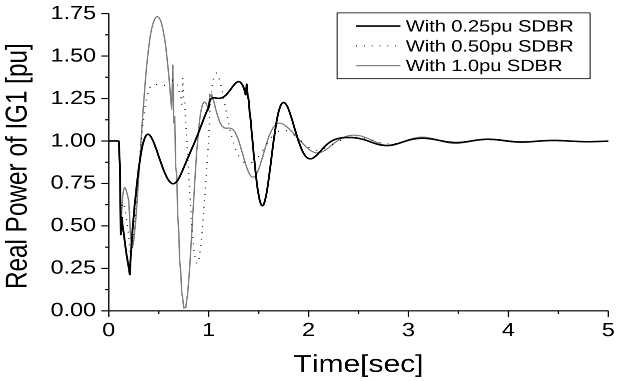


Fig. 11. Real power of IG-1 with different values of SDBR (100msec fault, one-mass, 3LG)

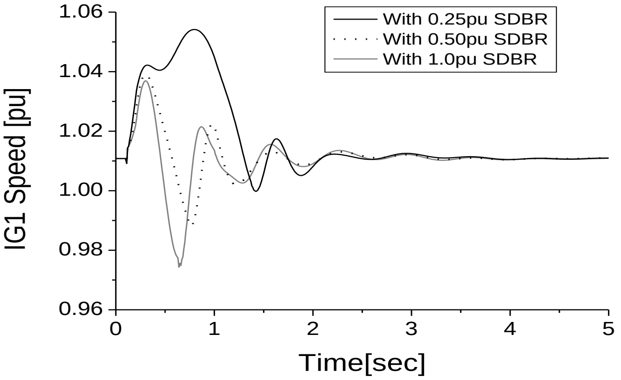


Fig. 12. Rotor speed of IG-1 with different values of SDBR (100msec fault, one-mass 3LG)

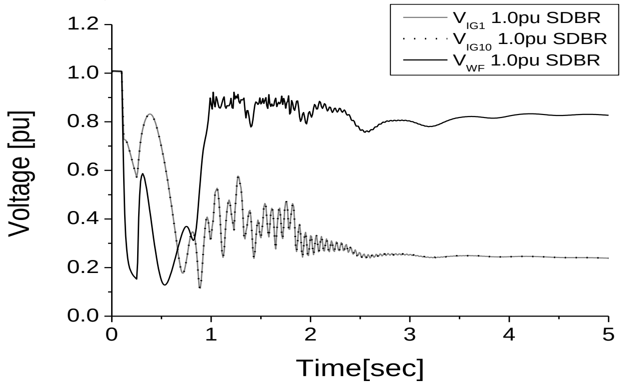


Fig. 13. Voltage responses with different values of SDBR (150msec fault, 3LG)

B. Transient Analysis using Six-Mass Drive Train of WTGS Considering only SDBR

In this case, six-mass drive train model of fixed speed WTGS is used and the transient effect of SDBR are analyzed considering both 100 and 150msec 3LG faults. The terminal voltage of wind farm for different values of SDBR are shown in Fig. 14 for the fault with 100msec. It is seen that SDBR with 0.25pu value is not sufficient to achieve FRT when six-mass model is considered. At 0.45pu SDBR the system is found to be stable with

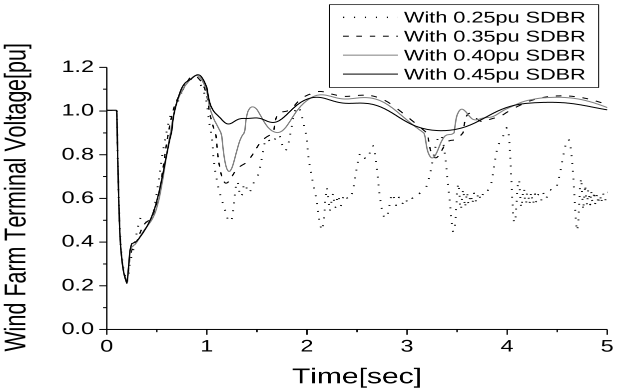


Fig. 14. Voltage responses with different values of SDBR (100msec sec fault, multi-mass, 3LG)

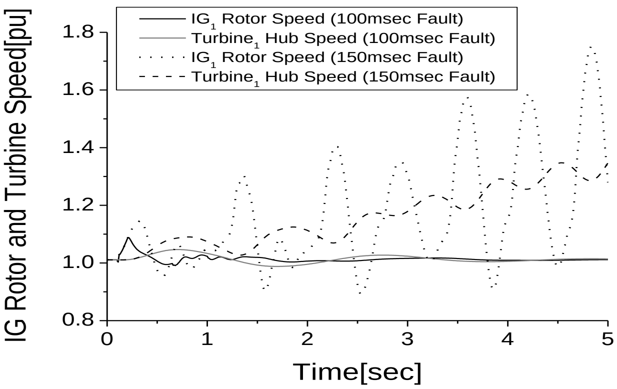


Fig. 15. IG rotor and turbine hub speed of WTGS-1 with SDBR value of 0.45pu (100 and 150 msec faults, multi-mass 3LG)

100ms 3LG fault. The IG rotor and turbine speed of WTGS-1 are shown together in Fig. 15 using 0.45pu SDBR for both 100 and 150 sec faults and WTGS is found to be unstable for longer fault duration. The synchronous generator becomes stable quickly as can be seen in Fig. 16 for both 100 and 150 msec faults, though SG is found unstable for longer fault duration when SDBR is not considered. The power and energy dissipated by the 0.45pu SDBR is shown in Fig. 17. It is needed to mention that the low speed shaft stiffness of six-mass drive train model has significant effect on the fault analysis of fixed speed WTGS. This is because the torque stress on shaft has direct influence on stiffness and rotational speed as reported in [6]. The turbine and generator rotor speed oscillations considering different values of shaft stiffness are demonstrated in Fig. 18.

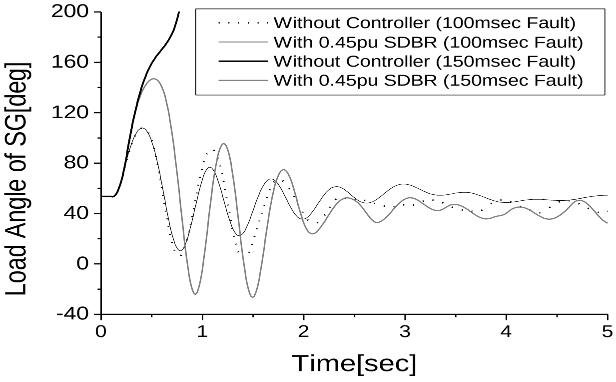


Fig. 16. Load angle of SG (100 and 150msec faults, multi-mass, 3LG)

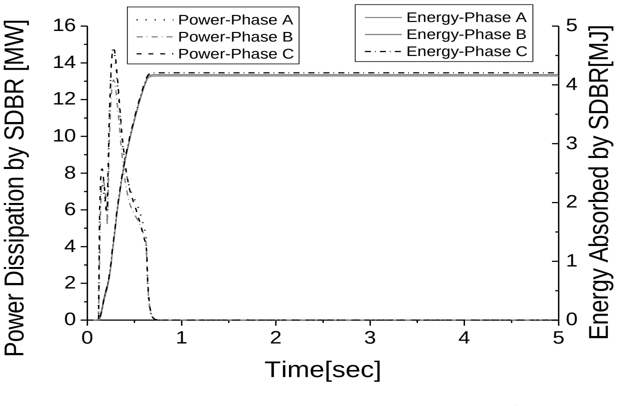


Fig. 17.Power and Energy dissipated by SDBR (100msec fault, multi-mass, 3LG)

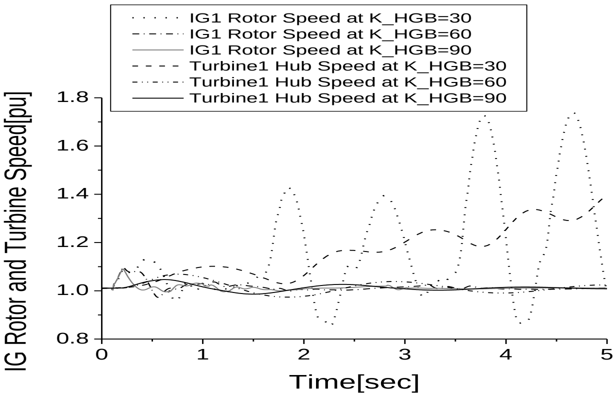


Fig. 18. Effect of shaft stiffness on fault analysis (100msec fault, multi-mass, 3LG)

Therefore, it is needed to consider multi-mass drive train model of WTGS for the fault analysis using SDBR. Also, it may be difficult to achieve the FRT of power system connected wind farm as per grid code, especially in the case for longer fault duration, using SDBR only.

C. *Transient Analysis with SDBR & STATCOM*

In this section, extensive simulation analysis is presented using different values of SDBR and STATCOM to determine the minimum value of the proposed system that is sufficient to augment the FRT of wind farm as described below.

1) *SDBR & 50MVA STATCOM*

At first, a 3LG fault of 150msec is considered to occur at the fault point F of the model system shown in Fig. 1. STATCOM rating is considered same as wind farm rating, i.e., 50MVA. The terminal voltage of wind farm with 50MVA STATCOM and different values of SDBR are shown in Fig. 19. It is seen that using only a 50MVA STATCOM is sufficient to overcome the 150msec fault and meet the grid code requirement. 50MVA STATCOM along with 0.45pu SDBR and a reduced 0.15pu SDBR can augment the fault ride through better than using only STATCOM. IG rotor speed and turbine speed of WTGS-1 shown in Fig. 20 also validates the effectiveness of the combined use of STATCOM and SDBR. However, incorporation of a 50MVA STATCOM increases the total investment cost of the overall system which can be reduced by minimizing the size of STATCOM unit and finding the suitable size of SDBR unit.

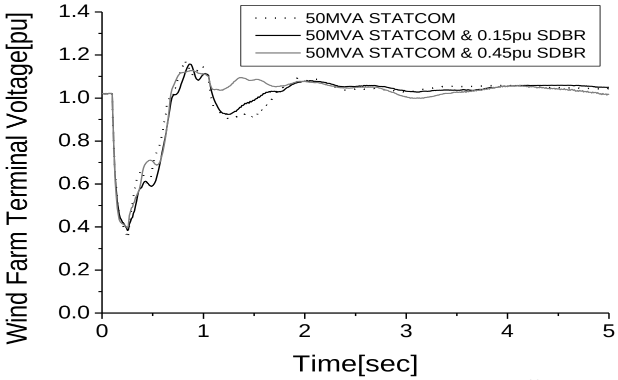


Fig. 19. Voltage responses with 50MVA STATCOM and different values of SDBR (150msec fault, multi-mass, 3LG)

2) *SDBR & 12.5MVA STATCOM*

In this analysis, 3 inverter modules of STATCOM shown in Fig. 5 are switched off and therefore, a 12.5MVA STATCOM is in service. SDBR value is kept constant at 0.45pu and a 3LG fault with 100msec and 150msec are considered. The response of wind farm terminal voltage is shown in Fig. 21. The load angle response of SG is also shown in Fig. 22. It can be said that integration of a small STATCOM with 0.45pu SDBR cannot augment the FRT capability of wind farm as per grid code shown in Fig. 8 for a 150msec fault, though it shows better FRT characteristic than using only 0.45pu SDBR as can be seen from Figs. 14 and 21, in the case of 100ms fault. The transient stability improvement of synchronous generator is also not evident for longer fault duration, in this case, as can be seen from Figs. 16 and 22.

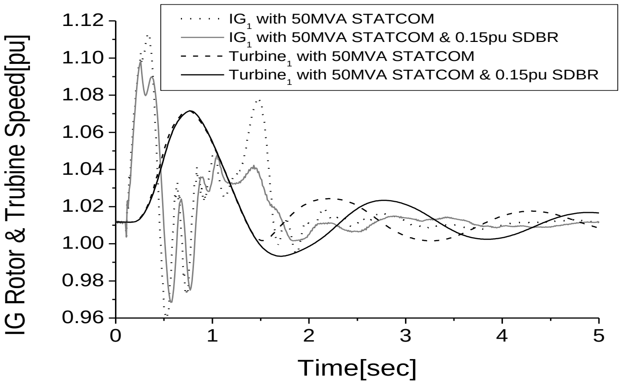


Fig. 20. IG rotor and turbine speed of WTGS-1 with 50MVA STATCOM and different values of SDBR (150msec fault, multi-mass, 3LG)

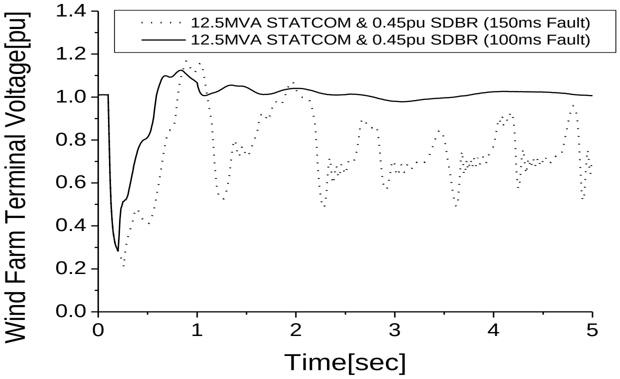


Fig. 21. Voltage responses with 12.5MVA STATCOM and 0.45pu SDBR (100 and 150msec faults, multi-mass, 3LG)

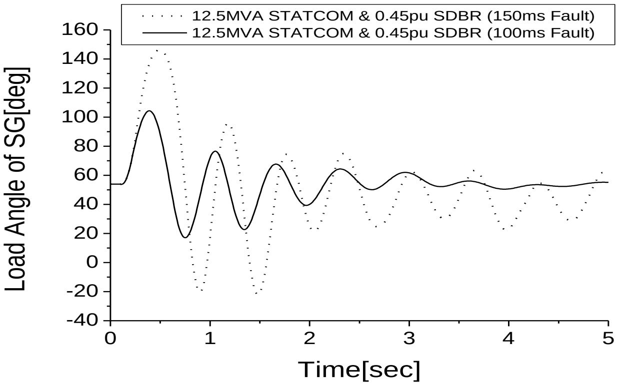


Fig. 22. Load angle of SG with 12.5MVA STATCOM and 0.45pu SDBR (100 and 150msec faults, multi-mass, 3LG)

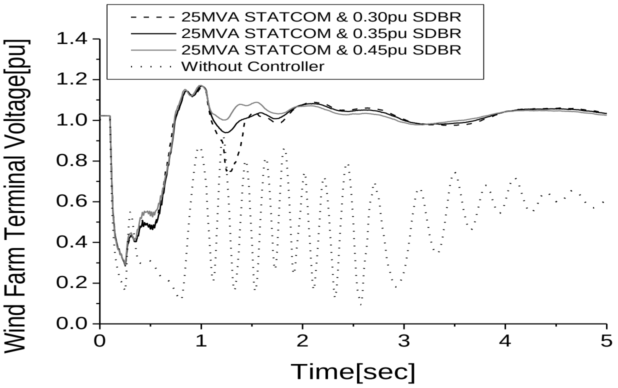


Fig. 23. Voltage responses with 25MVA STATCOM and different values of SDBR (150msec fault, multi-mass, 3LG)

3) *SDBR & 25MVA STATCOM*

In this analysis, 2 inverter modules of STATCOM shown in Fig. 5 is switched off and therefore 25MVA STATCOM is in service. Wind farm terminal voltage with 25MVA STATCOM and different values of SDBR are shown in Fig. 23, considering 150msec 3LG fault. The responses of IG rotor and turbine speed of WTGS-1 are shown in Fig. 24. It is seen that a 0.35pu SDBR along with 25MVA STATCOM gives sufficient FRT improvement of wind farm that also satisfies the grid code. Therefore, this combination is used as the base case for rest of the analysis, in this study. The responses of reactive power and DC-link voltage of STATCOM are shown in Figs. 25 and 26,

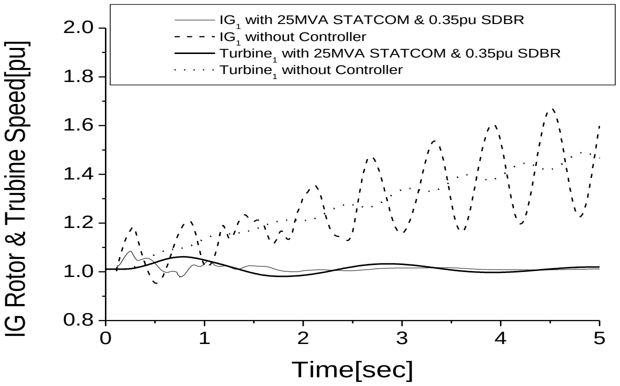


Fig. 24. IG rotor and turbine speed of WTGS-1 with 25MVA STATCOM and 0.35pu SDBR (150msec fault, multi-mass, 3LG)

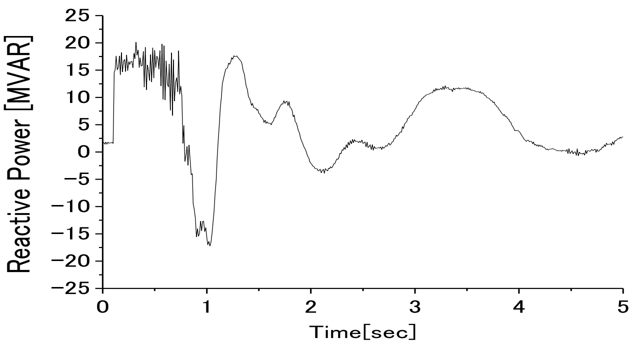


Fig. 25. Reactive power or STATCOM (150msec fault, multi-mass, 3LG)

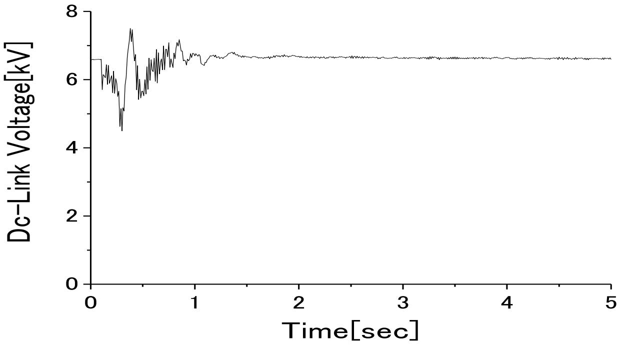


Fig. 26. DC-link voltage of STATCOM (150msec fault, multi-mass, 3LG)

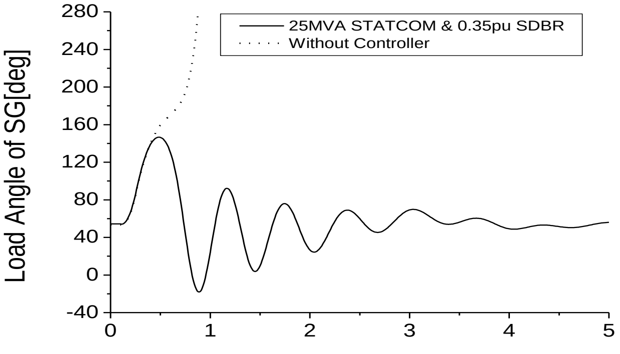


Fig. 27. Load angle of SG with 25MVA STATCOM and 0.35pu SDBR (150msec fault, multi-mass, 3LG)

respectively. It is found that the transient stability of synchronous generator improves significantly using this combination as can be seen from Fig. 27.

D. Unsymmetrical Fault Analysis

Using the combination of reduced 0.35pu SDBR and 25MVA STATCOM, the FRT of the wind farm for 150 duration unsymmetrical faults are analyzed. The responses of wind farm terminal voltages for 2LG, 2LS, and 1LG faults are shown in Fig. 28. From this figure, it can be understood that 0.35puSDBR and 25MVA STATCOM is even augments the wind farm FRT capability for unsymmetrical faults. The improvement of transient stability of synchronous generator is also evident for this combination as can be seen from Fig. 29.

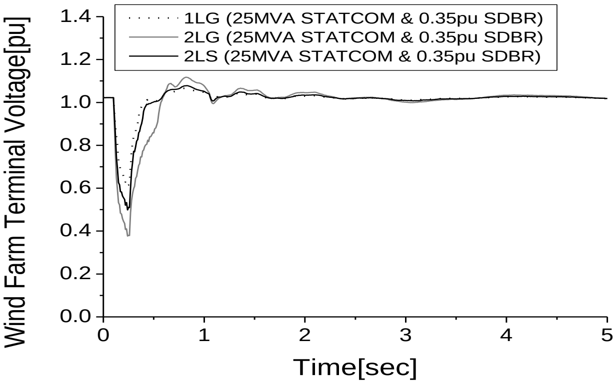


Fig. 28. Voltage responses with 25MVA STATCOM and 0.35pu SDBR (150msec fault, multi-mass, 2LG, 2LS, 1LG)

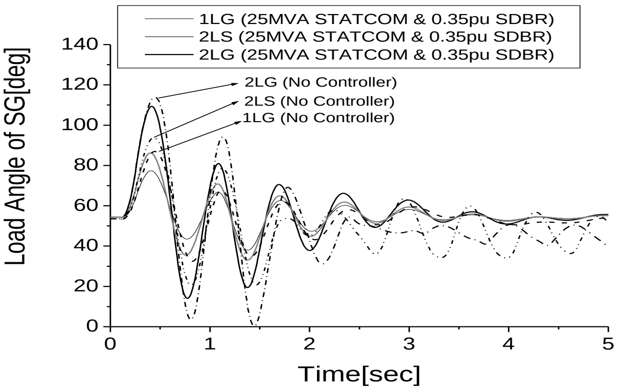


Fig. 29. Load angle of SG with 25MVA STATCOM and 0.35pu SDBR (150msec fault, multi-mass, 2LG, 2LS, 1LG)

E. Blade-Shaft Torsional Oscillation Reduction of WTGS

In this analysis, it is observed that how much the blade-shaft torsional oscillations of fixed speed WTGS can be reduced using the proposed 0.35pu SDBR and 25MVA STATCOM, when symmetrical 3LG fault occurs in power system. The high speed side of the shaft between generator and gearbox is relatively stiff compared to low speed side of the shaft between gearbox and turbine hub. The eigen frequency of the high speed shaft is about 30–40 Hz. On the other hand the low speed shaft natural frequency is about 2–3 Hz [36]. The symmetrical and unsymmetrical faults cause 50 Hz and 100 Hz torque oscillations, respectively, in the induction generator of fixed speed wind turbine generator system [6]. Due to the high stiffness of shaft between generator and gearbox, this oscillations is expected to be reached at the gearbox. Therefore, proper care should be taken to damp out the torque oscillations.

The return maps of high speed shaft torque, low speed shaft torque, and torque between hub and blade with and without considering the proposed scheme are shown in Figs. 30-32, respectively, for WTGS-1 of the wind farm. It is found that the proposed scheme can reduced well the blade-shaft torsional oscillations of fixed speed WTGS. It is expected that 50Hz torque oscillation will be transmitted to the high speed shaft as can be understood also from Fig. 30. Due to relatively high spring constant of high-speed shaft, those oscillations reach to the gearbox and then it is damped out as can be seen from Figs. 31-32, when the SDBR and STATCOM are used together.

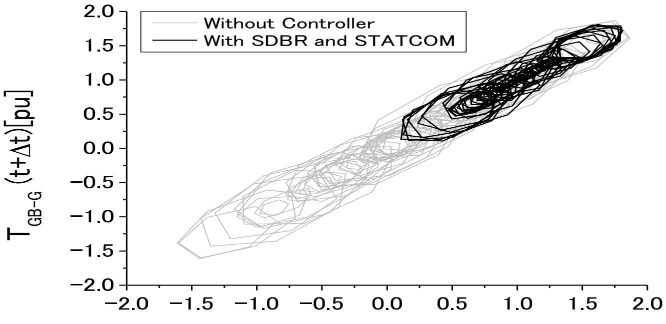


Fig. 30. Return map for high speed shaft torque (3LG)

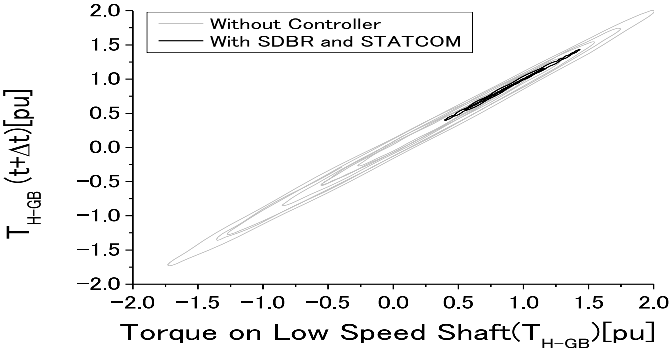


Fig. 31. Return map for low speed shaft torque (3LG)

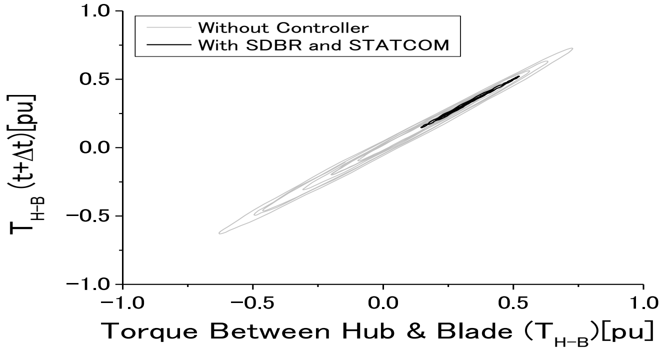


Fig. 32. Return map for torque between hub and blade-1 (3LG)

F. Dynamic Analysis

Real wind speed data measured at the Hokkaido Island, Japan is used in different WTGSs of the wind farm as shown in Fig. 33. It is seen that using the reduced value of STATCOM can even compensate the reactive power demand of wind farm terminal during normal operation, and therefore, can maintain the terminal voltage at the desired level set by transmission system operators (TSOs) as shown in Fig. 34.

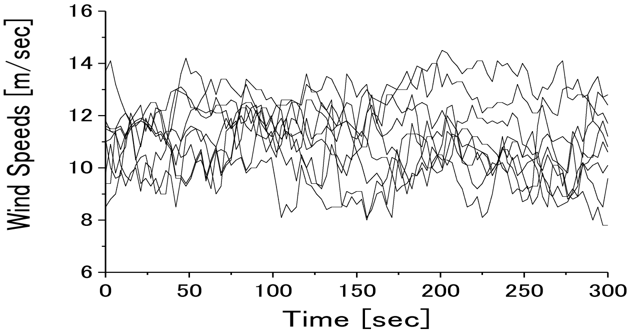


Fig. 33. Wind speed data

VI. Conclusions

This paper focuses on the transient and dynamic stability augmentation of grid connected wind farm composed of fixed speed wind turbine generator systems using a combination of SDBR and STATCOM in a cost-effective proportion. From the extensive simulation analyses, it is found that a 0.3-0.35pu SDBR (based on system base) and 20-25MVA STATCOM (40-50% of the wind farm capacity) is a good proportion to stabilize the transient and dynamic stabilities of the wind farm. This proportion is considered for analyzing all types of

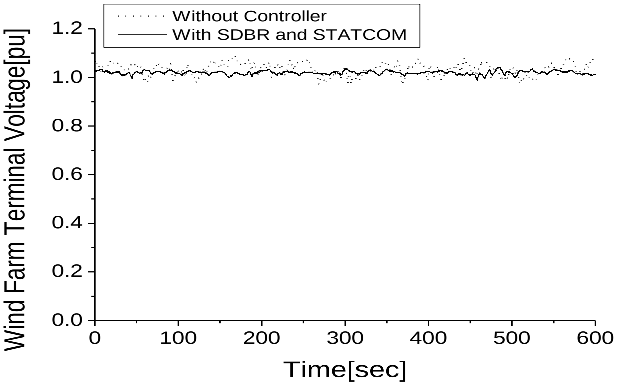


Fig. 34. Wind farm terminal voltage at randomly varying wind speed

symmetrical and unsymmetrical fault conditions and it is found that wind farm FRT requirement is fulfilled as per recent grid code. It is also investigated that this proportion can significantly minimize the blade-shaft oscillation of the fixed speed WTGS, which is one of the important observations from this study. Through the extensive simulation analysis few more relevant observations and are given below for further study on SDBR and STATCOM for stability augmentation of grid connected wind generators.

1. It was found that only SDBR may not fulfill the FRT requirement of wind farm as per recent grid code when it is connected to power grid, especially for longer duration of fault case scenario. The other generators available in the power system may have some pessimistic impact during the fault ride through of wind farm for longer duration fault as the braking resistor is dynamically inserted in series, in this configuration.
2. To determine the size of the SDBR precisely that is inserted at the terminal of the wind farm composed of fixed speed WTGSs, multi-mass drive train model should be considered in the analysis.
3. A pertinent proportion of SDBR and STATCOM is eventually related to active and reactive power balance and thus special attention should be given to determine the size of SDBR and STATCOM to augment dynamic and transient stability of power system connected wind farm.

Finally, it is concluded that if the capacity of SDBR and STATCOM can be chosen properly, the combination will be a cost-effective means to augment the dynamic and transient stability of grid connected wind farm composed of fixed-speed wind turbine generator systems.

VII. Appendix

The six-mass and three-mass drive train parameters in per unit based on high speed rotation are as follows [6,36]:

Inertia Constants		Spring Constants	
$H_{B(1,2,3)}$	0.95	$K_{HB(1,2,3)}$	1259.8
H_H	0.02	K_{HGB}	60.0
H_{GB}	0.13	K_{GBG}	1834.1
H_G	0.30		

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