This is the author's version of an article published in Energy Conversion and Management. Changes were made to this version by the publisher prior to publication. DOI: https://doi.org/10.1016/j.enconman.2011.02.001

Variable Speed Wind Turbine Generator System with Current Controlled Voltage Source Inverter

S. M. Muyeen* and J. Tamura

*Dept. of Electrical Engineering, The Petroleum Institute, Ruwais Building, Abu Dhabi, UAE

Dept. of EEE, Kitami Institute of Technology, 165 Koen-cho, Kitami, 090-8507, Japan.

E-mail: *muyeen0809@yahoo.com*

Abstract: *The present popular trend of wind power generation is to use variable speed wind turbine (VSWT) driving a doubly fed induction generator (DFIG), wound field synchronous generator (WFSG) or permanent magnet synchronous generator (PMSG). Among them, stability analyses of DFIG type of VSWT have already been reported in many literatures. However, transient stability and low voltage ride through (LVRT) characteristics analyses for synchronous generator type of VSWT is not sufficient enough. This paper focuses on detailed LVRT characteristic analysis of variable speed wind turbine driving a PMSG (VSWT-PMSG) with current controlled voltage source inverter (CC-VSI). Modeling and suitable control strategies for overall system are developed to augment the low voltage ride through capability of variable speed wind generator, considering recent wind farm grid code. Both symmetrical and unsymmetrical faults are analyzed as network disturbances in this paper. The permanent fault due to unsuccessful reclosing of circuit breakers is taken into consideration, which is a salient feature of this study. Moreover, the dynamic characteristic is analyzed using real wind speed data measured in Hokkaido Island, Japan. The proposed control scheme is simulated by using the standard power system simulation package PSCAD/EMTDC and results are verified by comparing that of voltage controlled voltage source inverter scheme available in power system literature.*

Keywords: *Variable speed wind turbine (VSWT), low voltage ride through (LVRT), permanent fault, permanent magnet synchronous generator (PMSG), current controlled voltage source inverter (CC-VSI), and frequency converter.*

Research Abstract:

- Current Controlled Voltage Source Inverter
- Low Voltage Ride Through of Wind Farm
- Variable Speed Wind Turbine Driven Permanent Magnet Synchronous Generator

1. Introduction

Electrical power generation from the wind energy is getting much attention throughout the world due to environmental problems such as global warming and the exhaustion of fossil fuel. In 2007, 20,000 MW wind power was installed all over the world, bringing world-wide installed capacity to 94,112 MW. This is an increase of 31% compared with the 2006 market, and represents an overall increase in the global installed capacity of about 27% [1]. In the past few years, the variable speed wind generators have become more popular than the fixed speed ones [2]. One of the reasons is that the former has the ability to extract maximum power from the wind due to its variable speed operation. A doubly fed induction generator (DFIG), wound field synchronous generator (WFSG), and permanent magnet synchronous generator (PMSG) are variable speed wind generators. Among them, operation and stability analyses of DFIG type of variable speed wind turbine (VSWT) have been reported in many researches [3-7]. On the other hand, though the stability analyses of conventional synchronous generators have been extensively reported in many literatures [8-9], the analysis is still insufficient for synchronous generators using full rating of frequency converters which are used in variable speed operation of wind generators. A detailed study on VSWT driving a WFSG is presented in [10], where both dynamic and transient stability analyses are presented. However, in this paper, analyses of operation and stability of VSWT driving a permanent magnet synchronous generator are emphasized.

Permanent magnet machines are characterized as having large air gaps, which reduce flux linkage even in machines with a lot of magnetic poles [11-12]. As a result, low rotational speed generators can be manufactured with relatively small sizes with respect to its power rating. Moreover, gearbox can be omitted due to low rotational speed in PMSG wind generation system, resulting in low cost. In a recent survey, gearbox is found to be the most critical component, since its downtime per failure is high in comparison to other components in a wind turbine generator system (WTGS) [13].

Variable speed wind turbine driven PMSG is connected to the grid through a frequency converter. Two types of frequency converter topologies are available those can be used for variable speed operation of permanent magnet synchronous generator In the first topology, the PMSG should be connected to the grid using a rectifier, boost converter, DC-link, and grid side inverter [14, 15]. In the second, the PMSG grid interfacing is made through a generator side converter, dc-link, and grid side inverter [16]. The generator side converter used in second topology and grid side inverters used in both topologies can be a two level [15, 16] or three-level [17] structure. As this study focuses mainly on the control strategy of grid side inverter, a simple two level structure is considered in the first frequency topology discussed earlier.

A generator side converter [16] or a boost converter [15, 18] usually is used for maximum power point tracking (MPPT) control. The grid side inverter is used to control the grid voltage as desired level set by transmission system operators (TSOs) and DC-link voltage, which is demonstrated in [15] based on voltage controlled voltage source inverter (VC-VSI) scheme. A current controlled inverter is also applicable in VSWT-PMSG as demonstrated in [19], grid voltage and DC-link voltage regulation are not adopted there. The converter/inverter used in VSWT-PMSG can be controlled using nonlinear control [20], which is not easy to implement. Another popular way is to use the vector control scheme [15, 16], where it is difficult to determine the parameters of 4 cascaded PI controllers for all operating conditions.

In this study, the frequency converter composed of rectifier, boost converter, and current controlled voltage source inverter (CC-VSI) is proposed for the operation and control of VSWT-PMSG. CC-VSI is adopted in this study to obtain best performance in all operating condition as well as to avoid the intricacy of controller designing. The detailed modeling and suitable control strategies are developed for the overall system. The dynamic characteristic is analyzed using rapidly and quickly changing real wind speed data which is measured in Hokkaido Island, Japan. The low voltage ride through (LVRT) characteristic of the wind generator system is analyzed considering both symmetrical and unsymmetrical faults as network disturbances. The permanent fault due to unsuccessful reclosing of circuit breakers is also analyzed. The circuit breakers are usually reclosed automatically to improve service continuity. The re-closure may be either high-speed or with time delay. High-speed re-closure refers to the closing of circuit breakers after a time just long enough to permit fault-arc de-ionization. However, high-speed re-closure is not always acceptable. Reclosure into a permanent fault, i.e., unsuccessful reclosure may cause system instability. Thus, the application of automatic reclosing is usually constrained by the possibility of a persistent fault, which would create a second fault after reclosure. It should be noted that, the second fault occurs in such a condition when the system is not in stable position and therefore, it is important to see whether the proposed control system can stabilize the system or not during permanent fault. This is one of the salient features of this study. The recent wind farm grid code is considered when the LVRT characteristics are analyzed. The validity of the proposed system is verified by simulation analyses carried out by using PSCAD/EMTDC. Moreover, a comparison of the results for the proposed CC-VSI and voltage controlled voltage source inverter (VC-VSI) which is available in archived literature [15] are performed for both symmetrical and unsymmetrical fault conditions. Finally, it is concluded that the proposed VSWT-PMSG with CC-VSI can operate well in both dynamic and transient conditions.

2. Wind Turbine Modeling

The mathematical relation for the mechanical power extraction from the wind can be expressed as follows [21]:

$$P_w = 0.5\rho\pi R^2 V_w^{\ 3} C_P(\lambda,\beta) \tag{1}$$

where, P_W is the extracted power from the wind, ρ is the air density [kg/m^3], R is the blade radius [m], V_w is the 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 characteristics used in this study is shown in Fig. 1. The numerical explanation of it is available in [22].

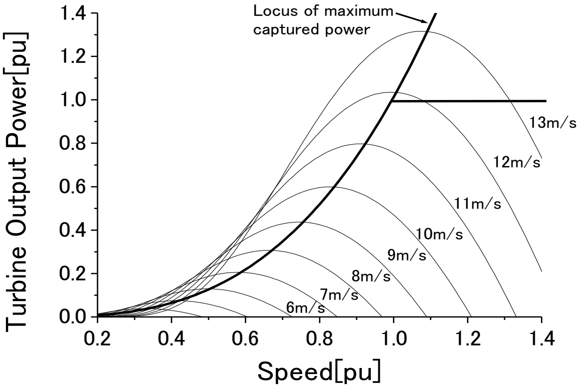

Fig. 1. Turbine characteristic with maximum power point tracking

In variable speed wind turbines, when the wind speed changes, the rotational speed of wind turbine is controlled to follow the maximum power point trajectory. Since the precise measurement of the wind speed is, in general, difficult, it is better to calculate the maximum power, P_{max}, without the measurement of wind speed as shown in eq.(2).

$$P_{max} = 0.5\rho\pi R^2 \left(\frac{\omega_r R}{\lambda_{opt}}\right)^3 C_{p\_opt} \tag{2}$$

where λ_{opt} and C_{p_opt} are optimum values of tip speed ratio and power coefficient, respectively. From eq.(2), it is clear that the maximum generated power is proportional to the cube of rotational speed as shown in eq.(3). The MPPT searching procedure can be explained using a simple block shown in Fig. 2.

$$P_{max} \propto \omega_r^{\ 3} \tag{3}$$

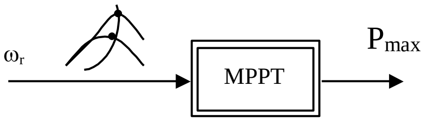

Fig. 2. MPPT searching block

The range of rotor speed variation is, in general, approximately 5 to 16 rpm. During the control of generator side boost converter, the maximum power, P_{max}, is calculated based on the MPPT, which becomes the reference power, P_{ref}, for the converter. If this reference power is greater than the rated power of PMSG, then the pitch controller shown in [16] is worked to control the rotational speed. Therefore, the PMSG output will not exceed the rated power.

3. Modeling and Control Strategies of VSWT-PMSG

In the simulation analyses, the PMSG model available in the package software PSCAD/EMTDC [23] is used. The nominal speed is considered as the maximum rotor speed. The pitch controller activates when the rotor speed exceeds the maximum rotor speed. In this study, the direct drive VSWT-PMSG equipped with a fully controlled frequency converter is used in the analyses. The frequency converter consists of rectifier, boost converter, and grid side DC/AC current controlled voltage source inverter (CC-VSI). The inverter model is a standard 3-phase two-level unit, composed of six IGBTs and antiparallel diodes.

Sinusoidal pulse width modulation (PWM) controller, composed of three main circuits (i.e., high-frequency carrier circuit, sinusoidal modulating reference signal circuit, and the interpolated firing pulse circuit), is modeled on the PSCAD /EMTDC software, which generates the switching signals for the IGBT gates in both boost converter and grid side inverter. The interpolated firing pulse circuit is a simulation technique concerned with generating firing pulses through interpolation procedure. This allows for exact switching between time steps based on a comparison between the sinusoidal reference and the high-frequency carrier signals. The triangular carrier frequency is chosen 1000 Hz for the converter and 1050 Hz for the inverter respectively.

A. Rectifier

The AC output voltage of PMSG is converted to DC voltage by a diode rectifier circuit. Simple bridge rectifier circuit is considered herein.

B. Boost Converter

It consists of an inductor, an IGBT switch, a diode, and the DC-link capacitor. Its purpose is to control the rectifier output current and power. The gate signal is generated depending on the duty cycle, D, as shown in Fig. 3.

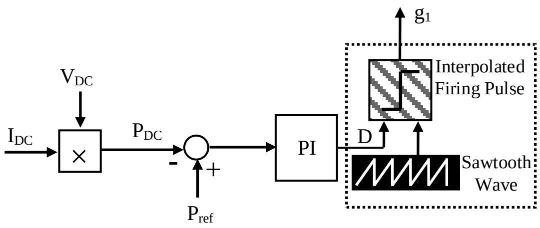

Fig. 3. Control block of boost converter

C. Grid Side Current Controlled Voltage Source Inverter

The current control VSI has the bidirectional real and reactive power control ability, avoiding the intricacy of the controller designing. Based on the inverter switching functions, inverter simulation model shown in Fig. 4 has been developed. The desired and actual currents are compared and the error signal is determined. Then the error signal is processed through the sinusoidal PWM controller to generate interpolated firing pulses of the IGBT switches of the VSI. Considering VSI connected with the ac network through the coupling transformer, it can be derived easily that real and reactive powers of the VSI are proportional to the d and q components of its current phasor. If we neglect the switching losses and harmonics, then the real power is proportional to the dc-link voltage of the VSI. On the other hand, the terminal voltage at the high voltage side of the transformer can be maintained constant by the reactive power control of VSI. Based on this concept, a very simple VSI control strategy has been developed in this work. Depending on the inverter switching functions, a very simple

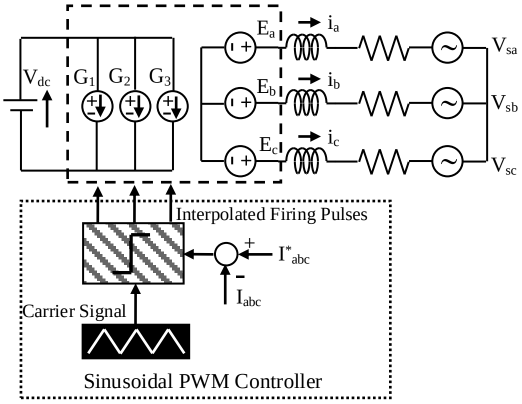

Fig. 4. Simulation model of PWM-VSI

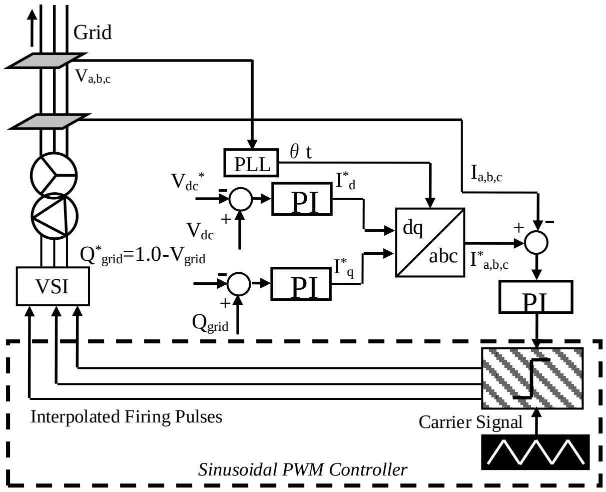

Fig. 5 Control block of the current controlled VSI

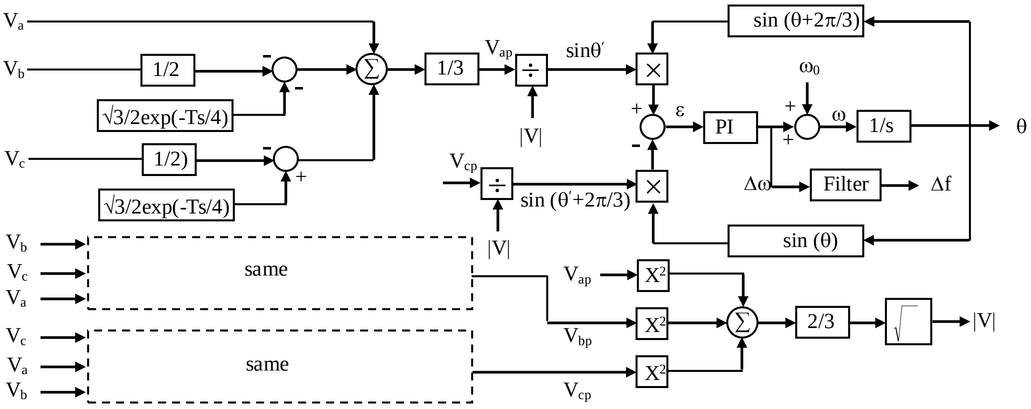

Fig. 6. Block diagram for PLL [23]

VSI control strategy shown in Fig. 5 has been obtained. The dq quantities and three-phase electrical quantities are related to each other by reference frame transformation. The angle of the transformation is detected from the three phase voltages (v_a,v_b,v_c) at the high voltage side of the grid side transformer using phase-locked-loop (PLL) as shown in Fig. 6 [24]. The rated dc-link voltage is 2.3 kV. The dc-link capacitor value is 10000 μF.

4. Model System

In this study, aggregated wind farm model is considered, where several WTGSs are lumped together to obtain a large WTGS. The reason is that the detailed switching models are used instead of the time average model in the frequency converter of VSWT-PMSG in this study and thus the simulation analysis needs considerably large computation time. The model system used in the dynamic and transient stability analyses is shown in Fig. 7. Here, one PMSG (5 MVA) is connected to the grid through a frequency converter, 1.25/11.4 kV step-up transformer, and a transmission line. The PMSG parameters are shown in Tables I. The system base is 5.0 MVA.

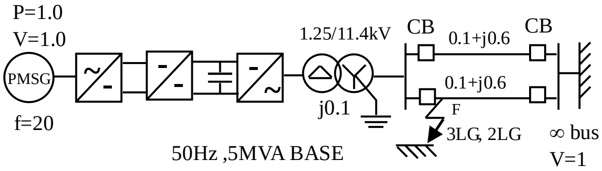

Fig. 7. Model System

TABLE I
PARAMETERS OF PMSG

Rated Power	5 [MW]	Stator Resistance	0.01[pu]
Rated Voltage	1.0 [kV]	d-axis Reactance	0.7[pu]
Frequency	20 [Hz]	q-axis Reactance	1.0[pu]
Number of Poles	150	Field Flux	1.55[pu]
H	3.0 [sec]		

5. Simulation Results

The wind farm grid codes are more or less similar. In this study, the simulation results are described in light of the recent grid code, set by E.On Netz. The fault ride-through (FRT) requirement is imposed on a wind power generator so that it remains stable and connected to the network during network faults. Disconnection from the grid may worsen a critical grid situation and can threaten the security standards when wind penetration is high. In Germany, wind generating plants are expected to acquit themselves during a low-voltage disturbance as summarized in a voltage versus time curve shown in Fig. 8. Wind turbines are required to stay on the grid within areas 1 and 2. [25-26].

Time step has been chosen 0.00005 sec. The simulation times are chosen 600 sec and 5 sec for dynamic and transient analyses, respectively. The simulations have been performed by using PSCAD/EMTDC [23].

A. LVRT Characteristic Analysis

In the simulation study, it is assumed that wind speed is constant and equivalent to the rated speed. This is because it may be considered that wind speed does not change dramatically during the short time interval of the simulation for the LVRT characteristic analysis. The performance of the proposed CC-VSI for augmentation of LVRT capability of wind generator is verified by comparing the results with that of VC-VSI used in [15]. In both cases, the same model system including individual component rating are considered which is important for verifying the results. It should be noted that in [15], the fault duration of 100 msec is considered. However, in this study longer fault duration of 150 msec is considered which is more realistic and grid code compatible. As the grid side inverter controls the DC-link voltage and grid voltage, the voltage responses of grid and DC-link using proposed CC-VSI and VC-VSI are compared only.

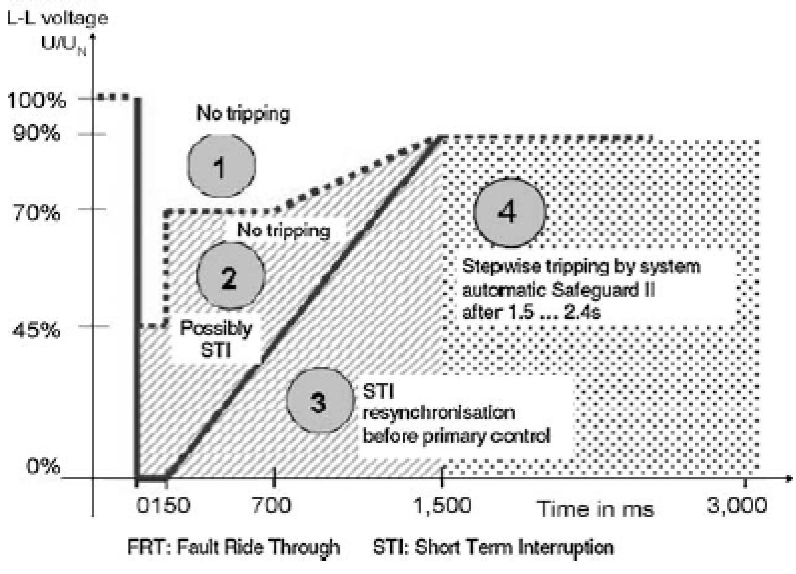

Fig. 8. Low voltage ride-through standard set by E.On Netz..

A.1. During Successful Reclosing of Circuit Breakers

Both the symmetrical three-line-to-ground fault (3LG) and unsymmetrical double-line-to-ground (2LG) and single-line-to-ground (1LG) faults are considered as the network disturbance, which occurs at fault point F in Fig. 7. The fault occurs at 0.1 sec, the circuit breakers (CB) on the faulted lines are opened at 0.25 sec, and at 1.05 sec the circuit breakers are reclosed. For detailed LVRT analysis of VSTW-PMSG during the successful reclosing of circuit breakers, two cases are considered as described below.

Case-1: In this case, a 150 msec duration 3LG fault is considered to occur at the sending end of one transmission line of Fig. 7. The current controlled grid side inverter can provide necessary reactive power during the network disturbance. Therefore, the terminal voltage shown in Fig. 9 can return quickly to its pre-fault level, which meets the E.On Netz. grid code requirement as shown in Fig. 8. Though 50 msec longer fault is considered in this study compared to the fault duration considered in [15] where VC-VSI is used, it can be seen from Fig. 9 that CC-VSI can effectively restore the grid voltage as per wind farm grid code. As a result of quick voltage restoration, the PMSG rotor becomes stable which can be understood from Fig. 10. The real power response of grid side inverter is shown in Fig. 11. The DC-link voltage responses of the frequency converter using both CC-VSI and VC-VSI are shown together in Fig. 12, from where it is seen that the CC-VSI is very much effective to keep the voltage variation within acceptable range. From the simulation results it is seen that the proposed control system augments the LVRT capability of VSWT-PMSG during the severe 3LG fault and achieves the requirements of wind farm grid code.

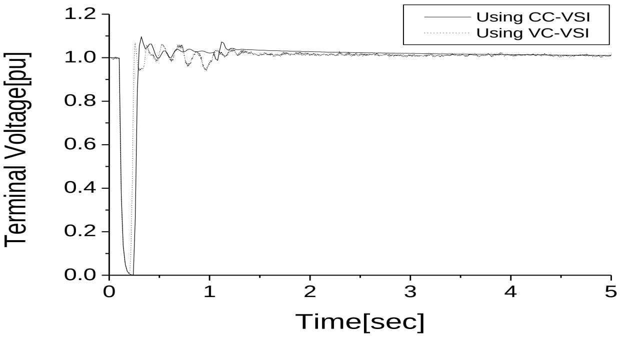

Fig. 9. Terminal voltage at the high voltage side of transformer (3LG)

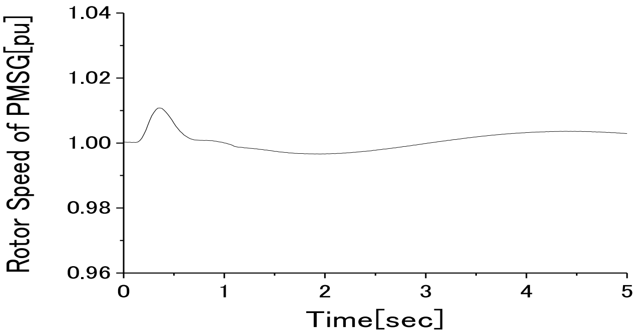

Fig. 10. Rotor speed of PMSG (3LG)

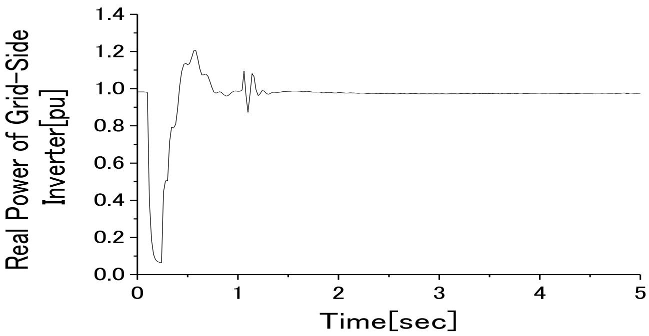

Fig. 11. Real power of the grid side inverter (3LG)

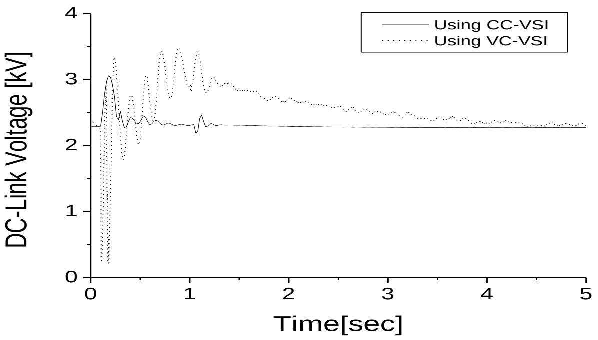

Fig. 12. Dc-link circuit voltage (3LG)

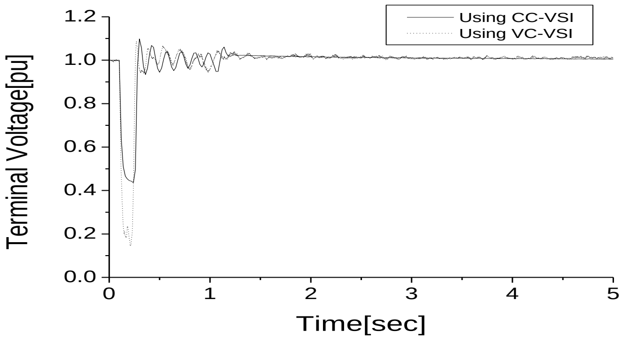

Fig. 13. Terminal voltage at the high voltage side of transformer (2LG)

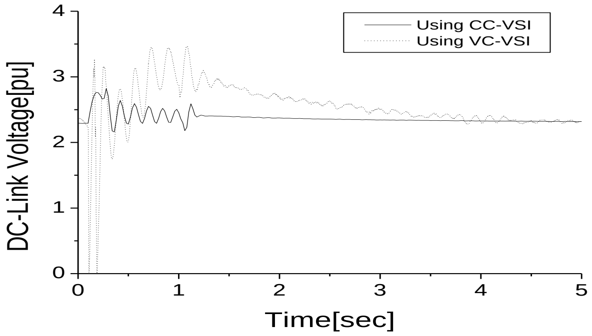

Fig. 14. DC-link circuit voltage (2LG)

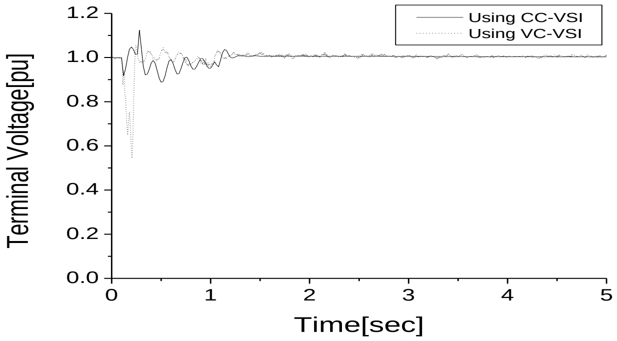

Fig. 15. Terminal voltage at the high voltage side of transformer (1LG)

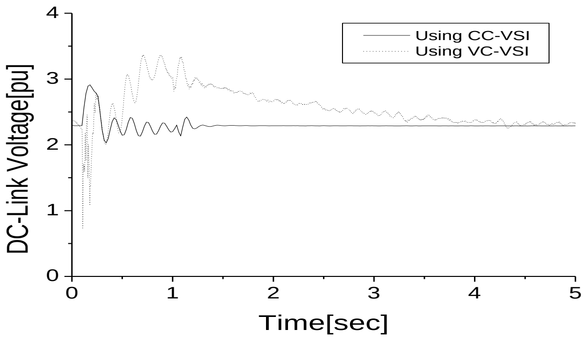

Fig. 16. DC-link circuit voltage (1LG)

Case2: In this case, 150 msec duration unsymmetrical 2LG and 1LG faults are considered to occur at the same location of the power system. The responses of the terminal voltage at the high voltage side of the transformer and DC-link voltage are shown in Figs. 13and 14, respectively, for 2LG fault. For 1 LG fault, the voltages at the grid and DC-link are shown in Figs. 15 and 16, respectively. From Figs. 13-16 it is clear that for the unsymmetrical faults CC-VSI improves the system performance considerably.

A.2. During Unsuccessful Reclosing of Circuit Breakers

In this section, it is assumed that a 3LG fault occurs at point F in Fig. 7. Fault occurs at 0.1 sec, circuit breakers on the faulted line are opened at 0.25 sec, and closed again at 1.05 sec. It is considered however that the reclosing of the circuit breakers is unsuccessful due to a permanent fault. Therefore, the circuit breakers are reopened at 1.15 sec. Eeach circuit breaker clears the line when the current through it crosses the zero level.

Fig. 17 shows the response of PMSG rotor speed. The terminal voltage shown in Fig. 18 can return back to its pre-fault level even when the circuit breakers on one transmission line are remaining open. The DC-link voltage response of the frequency converter is shown in Fig. 19. It is clear that the proposed control system can also augment the LVRT capability of VSWT-PMSG during the unsuccessful reclosing of the circuit breakers.

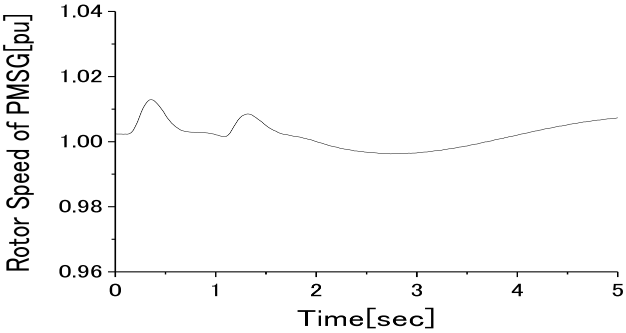

Fig. 17. Rotor speed of PMSG (3LG, PF)

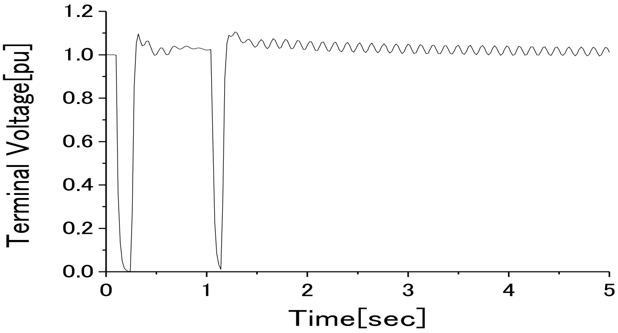

Fig. 18. Terminal voltage at the high voltage side of transformer (3LG, PF)

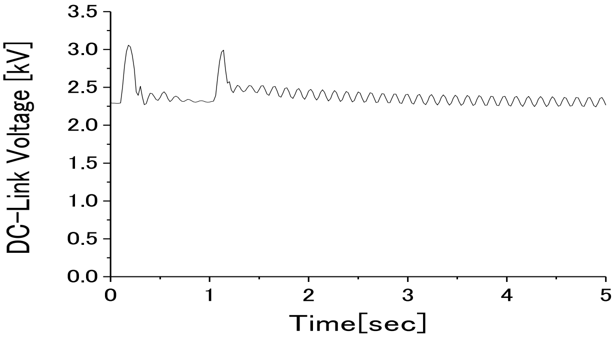

Fig. 19. DC-link circuit voltage (3LG, PF)

B. Dynamic Characteristic Analysis

Dynamic characteristic of VSWT-PMSG is analyzed under wide range of wind speed variation shown in Fig. 20, which is a real data measured in Hokkaido Island, Japan. One of the control objectives is to maximize the wind power capture by adjusting rotor speed of the wind turbine according to the wind speed variation, provided that the captured power should not exceed the rated power of PMSG. Fig. 21 shows the maximum power supplied to the grid, considering the gate device loss in the frequency converter. The response of the PMSG rotor speed is shown in Fig. 22. The responses of DC-link voltage and the rms voltage at the high-tension side of the transformer are shown in Figs. 23 and 24, respectively. It is seen that the wind generator terminal voltage can also be maintained constant at the desired level of transmission system operators (TSOs) under the proposed control strategy.

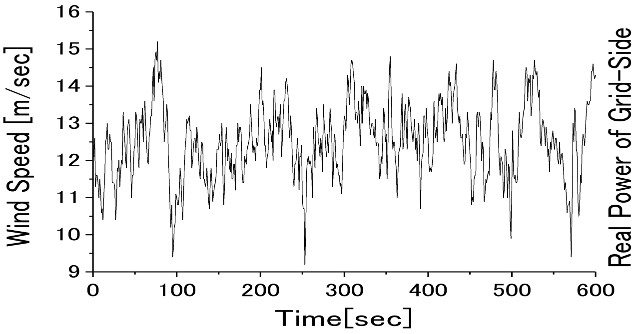

Fig. 20. Wind speed data

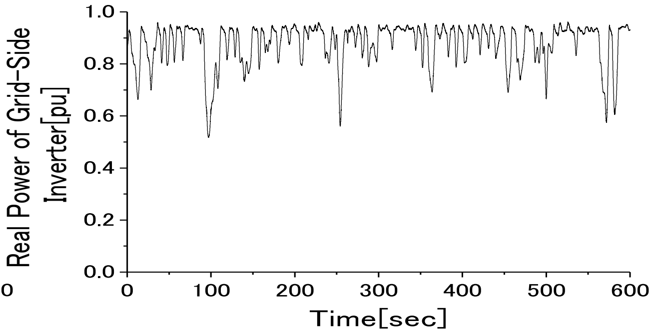

Fig. 21. Real power supplied to the grid

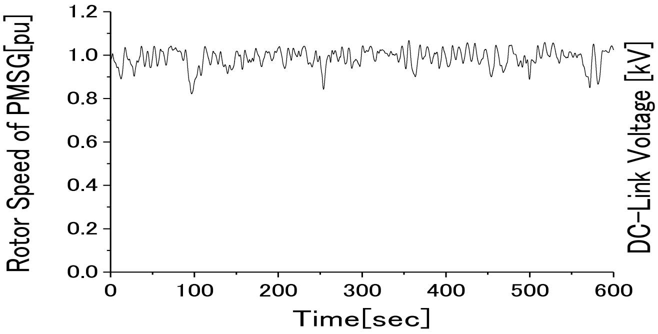

Fig. 22. Rotor speed of PMSG

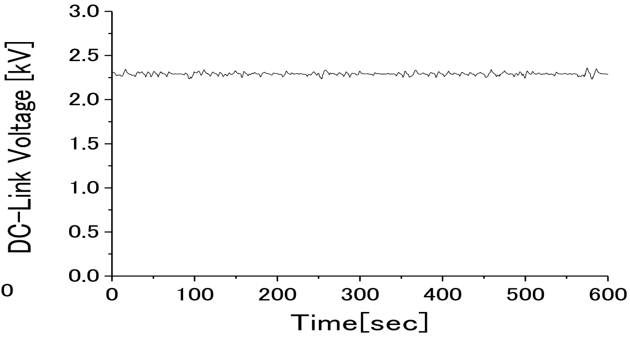

Fig. 23. DC-Link voltage of the frequency converter

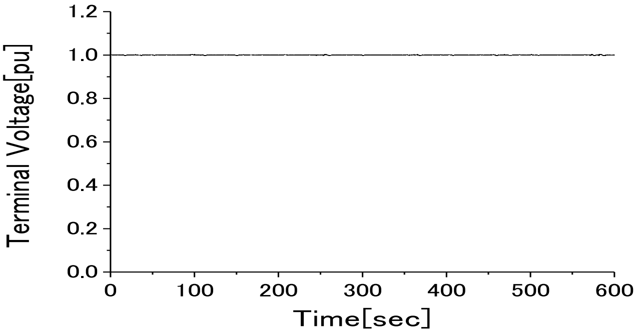

Fig. 24. Terminal voltage at the high voltage side of transformer

6. Conclusions

In this paper, variable speed wind turbine driving permanent magnet synchronous generator with current controlled voltage source inverter has been proposed. Detailed modeling and control strategies of the overall system has been developed. It is found that under the proposed control strategy the system runs smoothly under randomly and quickly varying wind condition. During both symmetrical and unsymmetrical fault conditions, the system is found stable and wind generator fault ride through requirement is fulfilled. The current controlled voltage source inverter performs well in grid fault condition compared to voltage controlled voltage source inverter scheme. It is also observed that the CC-VSI can even augment the LVRT capability of VSWT-PMSG during permanent fault condition due to unsuccessful reclosing of circuit breakers. Finally, it is concluded that CC-VSI works very effectively to operate the VSWT-PMSG in both dynamic and transient conditions.

References:

[1] The Global Wind Energy Council, GWEC Latest News, 2008, “US, China & Spain lead world wind power market in 2007,” February, 2008, [Online], http://www.gwec.net/

[2] F. V. Hulle, “Large Scale Integration of Wind Energy in the European Power Supply Analysis, Issue and Recommendations,” EWEA, Tech. Rep., December 2005.

[3] N. A. Janssens, G. Lambin, and N. Bragard, “Active Power Control Strategies of DFIG Wind Turbines,” IEEE Power Tech, Paper No. 167, Switzerland, July 2007.

[4] E. Muljadi, C. P. Butterfield, B. Parsons, and A. Ellis, “Effect of Variable Speed Wind Turbine Generator on Stability of a Weak Grid,” IEEE Trans. on Energy Conversion, Vol.22, No.1, pp.29-36, 2007.

[5] P. Ledesma and J. Usaola, “Doubly fed induction generator model for transient stability analysis,” IEEE Trans. on Energy Conversion, Vol.20, No.2, pp.388-397, 2005.

[6] P. La Seta and P. Schegner, “Comparison of stabilizing methods for doubly-fed induction generators for wind turbines,” International Conference on Future Power System, Conference CDROM, 2005.

[7] T. Sun, Z. Chen, and F. Blaabjerg, “Transient stability of DFIG wind turbines at an external short-circuit fault,” Wind Energy, Vol.8, No.3, pp.345-360, 2005.

[8] M. S. Morsy, H. H. Amer, M. A. Badr, and A. M. El-Serafi, “Transient Stability of Synchronous Generators with Two-Axis Slip Frequency Excitation,” IEEE Trans. on Power Apparatus and Systems, Vol.102, No.4, pp.852-859, 1983.

[9] L. Feng, M. Shengwei, X. Deming, M. Yongjian, J. Xiaohua, and L. Qiang, “Experimental evaluation of nonlinear robust control for SMES to improve the transient stability of power systems,” IEEE Trans. on Energy Conversion, Vol.19, No.4, pp.774-782, 2004.

[10] S. B. Papaefthimiou and S. A. Papathanassiou, “Simulation and control of a variable speed wind turbine with synchronous generator, ” CD Record of XVII International Conference on Electrical Machines (ICEM 2006), Ref. No.593, Chania, Crete Island, Greece, Sep 2-5, 2006.

[11] Peter Vas, “Electrical machines and Drives- A Space Vector Theory Approach,” Oxford University Press, New York, United States, 1992.

[12] T. J. E. Miller, “Brushless Permanent-Magnet and Reluctance Motor Drives,” Oxford University Press, New York, United States, 1989.

[13] J. Ribrant and L. M. Bertling, “Survey of Failures in Wind Power Systems With Focus on Swedish Wind Power Plants During 1997-2005,” IEEE Trans. on Energy Conversion, Vol. 22, No. 1, pp.167-173, March 2007.

[14] Ciprian Vlad, Iulian Munteanu, Antoneta Iuliana Bratcu, and Emil Ceanga, “Output Power Maxization of Low-power Wind Energy Conversion Systems Revisited: Possible Control Solutions,” Energy Conversion and Management, Vol.51, No.2, pp. 305-310, 2010.

[15] S. M. Muyeen, R. Takahashi, T.Murata, J.Tamura, “Transient Stability Enhancement of Variable Speed Wind Turbine Driven PMSG with Rectifier-Boost Converter-Inverter,” CD Record of XVIII International Conference on Electrical Machines (ICEM 2008), Ref. No.764, Portugal, Sep 6-9, 2008.

[16] S. M. Muyeen, R. Takahashi, T. Murata, and J.Tamura, “Miscellaneous Operations of Variable Speed Wind Turbine Driven Permanent Magnet Synchronous Generator,” International Review of Electrical Engineering (I.R.E.E.), Vol.3, No.5, pp. pp.912-921, 2008.

[17] R. Melicio, V.M.F. Mendes, and J.P.S. Catalao, “Fractional-order Control and Simulation of Wind Energy Systems with PMSG/full-power Converter Topology,” Energy Conversion and Management, Vol.51, No.6, pp. 1250-1258, 2010.

[18] Ying-Yi Hong, Shiue-Der Lu, Ching-Sheng Chiou, “MPPT for PM Wind Generator Using Gradient Approximation,” Energy Conversion and Management, Vol.50, No.1, pp. 82-89, 2009.

[19] K. Tan and S. Islam, “Optimum Control Strategies in Energy Conversion of PMSG Wind Turbine System Without Mechanical Sensors,” IEEE Trans. on Energy Conversion, Vol.19, No.2, pp.392-399, 2004.

[20] J. Zhang, M. Cheng, Z. Chen, “Nonlinear Control for Variable-speed Wind Turbines with Permanent Magnet Generators,” Proceeding of International Conference on Electrical Machines and Systems (ICEMS 2007), pp-324-326, Seoul, Korea, Oct 2007.

[21] S. Heier, Grid Integration of Wind Energy Conversion System, Chicester, UK, John Wiley & Sons Ltd., 1998.

[22] S. M. Muyeen, T. Murata, and J.Tamura, Stability Augmentation of a Grid-connected Wind Farm, Springer-Verlag London Limited, October 2008.

[23] PSCAD/EMTDC Manual, Manitoba HVDC Research Center, 1994.

[24] M. Akamatsu, M. Tsukada, D. Itoh, “A Novel PLL and Frequency Detecting Method Suited for the Abnormal Voltages under Fault Conditions in the Power System,” IEEJ Trans.PE., Vol.118-B, No.9, pp.955-961, 1998.

[25] E.On Netz, Grid Code, High- and Extra-High Voltage, April 2006, available at www.eon-netz.com/.

[26] Bharat Singh and S.N. Singh, “Wind Power Interconnection into the Power System: A Review of Grid Code Requirements,” The Electricity Journal, Vol.22, No.5, pp. 54-63, 2009.