Paper accepted for presentation at 2009 IEEE Bucharest Power Tech Conference, June 28th - July 2nd, Bucharest, Romania

Low Voltage Ride Through Capability Enhancement of Fixed Speed Wind Generator

S.M. Muyeen, *Member, IEEE,* R. Takahashi, *Member, IEEE,* T.Murata, and
J. Tamura, *Senior Member, IEEE*

***Abstract*— Fixed speed wind turbine generator system (WTGS) uses induction generator as wind generator. Besides some of its advantages, it suffers greatly to meet the requirements of new wind farm grid code due to the dependency on reactive power. Some flexible AC transmission systems (FACTS) devices have been proposed recently for compensating the reactive power of induction generator during network disturbances. However, integration of FACTS devices to wind farm definitely increase the overall cost. Therefore, in this paper, we focuses on a new topology, where fixed speed WTGSs are installed in a wind farm with variable speed wind turbines (VSWT) driving permanent magnet synchronous generators (PMSG). VSWT-PMSG uses a fully controlled frequency converter for grid interfacing and it has abilities to control its reactive power as well as to provide maximum power to the grid. Suitable control strategy is developed in this paper for the frequency converter of VSWT-PMSG. A real grid code defined in the power system is considered to analyze the low voltage ride through (LVRT) characteristic of fixed speed WTGSs. Simulation results clearly show that the proposed topology might be a good solution to augment the LVRT requirement of fixed speed WTGSs.**

***Index Terms*—Fixed speed wind generator (FSWG), Variable speed wind turbine (VSWT), low voltage ride through (LVRT), permanent magnet synchronous generator (PMSG), voltage source converter (VSC), and frequency converter.**

I. INTRODUCTION

DUE to its clean and economical characteristics, electrical power generation from wind energy is getting vast deliberation throughout the world. 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]. As huge numbers of wind farms are going to be connected to power system in the near future, it is essential to analyze the characteristics of wind generators during the network disturbances. Between the two types of trends (fixed and variable speed) of wind turbine generator system (WTGS), fixed speed wind generator has weaker fault ride through capability. Induction generators are used, in general, as fixed speed wind generator due to their superior characteristics such as brushless and rugged construction, low cost, maintenance free, and operational simplicity. However, it requires large reactive power to recover the air gap flux when a short circuit fault occurs in the power system [2], unless otherwise the induction generator becomes unstable and it requires to be disconnected from the power system. A shut down of large wind farm may have a serious effect on the power system operation. Therefore, a new set of grid codes [3-6] have been defined recently, which includes the low voltage ride through (LVRT) requirements for WTGSs during the network disturbances.

Voltage or current source inverter based flexible AC transmission system (FACTS) devices such as static var compensator (SVC), static synchronous compensator (STATCOM), dynamic voltage restorer (DVR), solid state transfer switch (SSTS) and unified power flow controller (UPFC), have been used for flexible power flow control, secure loading and damping of power system oscillation [7-9]. FACTS/ESS, i.e., FACTS with energy storage system (ESS) have recently emerged as more promising devices for power system applications [10]. Some of them are even applicable to wind farm stabilization. STATCOM, superconducting magnetic energy storage system (SMES), and energy capacitor system (ECS) composed of electric double layer capacitor and power electronic devices have already been proposed to enhance the LVRT capability of fixed speed wind farm [11-15]. However, the installation of FACTS devices at a wind farm composed of fixed speed wind generators increases the overall cost. On the other hand, variable speed WTGS equipped with full or partial rating power electronic converter has comparatively strong fault ride through capability [16-19]. Moreover, it can extract the maximum power from the wind due to its variable speed operation. Therefore, the use of variable speed WTGS has been becoming very popular these days. In [19], double fed induction generator (DFIG) is used for transient stability enhancement of induction generator. However, two-mass drive train model of WTGS is not considered therein, which has significant effect on the transient stability analysis of fixed speed WTGS [20-21]. Moreover, underground cable is not considered in that study for wind generator connection. In real system, a wind farm generally employs underground cables with high capacitance to connect neighboring wind generators. Therefore, for LVRT analysis

---

This work was supported by the Grant-in-Aid for JSPS Fellows from Japan Society for the Promotion of Science (JSPS).

S. M. Muyeen, R. Takahashi, T. Murata, and J. Tamura are with the Electrical and Electronic Engineering Department, Kitami Institute of Technology, 165 Koen-Cho, Kitami, Hokkaido, 090-8507, Japan (e-mail: muyeen@pullout.elec.kitami-it.ac.jp).

978-1-4244-2235-7/09/$25.00 ©2009 IEEE

underground cables should be considered for preciseness.

This study focuses on a suitable control method for enhancing the LVRT capability of fixed speed WTGS during network disturbances by using variable speed WTGS installed in the same wind farm. In the model system used in this paper, a VSWT driving a PMSG is connected to the power system through a fully controlled frequency converter, which consists of generator side AC/DC converter, DC-link capacitor, and grid side DC/AC inverter. The fixed speed WTGS is connected to the terminal of variable speed WTGS thorough a short underground cable. A Suitable control strategy is developed for the frequency converter of VSWT-PMSG, which can provide necessary reactive power demand of induction generator during the network disturbance as well as can extract maximum power from the wind. Two-mass drive train model and underground cables are considered in this study for preciseness of the analysis. Extensive simulation analyses have been carried out considering most severe three-line-to-ground (3LG) fault to analyze the LVRT characteristics of fixed speed WTGSs. Finally, it is concluded that the proposed WTGS topology is a good solution to enhance the LVRT capability of fixed speed wind generators.

II. WIND TURBINE MODELING

The mathematical relation for the mechanical power extraction from the wind can be expressed as follows [22]:

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

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]. Both fixed and variable speed wind turbine characteristics used in this study are shown in Figs. 1 and 2, respectively [22-24].

In variable speed wind turbine, 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 difficult, it is better to calculate the maximum power, P_{max}, without the measurement of wind speed as shown in eq.(2).

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

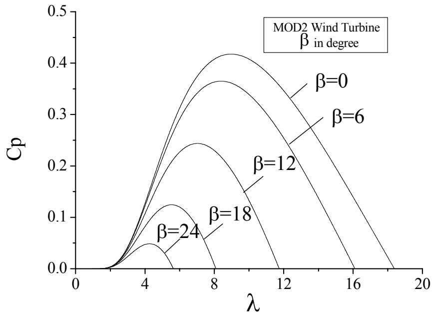

Fig. 1. C_P- λ curves for different pitch angles (used in VSWT)

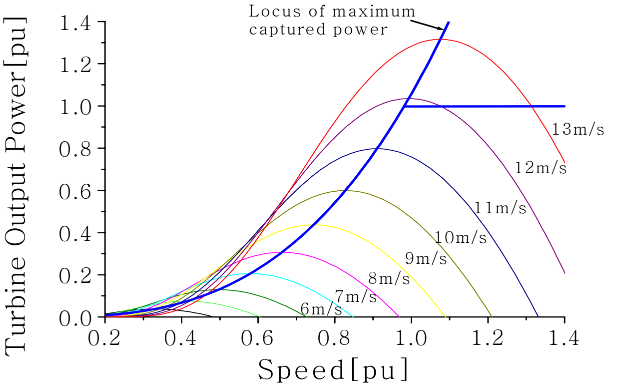

Fig. 2. Turbine characteristic with maximum power point tracking (used in VSWT)

where λ_{opt} and C_{p_opt} are optimum value 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.

The range of rotor speed variation is, in general, approximately 5 to 16 rpm. During the control of generator side AC/DC 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 [17] is worked to control the rotational speed. Therefore, the PMSG output will not exceed the rated power.

III. MODEL SYSTEM

The model system used for the LVRT analysis is shown in Fig. 3. Here, one PMSG (5 MVA) is connected to 11.4 kV distribution system through a frequency converter, 1.25/11.4 kV step-up transformer, and underground cable. One induction generator (5 MVA) is connected to the high voltage side of 1.25/11.4 kV transformer through 0.69/11.4 kV transformer and a short underground cable. A capacitor bank, C, has been

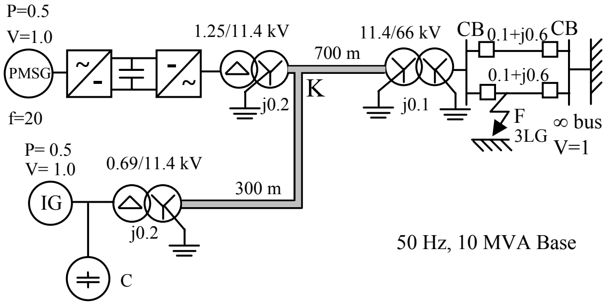

Fig. 3. Model System

TABLE I
PARAMETERS FOR PMSG

Rated Power	5 [MW]	Stator Resistance	0.01[pu]
Rated Voltage	1.0 [kV]	d-axis Reactance	1.0[pu]
Frequency	20 [Hz]	q-axis Reactance	0.7[pu]
Number of Poles	150	Field Flux	1.4[pu]
H	3.0 [sec]		

TABLE II
PARAMETERS FOR IG

IG	
Rated power	5.0 [MW]
r1 (pu)	0.01
x1 (pu)	0.1
Xmu (pu)	3.5
r21 (pu)	0.035
x21 (pu)	0.030
r22 (pu)	0.014
x22 (pu)	0.098
H_{WT} (sec)	3.0
H_G (sec)	0.3

considered to be connected to the terminal of induction generator (IG) for reactive power compensation at steady state. The value of capacitor C is chosen so that power factor of the wind generator during the rated operation becomes unity [25]. Output from the two wind generators are supplied to the utility grid though a common step-up transformer (11.4 kV to 66 kV) and a transmission line. PMSG and IG parameters are shown in Tables I and II, respectively. Underground cable parameters are given in the Appendix. The system base is 10 MVA.

IV. INDIVIDUAL COMPONENT MODELING OF VSWT-PMSG

A. PMSG

In the simulation analyses, the PMSG model available in the package software PSCAD/EMTDC [26] 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.

B. Generator-Side Converter

The well-known cascaded control scheme shown in Fig. 4 is used as the control methodology for the generator-side converter. As the converter is directly connected to the PMSG, its q-axis current is proportional to the active power. The active power reference, P_{ref}, is determined in such a way to provide the maximum power to the grid. However, when network disturbance occurs, the terminal voltage, V_{grid}, of the high voltage side of the transformer decreases considerably. Therefore, it is not possible to provide maximum power to the grid at that instant and any attempt to do so may causes system instability, especially in the case where large amount of reactive power is needed to supply from the frequency converter. Therefore, in this study, P_{ref} is varied according to the terminal voltage from fault occurring time to circuit breaker reclosing time, by multiplying P_{ref} with V_{grid}, which gives excellent transient performance as demonstrated in Sect. V. This is one of the salient features of this work which also augments the LVRT performance of the overall frequency converter. However, the concept of using a chopper circuit is not considered herein for simplicity to dissipate the surplus energy during voltage dip to limit the increase of the DC-link voltage. On the other hand, the d-axis stator current is proportional to the reactive power. The reactive power reference is set to zero to perform unity power factor operation. The angle, θ_r, for the transformation between abc and dq variables is calculated from the rotor speed of PMSG.

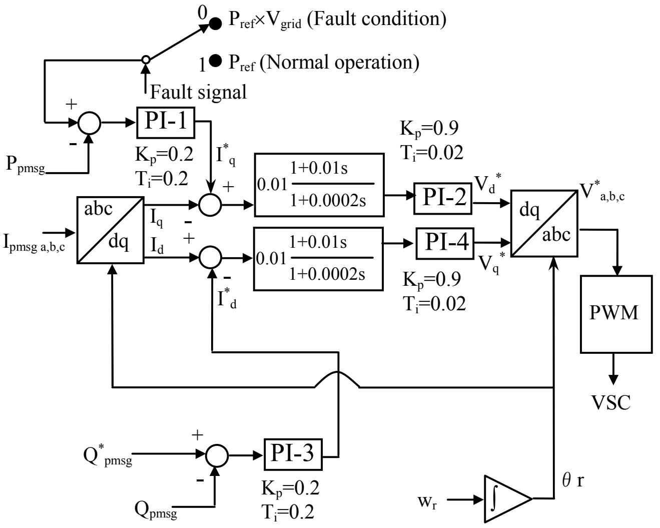

Fig. 4. Control block for the generator side converter

C. Grid Side Inverter

Control blocks for the grid side inverter are shown in Fig. 5, where the well-known cascaded control scheme is considered. 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. The DC voltage of the DC-link capacitor is controlled constant by two PI controllers. The d-axis current can control the DC-link voltage. On the other hand, the q-axis current can control the reactive power of grid side inverter. The reactive power reference is set in such a way that the terminal voltage at high voltage side of the transformer remains constant. Therefore, total three PI controllers are used to control the reactive power of grid-side inverter. The additional PI controller provides excellent transient characteristic during network disturbance as shown later.

In both converter and inverter, the triangular carrier signal is used as the carrier wave of PWM operation. The carrier frequency is chosen 1050 Hz for the converter and 1000 Hz for

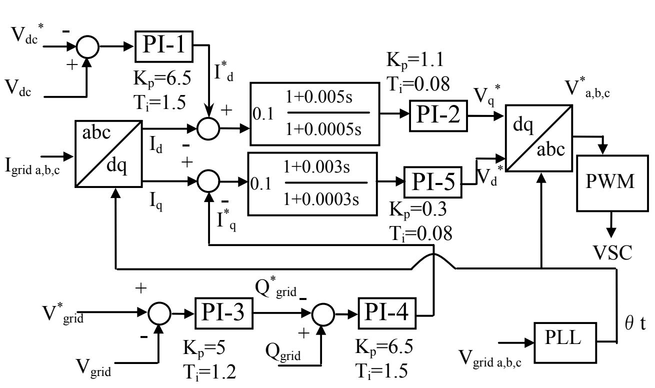

Fig. 5. Control block for the grid side inverter

the inverter respectively. The DC-link capacitor value is chosen 10000 μF. The rated DC-link voltage is 2.3 kV.

V. SIMULATION RESULTS

In many countries, new set of grid codes has been developed recently considering the huge penetration of wind power to the power system. The wind farm grid codes are more or less similar to each other. In this study, the simulation results are described in light of the US grid code only, set by Federal Energy Regulatory Commission (FERC). If the voltage does not fall below the minimum voltage indicated by the solid line in Fig. 6 and returns to 90 percent of the nominal voltage within 3 seconds after the beginning of the voltage drop, the plant must stay online [4].

In this study, a new topology of wind turbine generator system is considered which is composed of fixed and variable speed wind generators and LVRT characteristics are analyzed during network disturbance. The frequency converter of the VSWT-PMSG is controlled in such a way to maintain the grid voltage (point K in Fig 3) at desired reference level. In that way, the necessary reactive power of the induction generator can also be supplied to restore the electromagnetic torque. To obtain realistic responses, the two-mass shaft model of WTGS is considered. All types of dampings are disregarded to obtain the worse scenario [21]. The most severe symmetrical three-line-to-ground fault (3LG) is considered as a network disturbance, which occurs at fault points F in Fig. 3. The fault occurs at 0.1 sec, the circuit breakers (CB) on the faulted lines are opened at 0.2 sec, and at 1.0 sec the circuit breakers are reclosed. In the simulation study, it is assumed that wind speed is constant and equivalent to the rated speed for both fixed and variable speed WTGSs. This is because it may be considered that wind speed does not change dramatically during the short time interval of the simulation. Time step and simulation time are chosen 0.00002 sec and 10 sec, respectively. Simulations were carried out by using PSCAD/EMTDC [26]. The effectiveness of the control strategy of the proposed system to achieve LVRT requirement of fixed speed WTGSs are presented below.

The grid side inverter can provide necessary reactive power during the network disturbance as shown in Fig. 7. Therefore, the terminal voltage can return to its pre-fault level as shown in Fig. 8. As the necessary reactive power of the induction generator is provided by the VSWT-PMSG, the electromagnetic torque of IG can be restored quickly. Therefore, electromagnetic and mechanical torques balance to each other and as a result the IG rotor and turbine hub speeds become stable as shown in Fig. 9. The response of PMSG rotor speed is shown in Fig. 10. When the fault occurs, the reference of the real power reference for the generator side converter is determined by the fault signal shown in Fig. 4. Figure 11 shows the response of the real power reference. The real power responses of grid side inverter (real power from the PMSG) and induction generator are shown together in Fig. 12. The DC-link voltage response of the frequency converter is shown in Fig. 13. From the simulation results it is seen that the proposed system can augment well the fault ride through capability of wind farm.

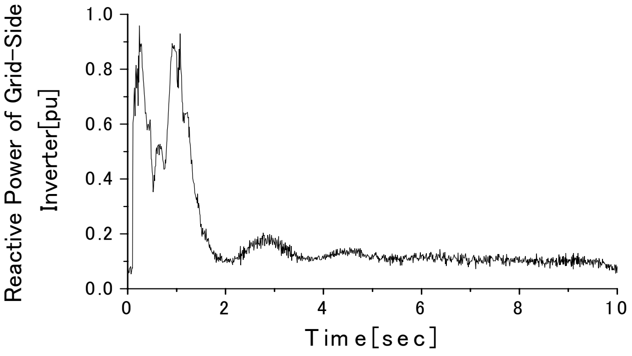

Fig. 7. The reactive power of grid side inverter

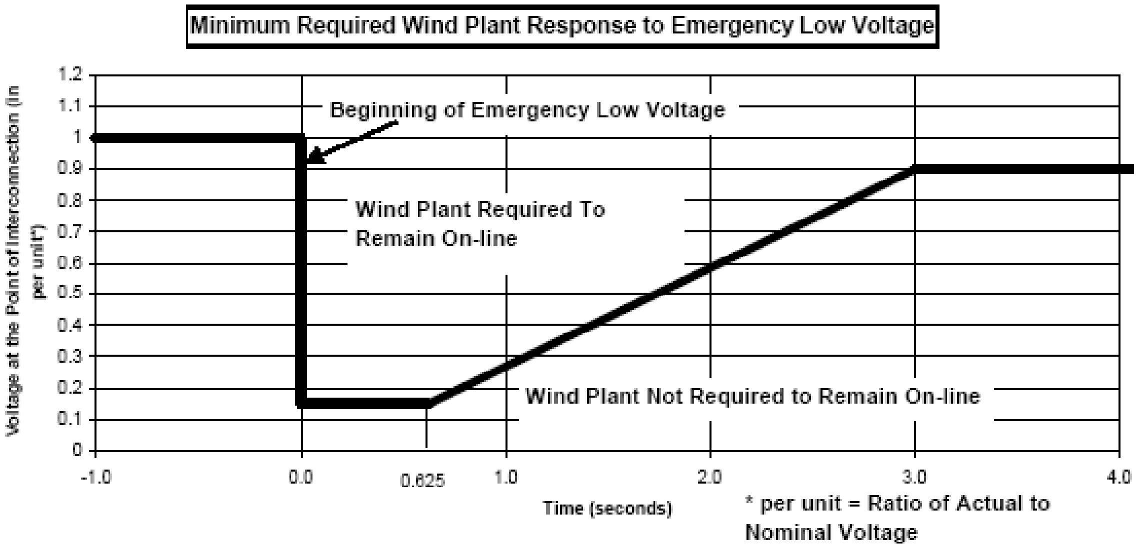

Fig. 6. Low voltage ride-through standard set by FERC, U.S.

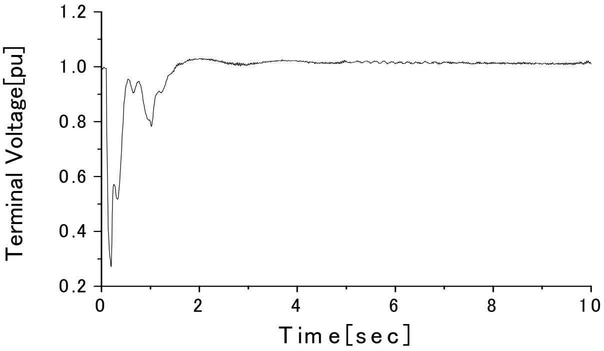

Fig. 8. The terminal voltage of the grid

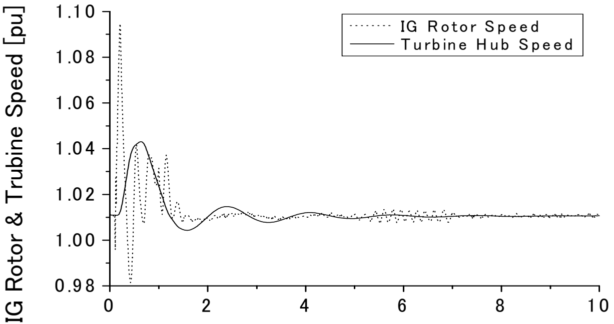

Fig. 9. The IG rotor and turbine hub speed

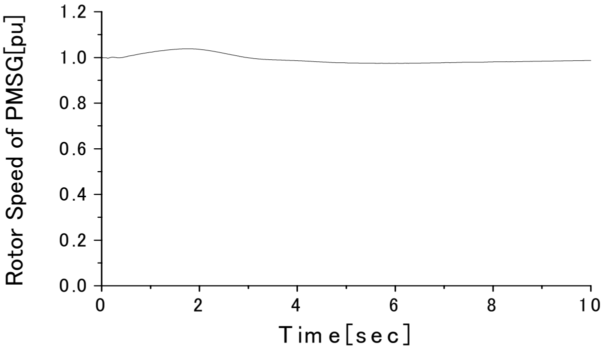

Fig. 10. Rotor speed of the PMSG

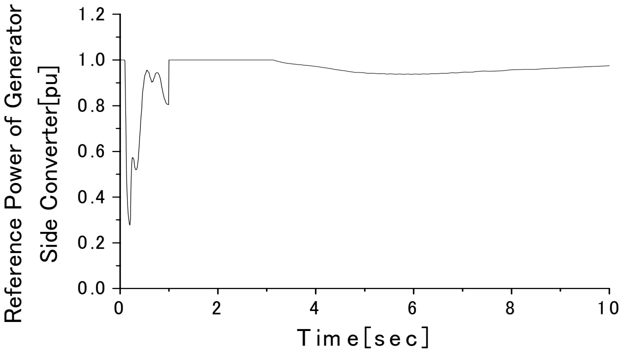

Fig. 11. Reference power of the generator-side converter

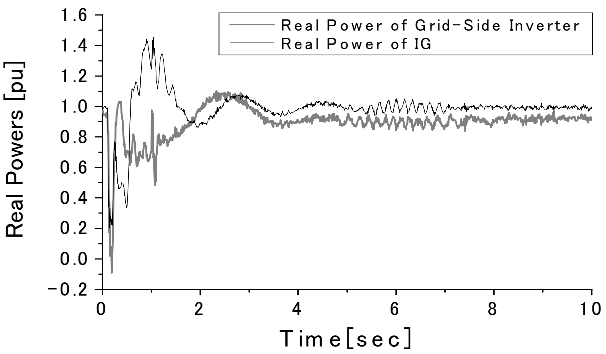

Fig. 12. Real powers of the PMSG and the IG

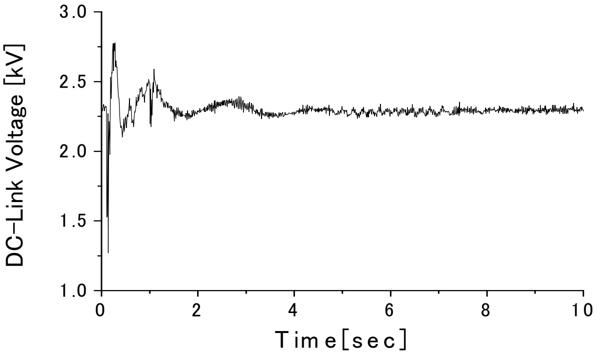

Fig. 13. The DC-Link voltage of the frequency converter

VI. CONCLUSIONS

In this paper, a new type of wind farm topology composed of fixed and variable speed wind turbine generator systems has been presented. The variable speed wind turbine driving a PMSG is connected to the grid through a fully controlled frequency converter which has reactive power control ability and hence the fault ride through capability. Taking this advantage, a fixed speed wind generator is connected to its terminal, and the latter can be supplied the reactive power compensation from the former during network disturbances. It is found that the variable speed as well as the fixed speed wind generators can satisfy well the LVRT standard. Therefore, additional cost to meet the LVRT requirement of fixed speed WTGS by integrating FACTS devices can be eliminated. Moreover, additional electrical output can supplied to the grid from VSWT-PMSG, which is not possible using FACTS devices. This topology might be suitable to new wind farm as well as to the existing wind farm where situations of wind farm expansion is considered.

VII. APPENDIX

The underground cable parameters are given below [27]:

(a) Underground cables between transformers, 1.25/11.4 kV and 0.69/11.4 kV (350 m): $X_L = 0.165$ Ω/km, $C_L = 0.14165$ μF/km, and $R_L = 0.487$ Ω/km.

(b) Underground cables between transformers, 1.25/11.4 kV and 11.4/66 kV (700 m): $X_L = 0.154$ Ω/km, $C_L = 0.08384$ μF/km, and $R_L = 0.303$ Ω/km.

VIII. 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] Claudio L.Souza et. al., "Power System Transient Stability Analysis Including Synchronous and Induction Generator," IEEE Porto Power Tech Proceedings, Vol.2, pp.6, 2001.

[3] R. Zavadil, N. Miller, A. Ellis, E. Muljadi, "Making connections," IEEE Power Energy Mag., 2005, 3, (6), pp. 26–37.

[4] Federal Energy Regulatory Commission (FERC), United States of America, Docket No. RM05-4-000 – Order No. 661, "Interconnection for Wind Energy," Issued June 2, 2005.

[5] Federal Energy Regulatory Commission (FERC), United States of America, Docket No. RM05-4-001; Order No. 661-A, "Interconnection for Wind Energy," Issued December 12, 2005

[6] Ireland National Grid, Grid Code Version 2, January, 2007, "Wind Farm Power Station Grid Code Provisions, WFPS1," pp.213-216.

[7] Laszlo Gyugyi, "Dynamic Compensation of AC Transmission Lines By Solid-State Synchronous Voltage Sources," IEEE Trans. On Power Delivery, Vol.9, No.2, pp.904-911, 1994.

[8] Dr.L.Gyugyi, "Unified Power-Flow Control Concept for Flexible AC Transmission Systems," IEE Proc.-C, Vol.139, No.4, pp,323-331, 1992.

[9] H.F.Wang, F.Li, and R.G.Cameron, "Facts Control Design Based on Power System Nonparametric Models," IEE Proc.-Gener. Transm. Distrib. Vol.146, No.5, pp.409-415, 1999.

[10] L. Zhang, C. Shen, M. L. Crow, L. Dong, S. Pekarek, and S. Atcitty, "Performance Indices for the Dynamic Performance of FACTS and FACTS with Energy Storage," Electric Power Component and System, vol.33, no.3, pp.299-314, March 2005.

[11] Z. Saad-Saoud, M.L. Lisboa, J.B. Ekanayake, N. Jenkins, G. Strbac, "Application of STATCOMs to Wind Farms," IEE Proc. Gener. Transm. Distrib. Vol.145, No.5, pp.511-516, 1998.

[12] S. M. Muyeen, Mohammad Abdul Mannan, Mohd. Hasan Ali, Rion Takahashi, Toshiaki Murata, and Junji Tamura, "Stabilization of Wind Turbine Generator System by STATCOM," IEEJ Trans.PE., Vol.126-B, No.10, pp.1073-1082, 2006.

[13] M.H.Ali, T.Murata, J.Tamura : Minimization of Fluctuations of Line Power and Terminal Voltage of Wind Generator by Fuzzy Logic-Controlled SMES, International Review of Electrical Engineering (I.R.E.E.), Vol.1, No.4, pp.559-566, 2006/10.

[14] T. Kinjo, T. Senjyu, N. Urasaki, and H. Fujita, "Output levelling of renewable energy by electric double-layer capacitor applied for energy storage system," IEEE Trans. on Energy Conversion, Vol. 21, Issue.1, pp. 221-227, 2006.

[15] S. M. Muyeen, R. Takahashi, Mohd. Hasan Ali, T. Murata, and J.Tamura, "Transient Stability Augmentation of Power System Including Wind Farms by Using ECS," IEEE Trans. on Power System, Vol.23, No.3, pp.1179-1187, August 2008.

[16] 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.

[17] S. M. Muyeen, R. Takahashi, T.Murata, J.Tamura, and M. H. Ali, "Transient Stability Analysis of Permanent Magnet Variable Speed Synchronous Wind Generator," Proceedings of International Conference on Electrical Machines and Systems 2007 (ICEMS 2007), pp.288-293, Seoul, Korea, October 2007.

[18] 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.

[19] R. Takahashi, J. Tamura, M. Futami, M. Kimura, and K. Ide, "A New Control Method for Wind Energy Conversion System Using a Double-Fed Synchronous Generator," IEEJ Power and Energy, Vol.126, No.2, pp.225-235, 2006 (In Japanese).

[20] S.K.Salman and Anita L.J.Teo, "Windmill Modeling Consideration and Factors Influencing the Stability of a Grid-Connected Wind Power-Based Embedded Generator," IEEE Trans. on Power Systems, Vol.18, No.2, p.793-802, 2003.

[21] S. M. Muyeen, Mohd. Hasan Ali, R. Takahashi, T. Murata, J.Tamura, Y. Tomaki, A. Sakahara, and E. Sasano, "A Comparative Study on Transient Stability Analysis of Wind Turbine Generator System Using Different Drive Train Models," IET-Proceedings on Renewable Power Generation (IET-RPG), Vol.1, No.2, pp.131-141, June, 2007.

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

[23] O. Wasynczuk, D. T. Man, J. P. Sullivan, "Dynamic behavior of a class of wind turbine generator during random wind fluctuations," IEEE Trans. on Power Apparatus and Systems, Vol. PAS-100, No.6, pp.2873-2845, 1981.

[24] J. G. Slootweg, S. W. H. De Hann, H. Polinder, W. L. Kling, "General Model for Representing Variable Speed Wind Turbines in Power System Dynamic Simulations," IEEE Trans. on Power System, Vol.18, No.1, 2003.

[25] S. M. Muyeen, Mohd. Hasan Ali, Rion Takahashi, Toshiaki Murata, and Junji Tamura, "Transient Stability Enhancement of Wind Generator by a New Logical Pitch Controller," IEEJ Trans.PE., Vol.126-B, No.08, pp.742-752, 2006.

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

[27] Li Wang, Jr-Yung Liou, "Simulations of a Commercial Wind Power Generation System with Four Wind-Turbine Induction Generators," IEEE Power Engineering Society General Meeting 2007, pages 1-7, Doi: 10.1109/PES.2007.385916, FL, USA, 2007.

IX BIOGRAPHY

S. M. Muyeen was born in Khulna, Bangladesh on September 08, 1975. He received his B.Sc. Eng. Degree from Rajshahi University of Engineering and Technology (RUET), Bangladesh in 2000 and M. Sc. Eng. and Dr. Eng. Degrees from Kitami Institute of Technology, Japan, in 2005 and 2008 respectively, all in Electrical and Electronic Engineering. Presently he is doing research works under the JSPS (Japan Society for the Promotion of Science) Postdoctoral Fellowship Program at the Kitami Institute of Technology, Japan. Dr. Muyeen is a member of the IEEE. His research interests are power system, electrical machine, FACTS, energy storage system (ESS), wind generator stabilization, and multi-mass drive train of wind turbine.

Rion Takahashi received the B.Sc. Eng. and Dr. Eng. Degrees from Kitami Institute of Technology, Japan, in 1998 and 2006 respectively, all in Electrical and Electronic Engineering. Now he is working as research assistant in Department of Electrical and Electronic Engineering, Kitami Institute of Technology. His major research interests include analysis of power system transient, FACTS and wind energy conversion system.

Toshiaki Murata completed his Electrical Engineering Curriculum of the Teacher Training School from Hokkaido University, Japan. Since 1969, he had been a Research Assistant at the Kitami Institute of Technology, Japan. He received Dr. Eng. degree from Hokkaido University in 1991. Presently he is an associate professor at Kitami Institute of Technology, Japan.

Junji Tamura received his B. Sc. Eng. Degree from Muroran Institute of Technology, Japan, in 1979 and M.Sc. Eng. and Dr. Eng. degrees from Hokkaido University, Japan, in 1981 and 1984 respectively, all in electrical engineering. In 1984, he became a lecturer and in 1986, an associate professor at the Kitami Institute of Technology, Japan. Currently he is a professor at the Kitami Institute of Technology. He is the senior member of IEEE.