Low Voltage Ride Through(LVRT) Control Strategy of Grid-connected Variable Speed Wind Turbine Generator System

Hojoon Shin, Hyun-Sam Jung, and Seung-Ki Sul
School of Electrical Eng., Seoul National University, Seoul, Korea

***Abstract*-- In this paper, a Low Voltage Ride Through (LVRT) control strategy for variable speed full scale Wind Turbine Generator System (WTGS) is proposed. Grid-connected wind power system should satisfy LVRT requirement when grid fault occur, and the variable speed full scale WTGS has advantage of satisfying LVRT compared with the fixed speed WTGS. The proposed LVRT control strategy satisfies not only LVRT requirement but also stabilizing a DC link voltage regardless of reduced DC link capacitance. During the grid faults, especially three phase to ground fault, the grid side converter cannot control the DC link voltage because it is impossible to control grid side power. In this situation, the DC link voltage can be controlled by the generator side inverter using the proposed DC link voltage control scheme. The proposed control scheme can keep the power balance between grid and generator side power in any case of grid fault condition for LVRT. The compliance to Grid Codes has been evaluated by computer simulations. Though the experimental results, it is verified that the proposed method has satisfied the LVRT requirements and DC link voltage control specification simultaneously.**

***Index Terms*-- LVRT (Low Voltage Ride Through), variable speed FSWTGS (Full Scale Wind Turbine Generating System), DC link voltage control.**

I. Introduction

Recently, sustainable & renewable energies are in the spotlight as a next electric power generation source. Especially, wind power is getting popular in the world due to its rapidly growing market and better cost effectiveness. All over the world, around 40GW wind power systems are added in 2010, and the installed wind power capacity has been reached close to 200GW at the end of 2010 [1].

The portion of the wind power system has been increased in the grid power generation. And, the influence of large wind power system to nearby grid network has been also increased. Owing to these concerns, Grid Codes for the wind power systems have been established in many countries to make their grid network stable with the deep penetration of wind power to grid [2].

The main focus of the Grid Code is a Low Voltage Ride Through (LVRT) requirement, that is, the wind power system should work properly when the grid fault occurs. The LVRT requirement indicates rules or actions which have to be executed according to the voltage dip ratio and the fault duration. Especially the wind power system has to support the grid with specified reactive current to secure the grid stability when voltage variation ratio is over 10%. The specific requirements are explained in subsection A. In this paper, the control loop is developed to satisfy German Grid Code, which is known as the strictest Grid Code in the world.

A. LVRT in German Grid Code

In Fig.1 the LVRT limit curve in German Grid Code is shown [3]. The reference of the voltage for the calculation of the voltage variation ratio is the largest value among three line-to-line grid voltages at the Point of Common Coupling (PCC). When a grid fault occurs whose voltage variation ratio and duration is placed in area A in Fig.1, Wind Turbine Generation System (WTGS) should maintain the connection to the grid regardless of the fault. In the case of area B, a brief disconnection of the wind power system from the grid is allowed. However, after fault clearance resynchronization should be done within 2 seconds and the active power at the rate of 10% of rated power per second should be provided to the grid. . In area C, it is possible Wind Turbine Generation System (WTGS) to be disconnect from the grid. For all wind power system that do not disconnect from grid during the fault, the active power should be supplied till after the fault clearance and increased to nominal value with a gradient of at least 20% of the rated power per second.

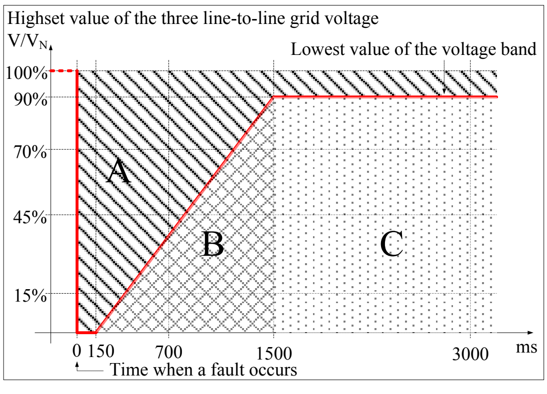


Fig. 1. LVRT limit curve in German Grid Code

WTGS must support the grid voltage with additional reactive current during the grid fault according to voltage variation. The grid voltage variation versus required reactive current curve is shown in Fig. 2.

The area called dead band is from $0.9V_N$ to $1.1V_N$. In dead band, the reactive current to support the grid is not required, and it is possible to keep the reactive power to satisfy the power factor as commanded. The supporting action must take place within 20ms (1 cycle of 50Hz) after recognition of the fault and the reactive current should be supplied at least 2% of the rated current per each percent of grid voltage variation. A 100% reactive current must be supplied if necessary. Even after the voltage returns to the dead band, the voltage support must be maintained for further 500ms in accordance with the specified characteristic.

The range of dead band for offshore grid connection is changed to $0.95V_N$ to $1.05V_N$ in E.ON Grid Code updated in 2008.

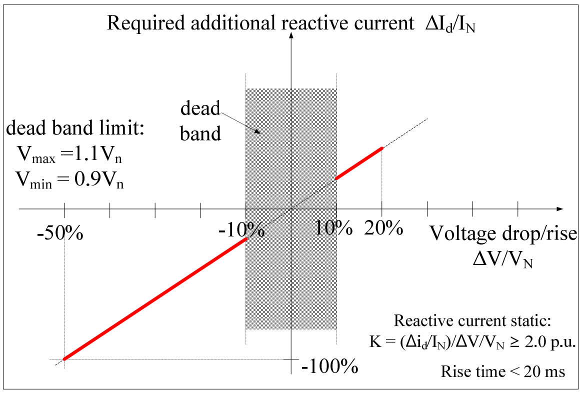


Fig. 2. Required reactive current according to grid voltage variation in German Grid Code

II. Control Loop for Variable Speed WTGS

A. Variable speed FSWTGS

There are two types of WTGS, namely, fixed and variable speed. Generally fixed speed WTGS has merits of lower cost, simpler structure, and lower maintenance [4]. But the fixed speed WTGS are very susceptible to grid fault situation, and it is necessary to add an extra system to WTGS to fulfill LVRT requirement such as Static synchronous Compensator (STATCOM), or Static VAR Compensator (SVC)[5][6]. This extra system results in additional cost and maintenance, so recently, the variable speed FSWTGS is getting popular in the industry.

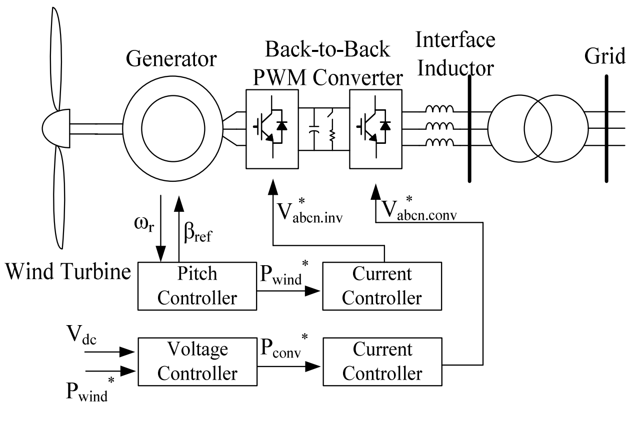


Fig. 3. Configuration of variable speed FSWTGS

A conventional control loop of the variable speed FSWTGS is shown in Fig. 3 as a block diagram. Because it is possible to handle the active and reactive power freely between grid side and generator side, this system has great advantage of satisfying LVRT requirement. Because of the reduced cost of the power switching device and severe Grid Code, variable speed WTGS has a lot of potential for future WTGS market.

In Fig. 3, a conventional control loop of a FSWTGS is shown, where the generator side inverter performs pitch control, the grid side converter regulates the power flow through DC link voltage controller. The control block diagram of a DC link voltage controller is shown in Fig. 4

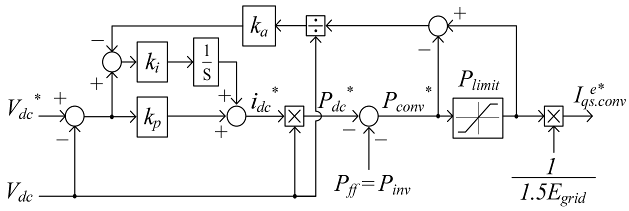


Fig. 4. DC link voltage control block diagram

and the transfer function of the controller is in (1).

$$\frac{V_{dc}^{*}}{V_{dc}} = \frac{\frac{k_p}{C_{dc}}s + \frac{k_i}{C_{dc}}}{s^2 + \frac{k_p}{C_{dc}}s + \frac{k_i}{C_{dc}}} \tag{1}$$

Gains can be defined as $k_p = 2C_{dc}\zeta\omega_n$, $k_i = C_{dc}\omega_n^2$ in order to set the characteristic equation as the second order system. In general, for easier tuning of voltage and current controller gains, the bandwidth of DC link voltage control loop should be less than one fifth of the bandwidth of current control loop.

The controller in Fig.4 works well in normal operation. However, in the case of a grid fault, especially three phase to ground fault occur, DC link voltage increases rapidly because all active power from the generator should be transferred into DC link capacitor not to the grid. Eventually, if there is no counter measure, DC link over voltage fault would occur. To prevent this situation, generator side power reference should be curtailed properly.

Using de-loading droop shown in Fig.5, it is possible to suppress DC link over voltage [7]. However in the case of 3 phase to ground fault, DC link voltage cannot be

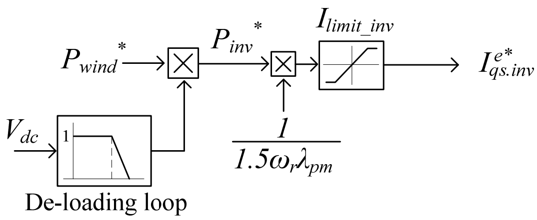


Fig. 1. De-loading droop method

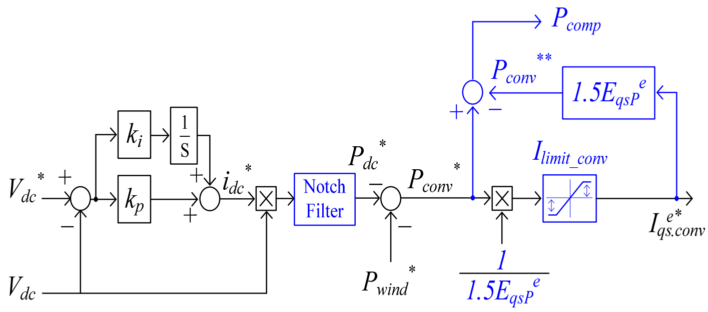


Fig. 6. Proposed DC link voltage control block diagram

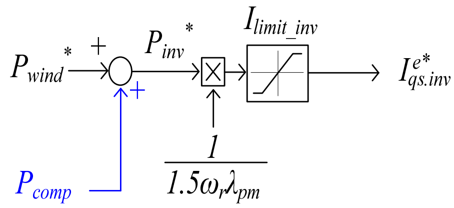


Fig. 7. Inverter side current reference generator

regulated because of the power from the wind turbine. DC link capacitor should absorb the power until reducing inverter side power reference. Hence, the capacitance of DC link should be properly sized to handle this power to prevent over-voltage fault.

B. DC link voltage control for LVRT

The proposed control block diagram is shown in Fig. 6. In LVRT condition, supporting reactive current is the most important concern. Therefore q-axis current is bounded as $\pm\sqrt{I_{rated}^{2}-(i_{ds}^{e})^{2}}$ after supplying required reactive current. And, the reactive current according to Grid Code up to the rated value is always possible.

For faster DC link voltage regulation, the compensating power (P_{comp}) is calculated and transfer to inverter side directly. P_{comp} is the excessive power that cannot be handled in grid side converter. Due to the direct transfer of P_{comp} to the turbine side inverter, in the case of three phase fault, generator side inverter can control DC link voltage rapidly without the intervention of DC link voltage controller. The current reference of inverter side is updated with the consideration of the compensating power as shown in Fig.7.

In the calculation of q-axis current reference of grid side converter, positive sequence components of measured grid voltage are used. To suppress 120Hz component due to the unbalanced grid fault, an 120Hz notch filter is added in the current loop.

III. Simulations

The simulation is based on 5MW FSWTGS and the parameters are listed in Table.1. In Fig. 8~9, it is the case that three phase to ground fault occurs at 1s and is cleared at 1.15s. It can be seen in Fig.8 and Fig.9, DC link voltage is well bounded with the proposed control loop during three phase grid fault because of the rapid update of inverter side q-axis current through the compensating power. Also as shown in Fig.9, it is confirmed that the system satisfied LVRT requirement by supporting 100% reactive current during the fault.

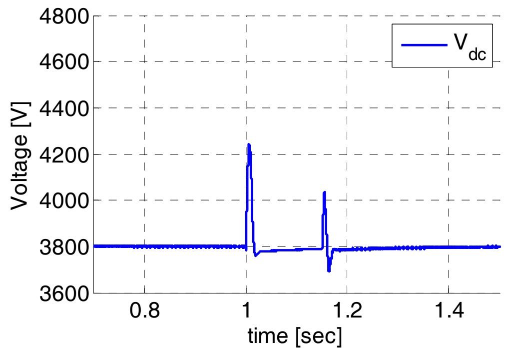


Fig. 8. DC link voltage (3 phase to ground fault: simulation)

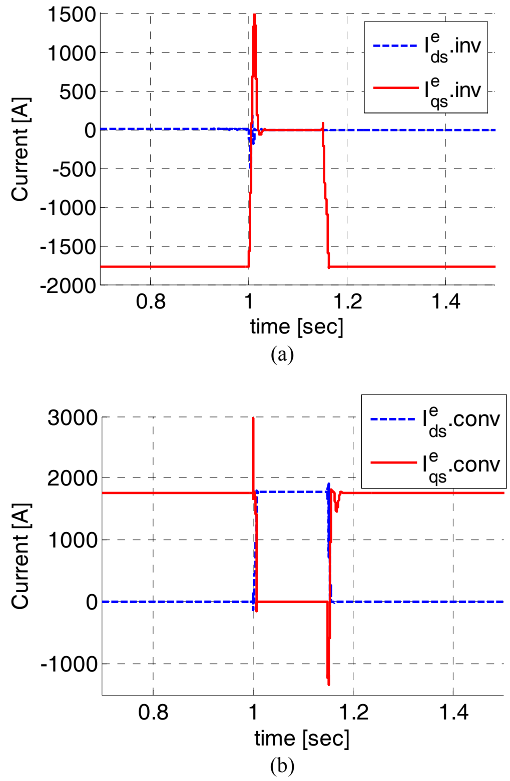


Fig. 9. inverter and converter side dq axis current (3 phase to ground fault: simulation) (a) Inverter side dq axis current (b) Converter side dq axis current

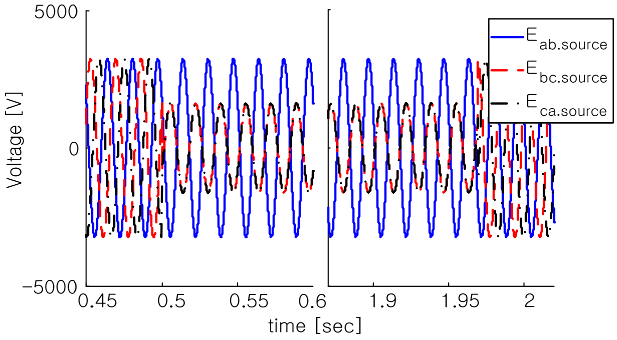


Fig. 10. line to line voltages (line to line short fault: simulation)

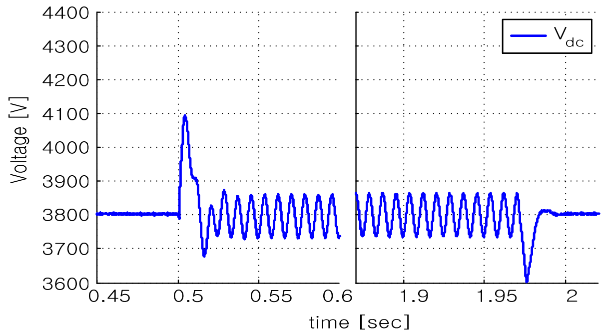
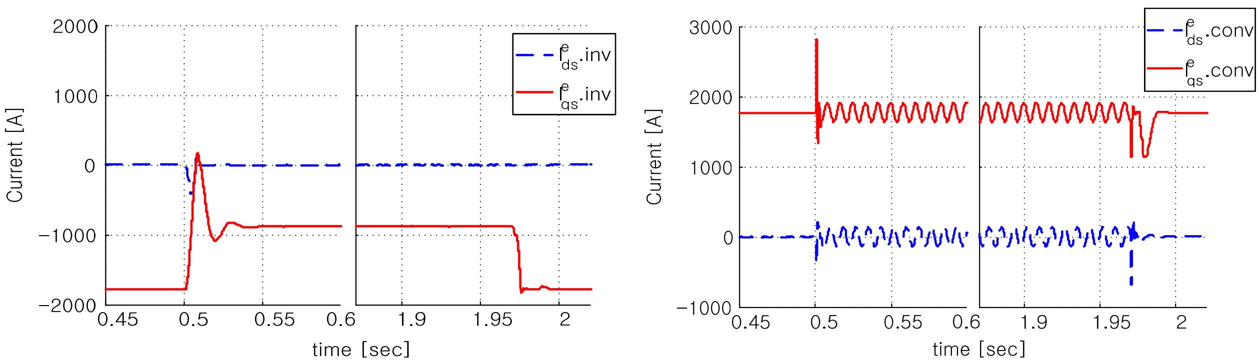


Fig. 11. DC link voltage (line to line short fault: simulation)



(a) (b)

Fig. 12. inverter and converter side dq axis current (line to line short fault: simulation) (a) Inverter side dq axis current (b) Converter side dq axis current

TABLE 1
PARAMETER OF 5MW SIMULATION

Grid voltage	3300V_{rms}
Delta-wye transformer	3300/2300V_{rms}
DC link voltage reference	3800V
DC link capacitor	15mF
5MW PMSG	
Rated power	5MW
Rated voltage	2300V_{rms}
Rated current	1255A_{rms}
pole	150
Rated speed(ω_{rm})	16 r/min
d-q- axis inductance	2.5mH
resistance	0.044Ω
Flux linkage	14.9442V/(rad/s)

Line to line shorted fault (a, c phase) is shown in Fig. 10~12. The fault lasts around 1.47s (form 0.5s to 1.97s). As shown in Fig. 10, because of the delta-wye transformer, one of the measured line to line voltages at PCC has no voltage reduction. It means there is no required reactive current for the grid. Because of the delay in digital control, some 120Hz negative sequence component is still included in the system. Hence, the DC link voltage is fluctuating at 120Hz because of the power from the negative sequence to DC link as shown in Fig.11. But the magnitude of the fluctuation is negligible compared to nominal DC link voltage. Also, As shown in Fig.12, in d-q axis current of converter, there are some 120Hz current components exist as explained.

IV. EXPERIMENTAL RESULTS

A scaled version of a variable speed WTGS based on 5 kW PMSG is used to verify the effectiveness of the control algorithm experimentally. The parameters of the experimental set-up are in Table. 2. In experiment, the LVRT tester is used for the simulation of the grid faults.

TABLE 2
PARAMETER OF 5KW EXPERIMENTAL SET

Grid voltage	220V_{rms}
Delta-wye transformer	220/380V_{rms}
DC link voltage reference	580V
DC link capacitor	530uF
5kW PMSG	
Rated power	5kW
Rated voltage	289.2566 V_{rms}
Rated current	9.98A_{rms}
pole	32
Rated speed(ω_{rm})	191 r/min
d-q- axis inductance	19.6mH
resistance	0.72Ω
Flux linkage	0.738V/(rad/s)

Configuration of LVRT tester is in Fig. 13. By adjusting voltage level by inductors (L_1, L_2, L_3, L_4 : L_1 is 3 phase inductor, L_2, L_3, L_4 are taps in one single phase inductor) several different voltage reduction level

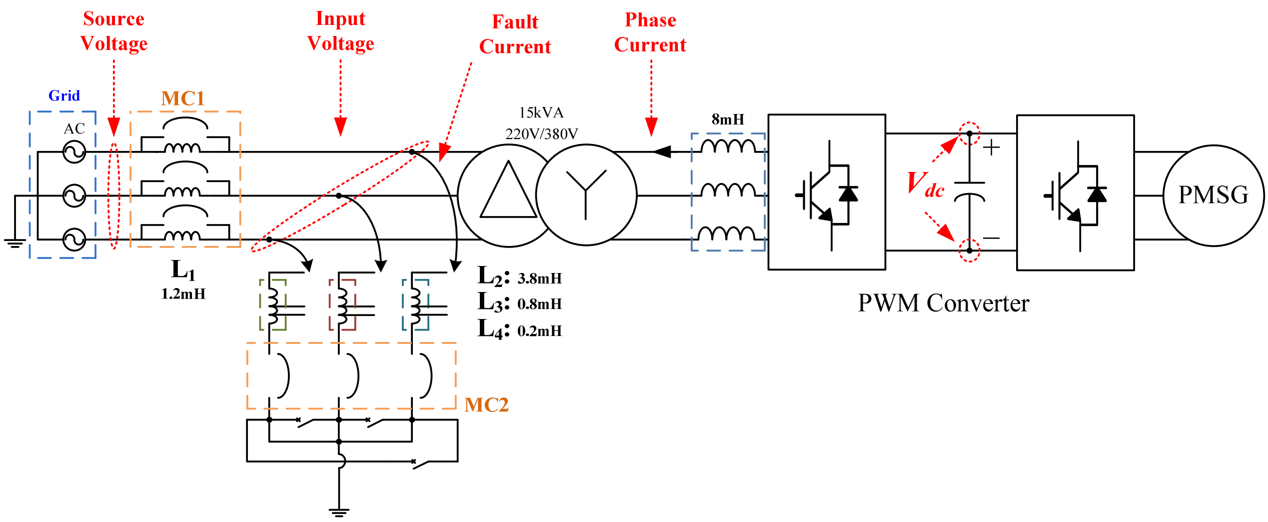


Fig. 13. Configuration of system with LVRT tester

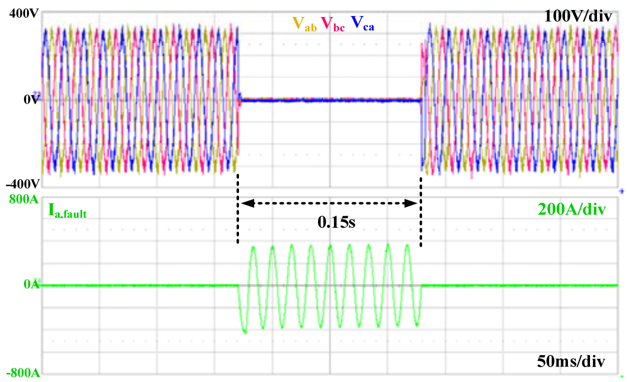


Fig. 14. line to line voltages (3 phase to ground fault: experimental result)

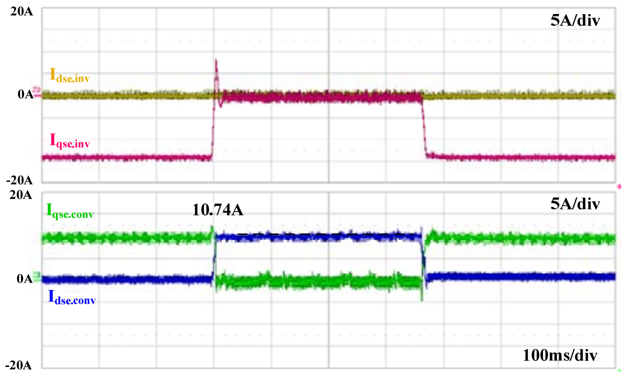


Fig. 16. dq axis current (3 phase to ground fault: experimental result), Inverter side dq axis current (top) and converter side dq axis current (Bottom).

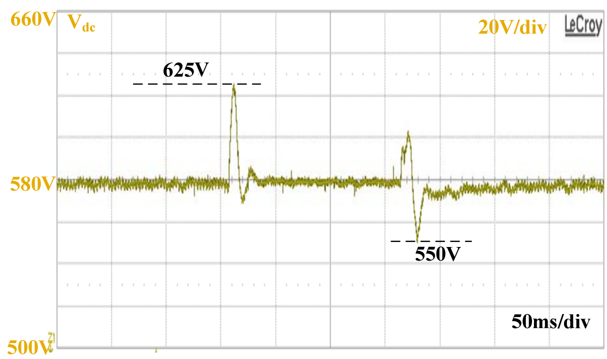


Fig. 15. DC link voltage (3 phase to ground fault: experimental result)

can be simulated and the duration of simulated faults is controlled by MCs (magnetic contactors). In normal situation, MC1 is on and MC2 is turned off. After removing MC1 from the system (MC1 off), MC2 becomes on to make grid fault. Type of fault can be set through combination of inductors.

Generally, inductances are able to set that the fault current can be 5~10 times larger than the rated current in Fig.13. In this paper, L_1, L_2, L_3, L_4 are 1.2mH, 3.8mH, 0.8mH and 0.2mH respectively to simulate 20%, 60%, 85% of voltage reductions.

Fig. 14~16 are the experimental results of 3 phase to ground fault. In Fig.14, line to line input voltages are measured at grid side (PCC, input voltage at Fig. 13) and fault duration is around 150ms.

The fault current is measured around 380A peak. Because the rated power of input transformer is 15kW, the rated current of 220V grid side can be calculated at 55.66A peak. Therefore the fault current is around 6.8 times larger than rated current.

DC link voltage is shown in Fig. 15. In all test results, the transient voltage of DC link is well limited within 10% of the nominal value. For LVRT requirement, converter d axis current should be supplied by rated current to grid side which is 10.74A. In Fig. 16, the reactive current is supplied and the other currents are also well regulated.

Fig. 17~19 are the experimental results of line to line shorted fault (a, c phase). In Fig. 17, because the line to

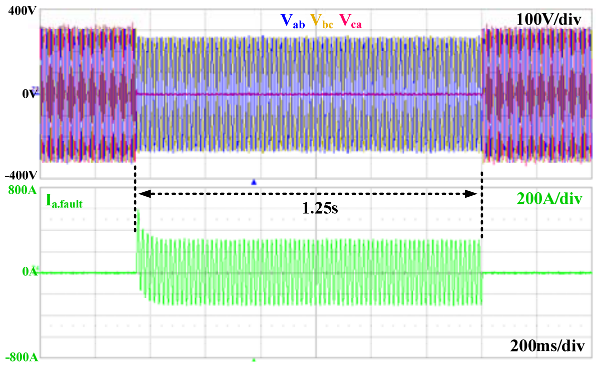


Fig. 17. line to line voltages (line to line short fault: experimental result)

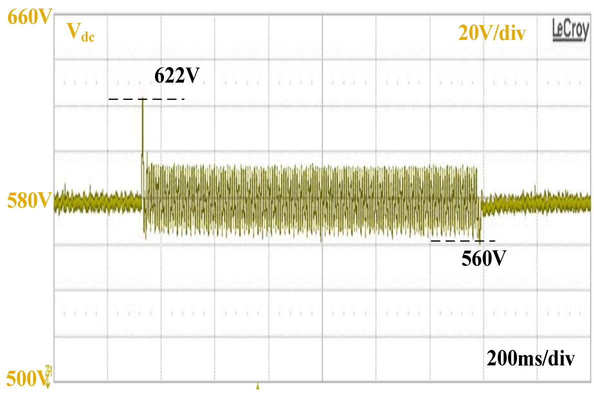


Fig. 18. DC link voltage (line to line short fault: experimental result)

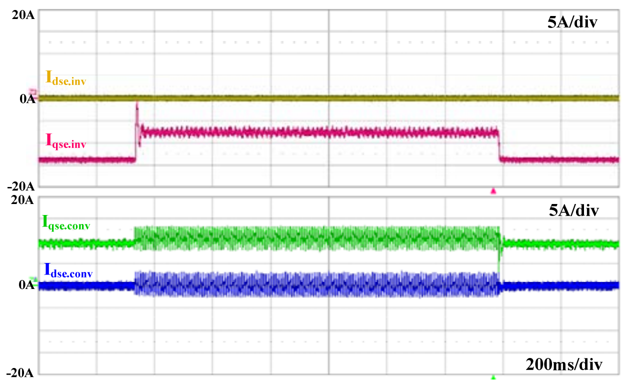


Fig. 19. inverter and converter side dq axis current (line to line short fault: experimental result), Inverter side dq axis current (top), converter side dq axis current (bottom)

line voltages are measured at grid side, the waveforms are different with simulation results which are measured at converter side(PCC). The results confirm that the proposed control loop is working satisfactory to meet Grid Code.

V. Conclusions

In this paper, a LVRT control strategy for variable speed FSWTGS to meet German Grid Code has been proposed. The LVRT requirement in German Grid Code is analyzed and considered. Through the computer simulation and the reduced scale experimental test, it is confirmed that the proposed control loop effectively limit DC link voltage due to direct transfer of the compensating power term to turbine side inverter. With the compensating power term, the torque reference current is updated without intervention of DC link voltage control loop. DC link voltage is well regulated regardless of reduced DC link capacitance. Also, the current reference for the active power of the grid side converter is bounded to guarantee the satisfaction of reactive current requirement of grid code for grid faults. The proposed control loop can meet not only LVRT requirement and but also regulate DC link voltage within the limit against grid faults.

References

[1] The Global Wind Energy Council, Sep 2010[Online], Available: http://www.gwec.net/.

[2] S.M. Muyeen, Rion Takahashi, Toshiaki Murata, Junji Tamura, “A variable speed wind turbine control strategy to meet wind farm grid code requirements,” *IEEE Trans.Ind.Application*, vol.25, no.1, Feb. 2010.

[3] “Grid Code for High and Extra High Voltage,” E.ON Netz GmbH, 1st April 2006

[4] S.M. Muyeen, R. Takahashi, T. Murata, J. Tamura, M.H. Ali, Y. Matsumura, A. Kuwayama, T. Matsumoto “Low voltage ride through capability enhancement of wind turbine generator system during network disturbance,” *Renewable Power Generation, IET*, vol.3, pp.65-74, March 2009

[5] Marta Molinas, Jon Are Suul, Tore Undeland, “Low voltage ride through of wind farm with cage generators: STATCOM versus SVC,” *Renewable Power Generation, IET*, vol.3, pp.65-74, March 2009

[6] M. Jahangir Hossain, Hemanshu R. Pota, Valeri A. Ugrinovskii, Rodrigo A. Ramos, “Simultaneous STATCOM and Pitch Angle Control for Improved LVRT Capability of Fixed-speed wind turbines,” *IEEE Transactions on sustainable energy*, VOL. 1, NO. 3, Oct 2010.

[7] Olimpo Anaya-Lara, Nick Jenkins, Janaka Ekanayake, Phill Cartwright, Mike Hughes, “Wind energy generation – modeling and control,” WILEY, pp 231-233, 2009.