

Stability Enhancement of a Hybrid Micro-grid System in Grid Fault Condition

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Abstract-Low voltage ride through capability augmentation of a hybrid micro-grid system is presented in this paper which reflects enhanced reliability in the system. The control scheme involves parallel connected multiple ac-dc bidirectional converters. When the micro-grid system is subjected to a severe voltage dip by any transient fault single power converter may not be able to provide necessary reactive power to overcome the severe voltage dip. This paper discusses the control strategy of additional power converter connected in parallel with main converter to support extra reactive power to withstand the severe voltage dip. During transient fault, when the terminal voltage crosses 90% of its pre-fault value, additional converter comes into operation. With the help of additional power converter, the micro-grid system withstands the severe voltage fulfilling the grid code requirements. This multiple converter scheme provides the micro-grid system the capability of low voltage ride through which makes the system more reliable and stable.

Keywords: Micro-grid, Low voltage ride through, Reliability, wind power generation system, PV system.

I. INTRODUCTION

At the present growing demand of electricity, widespread tripping of wind generators followed by disturbances can be one of the reasons of propagation of transient instability [1]. In terms of voltage stability, low voltage ride through is one of the most important issues. Due to lack of reactive power support, the possibility of voltage collapse is a critical issue. To withstand this kind of severe voltage dip, low voltage ride through capability (LVRT) has become a great requirement to be fulfilled in the grid codes [2-5].

In the present power scenarios, when it is mentioned about distributed generations of small scale generations to meet the customer demand, the coordination of these small scale generations consisting wind, photovoltaic, batteries and fuel cells are formed as Micro-grid [6-9]. Interest is rapidly increasing for micro-grid as it is based on the renewable energy sources, which connects the utility grid. In the grid tied mode, it is connected with utility whereas in case of islanded mode it is totally disconnected. In case of islanding mode it becomes totally independent and fulfills the customers' demands from the renewable energy sources. Even in the micro-grid the capability of low voltage ride through is of great importance. During the transient instability, the system has to withstand the severe voltage dip in order to enhance the stability and reliability of the system. In this paper, the low voltage ride through capability of the micro-grid system has been focused keeping in mind

that the enhancement of the reliability of the system is an important issue. The control scheme is designed to make the micro-grid system more reliable and efficient during transient conditions. The concept of parallel units of converters has been introduced so that during the transients when the terminal voltage crosses 90% of its pre-fault value, additional power converter can come into operation. The additional power converter supports extra reactive power needed to withstand the severe voltage dip. One case is shown out of the several in the simulation section. In the Section II and III, the proposed micro-grid system and dynamic system modeling are described. Section IV shows control strategy which explains how the alternate converter takes part in operation during the transient disturbance and how it gets back to its pre-fault state. Grid code is explained briefly in Section V. In Section VI, responses are shown to achieve the targets of the micro-grid system and finally the conclusions are made in the last section.

II. PROPOSED MICRO-GRID SYSTEM

A hybrid micro-grid system has been proposed and shown in Fig. 1 which consists of AC grid on the left and DC grid on the right side. Induction generator of 5MW power is connected at the ac side which is driven by fixed speed wind turbine. Fuel cell and Photovoltaic cells are connected as the dc source and Energy storage system is connected as well. Both ac and dc loads are considered in the system and whole system is connected with utility grid.

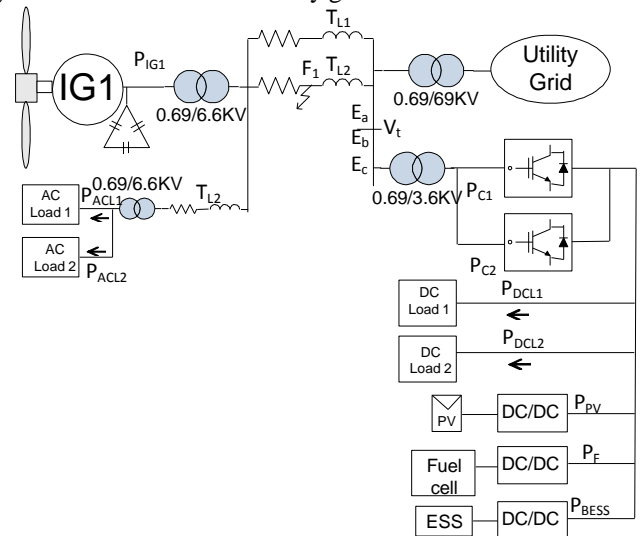


Fig. 1. Proposed ac-dc hybrid micro-grid model system

Fuel cell and energy storage system is connected by DC-DC boost converter at the dc bus whereas the solar cell is connected with DC-DC boost converter in order extract maximum power. Reactive power compensation at the grid voltage terminal can be handled by bidirectional AC-DC converter which is the main focus in this system as the additional converter along with the main converter play an important role for achieving the low voltage ride-through capability. During the transient disturbance the additional converter comes into operation and provides necessary reactive power to withstand the severe voltage dip leading to an enhanced stable and reliable system.

The induction generator delivers 5 MW and solar cell generates 0.5 MW amount of power [10]. The total generation is distributed to the ac and dc loads through parallel bi-directional ac-dc converters. Capacitor bank is used to maintain unity power factor operation at the rated wind speed. Micro-grid parameters are given briefly in Table I. In the simulation, fuel cell and ESS at dc bus is not considered.

TABLE I
MICRO-GRID PARAMETERS

Parameters	Value
Base voltage of converter	3.6kv V_{LL}
Base current of converter	0.40093A
Resistance (TL1)	0.26368ohm
Inductance (TL1)	0.0004326H
Length (TL1)	2.06km
Resistance (TL2)	0.013312ohm
Inductance (TL2)	0.0002184H
Length (TL2)	104m
AC generation	5MW
DC generation	0.5MW
PWM carrier frequency	1000Hz
AC loads	3 MW
DC loads	2.5MW
DC link voltage	6.6kv
DC link capacitance	100000 μ F

III. DYNAMIC SYSTEM MODELING

A. Wind turbine modeling

Wind turbine is an electromechanical energy conversion device that is capable of capturing kinetic energy from the wind and can turn this energy into electrical energy. In order to model the wind turbine, its components consist of turbine rotor or prime mover, a shaft and a gearbox unit [11]. The wind turbine output torque and extracted power from the wind turbine can be expressed by [12-16] below equations.

$$T_m = \frac{1}{2} \cdot \rho C(\lambda) \pi R^3 V_w^2 [NM] \quad (1)$$

$$P_m = \frac{1}{2} \cdot \rho C_p(\lambda, \beta) \pi R^2 V_w^3 [W] \quad (2)$$

Where ρ is the air density, R is the radius of the turbine, V_w is the wind speed, $C_p(\lambda, \beta)$ is the power coefficient given by

$$C_p(\lambda, \beta) = \frac{1}{2} \cdot (\Gamma - 0.02\beta^2 - 5.6)e^{-0.17\Gamma} \quad (3)$$

Where, $\Gamma = \frac{R(3600)}{\lambda(1609)}$ and $\lambda = \frac{\omega_m R}{V_w}$ is the tip speed ratio.

The relationship between C_t and C_p is

$$C_t(\lambda) = \frac{C_p(\lambda)}{\lambda} \quad (4)$$

B. Solar panel modeling

Each photovoltaic cell consists of a diode, a current source, a series resistance and a parallel resistance which is the basic element of a solar model. The photo current produced from the current source is dependent upon the solar cell radiation and temperature. p-n junction of a solar cell is represented by the diode. The photovoltaic cell current equation can be expressed as [17]

$$I_{PV} = n_p I_{ph} - n_p I_{rs} \left[e^{\left(\frac{qV_{dc}}{kT_c A n_s} \right)} - 1 \right] \quad (5)$$

Where,

$$I_{rs} = I_{rr} \left[\frac{T_c}{T_r} \right]^3 e^{\left(\frac{qE_g}{KA} \right) \left(\frac{1}{T_r} - \frac{1}{T} \right)} \quad (6)$$

$$I_{ph} = 0.01 [I_{scr} + K_v (T_c - T_r)] S \quad (7)$$

Where, n_s and n_p are the number of cells connected in series and parallel respectively. I_{ph} is the photo current, I_{rs} and I_{rr} are reverse saturation current at T and T_r . T is cell temperature and T_r is reference temperature. I_{scr} is the cell short circuit current at T_r . S stands for irradiance in mw/cm^2 . K is Boltzmann constant, K_v is the short circuit temperature coefficient at I_{scr} and q is charge of electron. A is the identity factor. I_{PV} is current from the photovoltaic cell.

C. Fuel cell modeling

Fuel cells are electrochemical devices which convert the chemical energy of a reaction into electrical energy. A fuel cell basically consists of an electrolyte layer (Ion conductor) in between a porous anode and cathode. Electric current is produced from the electrochemical reactions at the electrode, when gaseous fuel is injected to the anode and oxidant is fed to cathode [18-19].

D. Energy storage system

Energy storage device which is also known as ESS is a device which can store energy and discharge energy during its operation. Nowadays it has become an important part in wind farms and photovoltaic cells in micro-grids.

When demand is greater than the generation ESS can deliver energy in the system and it is also used to smoothen the power of wind farms. In the proposed micro-grid system, ESS is considered to be connected at the terminal of fixed speed wind turbine generator system which ensures constant power delivery by absorbing the fluctuating quantity of the wind power as shown in Fig. 2. According to [20], the ESS charges the first half cycle of the variable power and then discharges it at the next cycle so that the constant power can be delivered to the power grid.

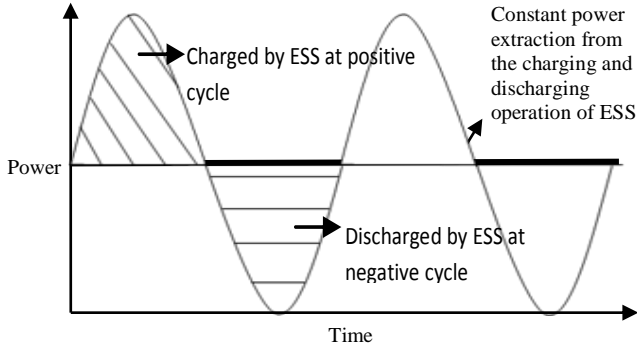


Fig. 2. Wind power smoothing operation by ESS

IV. CONTROL STRATEGY

To enhance the stability of the hybrid micro-grid system during transient condition, control strategy has been used. During the steady state condition, single power converter operates. When transient fault occurs, the micro-grid experiences a severe voltage dip. To withstand this severe voltage dip, additional converter is used to provide extra reactive power. After the transient fault, when the terminal voltage decreases to 90% of its pre-fault value, the additional converter is switched on so that it can provide necessary reactive power support.

Figure 3(a) shows the control block diagram of individual power converter unit, where PLL provides the angle θ_{PLL} for the abc-to-dq0 (and dq0-to-abc) transformation. This control block is interlinked with the power converter reference control scheme which is shown in detail in Fig. 3(b). At steady state, real power through the power converter P_{REF_CONV} is controlled and reactive power through the power converter Q_{ref} is forcefully made zero. When transient fault occurs the real power through the power converters P_{REF_CONV} and terminal voltage V_t is controlled. This way, the power converters provide reactive power to withstand the voltage dip.

A test case for having the low voltage ride through capability of the micro-grid system using multiple converter schemes is summarized in Table II.

TABLE II
MICRO-GRID DETAILS

AC/DC	Generations	Loads		Converters		Total Loads (MW)
		L	L2	PC1	PC2	
		1				
AC	5	1.5	1.5	2	0	3
DC	0.5	2	0.5			2.5
During transient analysis						
AC	5	1.5	1.5	1	1	3
DC	0.5	2	0.5			2.5
Total	5.5					5.5

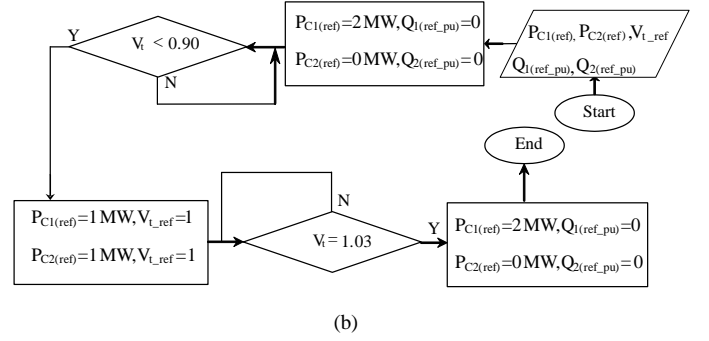
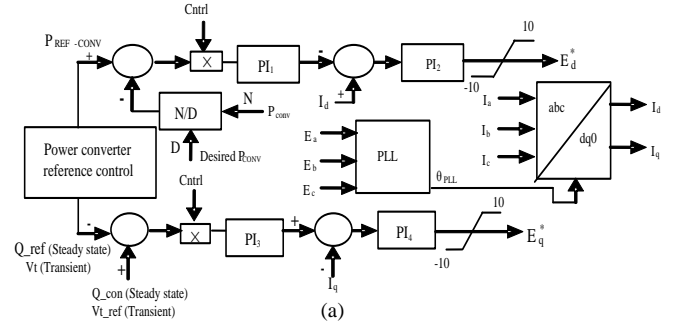


Fig. 3. (a) Real and reactive power control of power converters with load management control (b) Power converter reference control scheme

In the test case shown in Table II, it is seen that during steady state condition, one power converter is operating and other power converter is turned off. The real power through converter 1, PC1 is 2MW and converter 2 is 0MW. During the transient condition, additional converter 2 is turned on and real power through each converter is 1MW. The control strategy shown in Fig. 3(a) discusses the control strategy of each converter. As mentioned earlier, during the transient fault, additional converter is turned on and terminal voltage V_t control is set from Q_{ref} control. This operation is performed by the power converter reference control block shown in Fig. 3(b)

The control strategy of the power converter reference control block is shown in Fig. 3(b). This control is developed for the test case shown in Table II. During steady condition the real power reference through each converter, $PC1(ref)$ and $PC2(ref)$ is set 2MW and 0MW respectively. Both the reactive power through each converter, $Q1_{ref}(pu)$ and $Q2_{ref}(pu)$ is set as zero. When terminal voltage reaches less than 0.90pu, the real power through the power converters $PC1(ref)$ and $PC2(ref)$ are changed to 1MW. Terminal voltage control is set by providing the reference for the terminal voltage as $V_{t_ref} = 1$. This operation by providing real power reference turns on the additional power converter. Terminal voltage reference enables the additional power converters along with the converter 1 to provide necessary reactive power to withstand the severe voltage dip. When the terminal voltage reaches to its pre-fault value, the reference signals are set back to the previous state and additional converter is automatically turned off.

V. GRID CODES

The most worrying problem that wind farm must face is a voltage dip in the grid during grid fault. The magnitude of the voltage is controlled by the reactive power exchange, since in most networks as $Q \propto \Delta V$. Grid code requirement for low voltage ride through has to take into consideration. According to [21-22], 1.5 second is considered as the threshold time within which grid voltage should recover 90% of its pre-fault level. System that can recover within that threshold time is considered as stable.

TABLE III
RECOVERY TIME FOR DIFFERENT TYPES OF FAULT

Fault location	Fault type	Recovery time (sec)
F1	3LG	0.80
F1	2LG	0.45
F1	1LG	0.24
F1	3LL	0.80

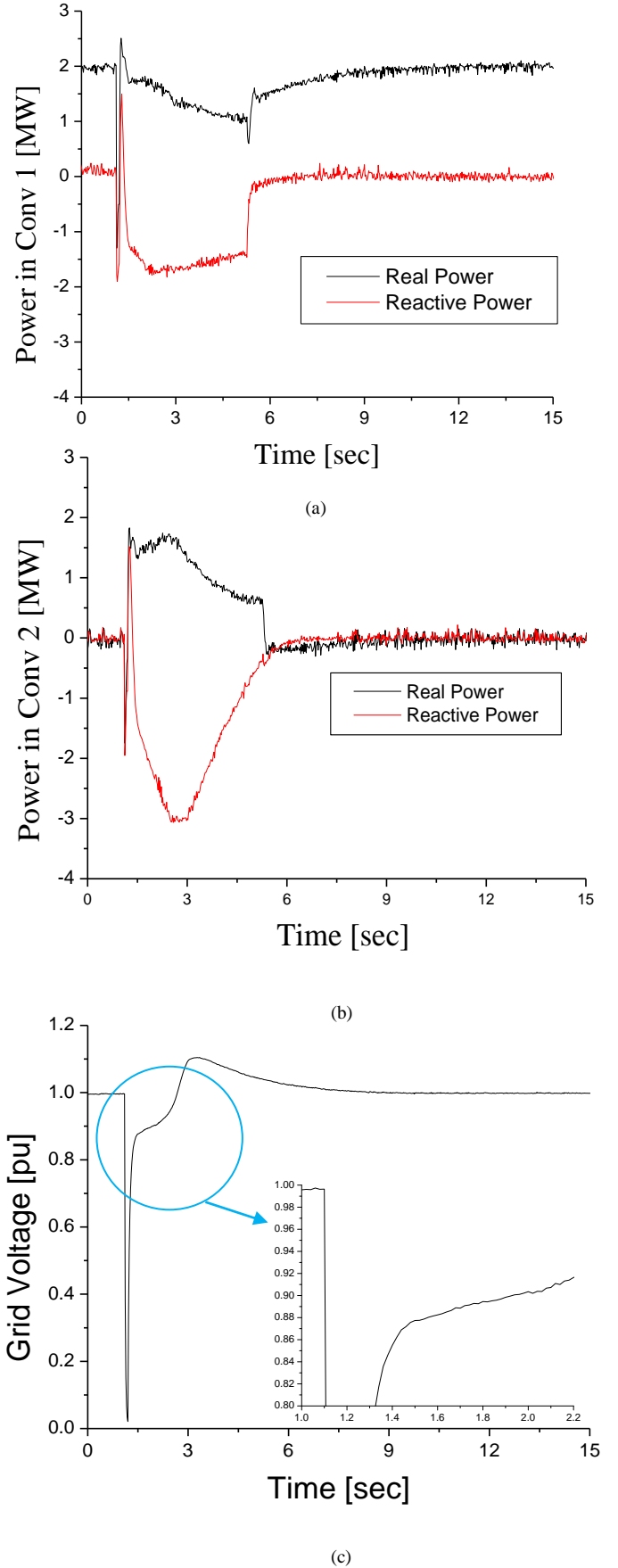
As mentioned above, in this micro-grid system different transient faults at F1 locations have been considered. For all cases, the grid code requirement is met and it has been summarized in Table III which is further discussed with proper verification in the simulation section.

VI. SIMULATION RESULTS

Simulations for the ac-dc hybrid micro-grid system are performed in PSCAD/EMTDC [23] with 3LG, 2LG, 1LG faults at F1 location of the micro-grid. The fault is occurred at 1.1 second with duration of 0.1 second. The fault is cleared at 1.2 second.

In Fig. 4, Real and reactive power through the converters, grid voltage, total generation and loads both ac and dc are shown. Figure 4 (a, b) depict the real and reactive power through converter 1 and 2 respectively. It is observed from Fig. 4(a, b) that before the transient fault, the converter 1 was in operation and the additional converter was switched off. So the alternate converter was not delivering any real and reactive power to the system. During transient, according to the control strategy, when the grid voltage drops to 90% of its pre-fault value, the alternate converter comes into operation and at 9th second when the grid voltage reaches to close to 1.03 p.u. the converters again goes to its previous state. Breaker recloses at 2 sec. From Fig. 4(a, b), it can be clearly observed that the additional converter reaches to its pre-fault state and it only operates during the transient fault condition and provides additional reactive power to support in withstanding severe voltage dip in the system.

Figure 4(c) shows the grid voltage of the micro-grid system. It is observed that the grid voltage recovers 90% of its pre-fault value within 0.80 sec which fulfills the grid code requirement. Figure 4(d) represents the apparent power of the both converters which stays within the rated value.



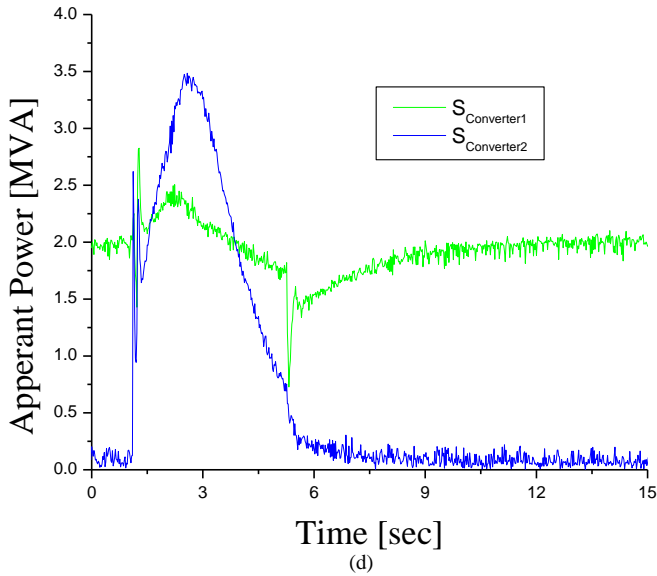


Fig. 4. System responses in Micro-grid system with 3LG fault (a) Power through converter1 (b) Power through converter 2 (c) Grid voltage (d) Apperant power of converters

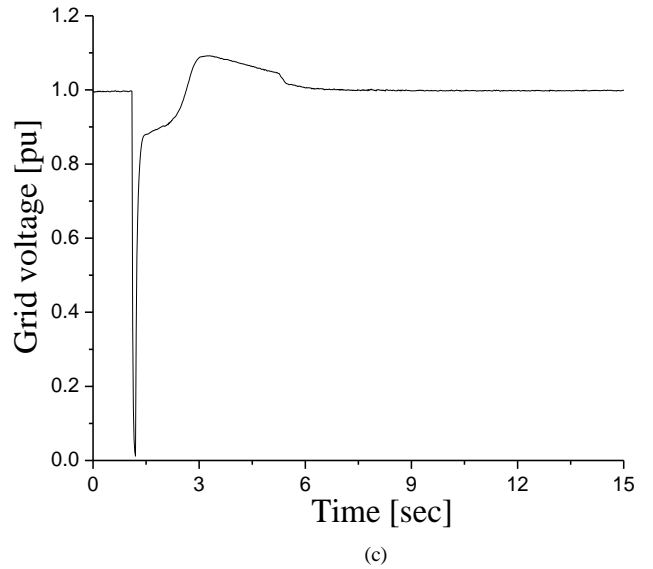
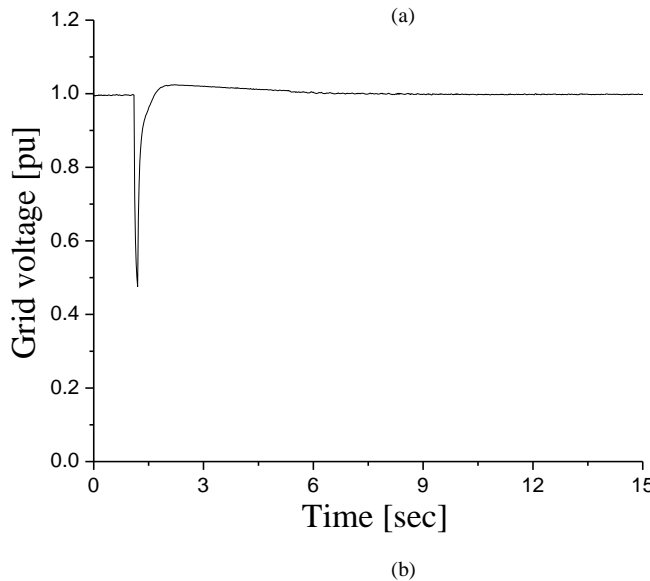
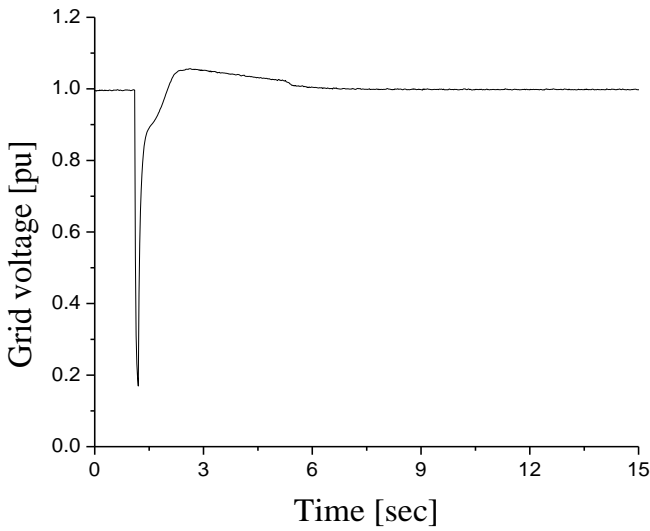


Fig. 5. Grid Voltage responses in Micro-grid system at F1 location during (a) 2LG (b) 1LG (c) 3LL faults



In Fig. 5, grid voltage at F1 location for 2LG, 1LG and 3LL faults are shown as well. The recovery time to reach 90% of its pre-fault value after the transient faults meets the grid code requirement. The recovery times shown in the simulations are summarized in Table II as mentioned before. The simulation results verify that the hybrid micro-grid system can withstand severe voltage dip during the transient disturbances during different transient faults.

V. CONCLUSION

The main focus of this paper is to have the capability of low voltage ride through (LVRT) for the multiple parallel converter based ac-dc hybrid micro-grid system. The effectiveness of the proposed control system has been verified by simulation analysis. It is observed that during pre-fault condition, single power converter operates whereas during transient condition, the additional power converter delivers necessary reactive power along with the main converter and the micro-grid system can withstand severe voltage dip and the recovery time for the grid voltage to regain 90% of its pre-fault value meets the grid code requirement, which validates the effectiveness of the proposed control strategy. The multiple power converter scheme of the ac-dc hybrid micro-grid system enhances the stability during transient conditions.

REFERENCES

- [1] S.M. Muyeen, M. H. Ali, R. Takahashi, T. Murata, J. Tamura, Y. Tomaki, A. Sakahara and E. Sasano, "Comparative study on transient stability analysis of wind turbine generator system using different drive train models," *IET Renew. Power Gener.* Vol. 1, No. 2, pp. 131-141, June 2007.
- [2] "Grid Code High and Extra High Voltage," Tech. Rep., E.ON Netz GmgH Bayreuth, 2003 [Online]. Available: <http://eon-netz.com>.
- [3] M. Molinas, J. A. Suul and T. Undeland, "Low Voltage Ride Through of Wind Farms With Cage Generators: STATCOM versus SVC," *IEEE Trans. Power Elect.* Vol. 23, No. 3, pp. 1104-1117, MAY 2008.

- [4] J. F. Conroy and R. Watson, "Low-voltage ride-through of a full converter wind turbine with permanent magnet generator," *IET Renew. Power Gener.*, Vol. 1, No. 3, pp. 182-189, Sept. 2007.
- [5] C. Abbey and G. Joos, "Effect of Low Voltage Ride Through (LVRT) Characteristic on Voltage Stability," in *IEEE Power Engineering Society General Meeting*, Vol. 2, pp. 1901-1907, 2005.
- [6] Anne-Marie Borbely and Jan F. Kreider, *Distributed Generation: Power Paradigm for the New Millennium*; CRC Press., 2001.
- [7] R. H. Lasseter, "MicroGrids," *PES Winter Meeting*, vol. 1, pp. 305-308, 2002.
- [8] X. Liu, P. Wang and P. C. Loh, "A Hybrid AC/DC Microgrid and Its Coordination Control", *IEEE Trans. Smart Grid*, Vol. 2, No. 2, pp. 278-286, June 2011.
- [9] Y. Ito, Z. Yang and H. Akagi, "DC micro-grid based distribution power generation system," in *Proc. IEEE Int. Power Electron. Motion Control Conf.*, Aug. 2004, Vol. 3, pp. 1740-1745.
- [10] X. Liu, P. Wang and P. C. Loh, "A Hybrid AC/DC Micro-Grid," *IPEC, 2010*, pp. 746-751, 27-29 Oct. 2010.
- [11] S. Santos, and H. T. Le, "Fundamental Time-Domain Wind Turbine Models for Wind Power Studies," *Renewable Energy*, Vol. 32, pp. 2436-2452, 2007.
- [12] K.E. Okedu, S.M. Muyeen, R. Takahashi, and J. Tamura, "Comparative Study between Two Protection Schemes for DFIG-based Wind Generator," *Proceedings of International Conference on Electrical Machines and Systems*, pp. 62-67, 10-13 Oct. 2010.
- [13] R. Takahashi, J. Tamura, M. Futami, M. Kimura and K. Idle, "A New Control Method for Wind Energy Conversion System Using Double Fed Synchronous Generators," *IEEJ Trans. Power and Energy*, Vol.126, No.2, pp.225-235, 2006 (in Japanese).
- [14] T. Sun, Z. Chen and F. Blaabjerg, "Transient Stability of DFIG Wind Turbines at an External Short Circuit Fault," *Wind Energy Journal*, Vol. 8, pp. 345-360, 2005.
- [15] R. D. Fernandez, P.E. Battaiotto, and R. J. Mantz, "Wind Farm NonLinear Control for Damping Electromechanical Oscillations of Power Systems," *Renewable Energy*, Vol. 33, pp. 2258-2265, 2008.
- [16] K. E. Okedu, S.M. Muyeen, R. Takahashi and J. Tamura, "Stabilization of Wind Farms by DFIG-based Variable Speed Wind Generators," *International Conference on Electrical Machines*, pp. 464-469, 2010.
- [17] G. Vachtsevanos and K. Kalaitzakis, "A Hybrid Photovoltaic Simulator for Utility Interactive Studies," *IEEE Trans. Energy Conversion*, Vol. EC-2, No. 2, pp. 227-231, June 1987.
- [18] M.J Khan and M. T. Iqbal, "Dynamic Modeling and Simulation of a Small Wind-Fuel Cell Hybrid Energy System," *Renewable Energy*, pp. 421-439, 2005.
- [19] T. Tsao, P. Chen and H. Chen, "Dynamic Modeling and Simulation of Hybrid Power Systems Based on Renewable Energy", *International conference on Energy and Environment Technology*, pp. 602-605, Oct. 2009.
- [20] S. M. Muyeen, J. Tamura, and T. Murata, "Stability Augmentation of a Grid-connected Wind Farm," *Springer-Verlag London*, ISBN 978-1-84800-315-6, October 2008.
- [21] E.On NETZ GmbH, "Grid Connection Regulation for High and Extra High Voltage," 2006.
- [22] K.E Okedu, S.M.Muyeen, R. Takahashi and J. Tamura, "Participation of facts in stabilizing DFIG with crowbar during grid fault based on grid codes," *IEEE GCC conference and Exhibition*, pp. 365-368, Feb. 2011.
- [23] "*PSCAD/EMTDC Manual*," Manitoba HVDC Research Center, 1994.