

Grid Code Violation during Fault Triggered Islanding of Hybrid Micro-grid

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Abstract— The major advantage of a micro-grid is its ability to run in both grid connected and islanded mode of operation providing higher flexibility and reliability. With increasing popularity of micro-grids and their existence becoming more and more prominent in existing power systems, more stringent adherence to frequency and voltage standards are being requested by Distribution Network Operators (DNO's) in order to maintain proper functionality of the grid. In case of any violations to the aforementioned standards, the distributed generation will have to be disconnected to ensure system security. Fault triggered islanding causes large excursions in system voltage and frequency which may lead to disconnection of DG's thereby threatening the grid integrity and strength. In this paper a review of IEEE standards and North American Electric Reliability Corporation suggested standards is presented. The use of dynamic voltage restorer as series compensation to ensure successful islanding without violating the standards is proposed. A comprehensive analysis is conducted by time domain simulations using Matlab/Simulink software.

Index Terms-- Dynamic voltage restorer, grid codes, hybrid micro-grid, inverter based distributed generation, synchronous diesel generator.

I. INTRODUCTION

Integration of renewable energy into existing power systems is a modern day challenge. Hybrid micro-grids consisting of synchronous diesel generator and inverter based distributed generations are potential solution to the challenge [1]. Hybrid micro-grid may comprise of renewable and conventional energy resources to meet the desired load demand and to ensure system stability at different operating conditions.

A micro-grid may be islanded for autonomous operation either due to preplanned switching or any disturbance such as grid fault. Various islanding scenarios and its subsequent autonomous operation for a micro-grid comprising of an inverter based DG and a conventional diesel generator have been investigated in [2]. The paper shows that the micro-grid can maintain angle stability and resume normal operation after being subjected to severe islanding transients as in case of fault triggered islanding. Autonomous operation of a micro-

grid with two inverter based DG and one conventional synchronous machine with various power management strategies (PMS) has been investigated in [3]. It has been show that inverter based DG control and adopted PMS have significant impact on micro-grid dynamic behavior when islanded from the grid. In [4-6], small signal dynamic model of a micro-grid with inverter based DG and synchronous generator has been developed. In [4], it has been shown that the fast action of inverter based DG's can be exploited to maintain angle/voltage stability, to meet changes in power demand and improve voltage quality after, during and prior to islanding. In [7], the stability margins in terms of critical clearing times for preplanned islanding and fault triggered islanding have been determined. The stability margin for fault triggered islanding is much less compared to preplanned islanding.

In [2-7], the transition from grid connected mode to islanded mode has been discussed. The voltage and frequency variations with respect to protection relay coordination and unwanted equipment tripping have not been discussed. The main objective of this is to highlight the voltage and frequency excursions during the process of fault triggered islanding, which may in certain cases lead to DG disconnection for not being within the standards. Fault triggered islanding for all types of fault have been considered. A solution to successful islanding with the help of series compensating dynamic voltage restorer (DVR) is proposed.

The paper is organized as follows. The test system is described in section II. Section III presents the grid interconnection standards. Hybrid micro-grid response to faults provided in section IV. The use of DVR for successful islanding proposed in section V. Finally, in section VI, simulation results are discussed and conclusion is drawn.

II. TEST SYSTEM DESCRIPTION

Fig. 1 shows a layout of the test system used to investigate the dynamic response of a hybrid micro-grid. A section of Canadian benchmark distribution system with one feeder rated at 8MVA represents the utility grid [8]. A hybrid micro-grid is connected to the utility grid at bus 5. The hybrid micro-grid system includes a conventional synchronous

diesel generator and an inverter based DG, both rated at 0.75MVA. Linear R-L-C load (0.7 MVA) and two identical induction motors (2X150 kVA) constitute to the micro-grid loads. No-load excitation of the induction motors is provided by the shunt capacitor banks connected at the point of common coupling (PCC). One of the important constraints of a micro-grid, which has been fulfilled, is to have adequate capacity to supply its local load demand.

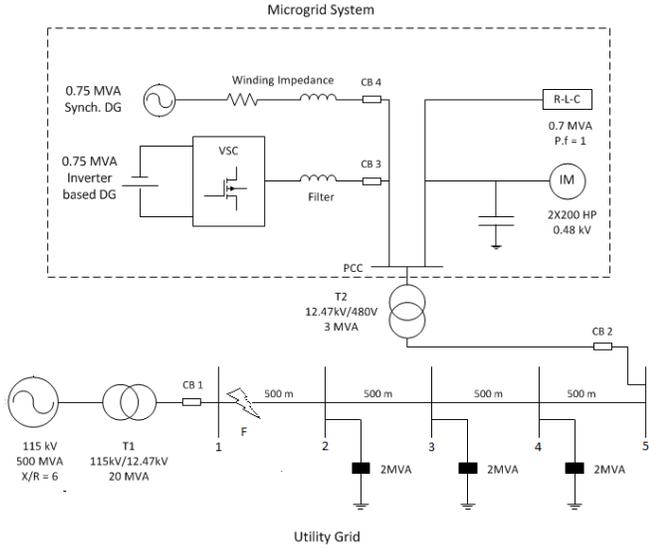


Fig. 1. Single line diagram of system under study

The synchronous diesel generator in this paper is modeled with excitation system and governor turbine. An IEEE type I standard excitation model as in [9], has been used. The excitation model parameters have been chosen in accordance with Westinghouse brushless excitation system design in [10]. The governor model used is derived based on model in [11]. Inverter based DG is connected to constant DC voltage source as it is assumed to be dispatchable. The power circuit consists of six pulse width modulation driven insulated-gate bipolar transistor (IGBT) switches followed by filter on AC side.

Inverter based DG's have fast transient response. Various control schemes for inverter based DG's have been discussed in [12]. Real and reactive power (P&Q) control scheme described in [7], has been used in this paper. The control block diagram is shown in Fig. 2. Real and reactive power output is measured and compared with the reference real and reactive powers and passes through a proportional and integral (PI) controller to generate the reference d-q component currents. The reference currents are compared with the actual currents and pass through PI controller in the current controller. The output of the current controller is used to generate the switching signals for the inverter.

Master Slave power management strategy is used for the hybrid micro-grid. Diesel generator is dedicated to voltage and frequency control (Master). The inverter based DG supplies constant active power irrespective of variations in frequency or voltage (Slave). Master slave power

management strategy can be used for both grid connected and islanded mode of operation.

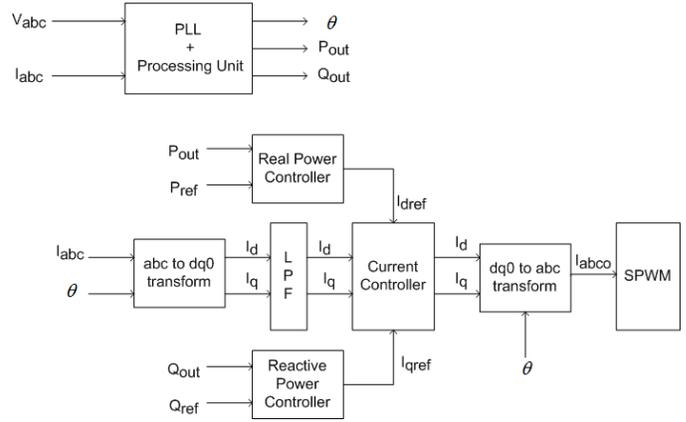


Fig. 2. Inverter control block diagram

III. GRID CODES

For interconnection and operation of distributed generation at a grid, certain technical and organizational requirements of the particular grids have to be fulfilled. These technical and organizational requirements are referred to as grid codes. A review of North American Electric Reliability Corporation (NERC) and IEEE standards for protection has been presented in Table I, Table II, Table III and Table IV [13-14]. This paper focuses on the voltage and frequency standards violation during a fault for a hybrid micro-grid and hence

TABLE I
NERC Interconnection System Response to Abnormal Voltage

Voltage Range (pu)	Default Clearing Times (s)
$V > 1.2$	0.2
$1.75 < V < 1.2$	0.5
$1.15 < V < 1.175$	1
$1.1 < V < 1.15$	4
$0.75 < V < 0.9$	3
$0.65 < V < 0.75$	2
$0.45 < V < 0.65$	0.3
$V < 0.45$	0.15

TABLE II
NERC Interconnection System Response to Abnormal Frequency

Frequency Range (Hz)	Default Clearing Times (s)
$f > 62.2$	instantaneous
$60.5 < f < 62.52$	600 - 10000
$59.5 < f < 60.5$	continuous
$57.8 < f < 59.5$	1800 - 10000
$f < 57.8$	instantaneous

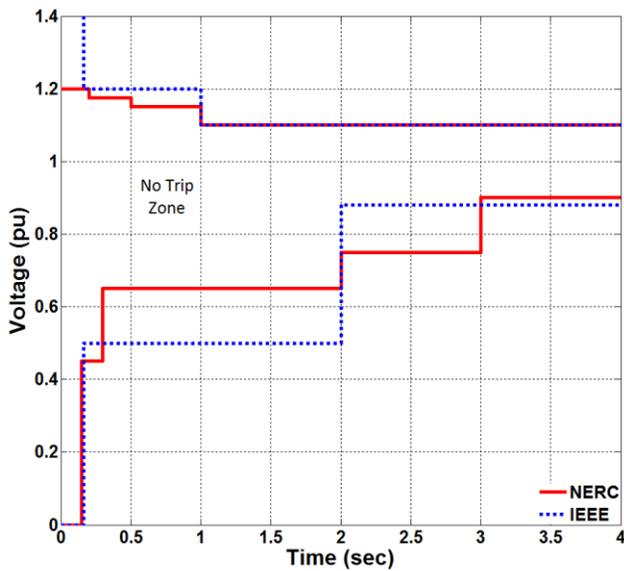
TABLE III

IEEE Interconnection System Response to Abnormal Voltage	
Voltage Range (pu)	Default Clearing Times (s)
$V > 1.2$	0.16
$1.1 < V < 1.2$	1
$0.5 < V < 0.88$	2
$V < 0.5$	0.16

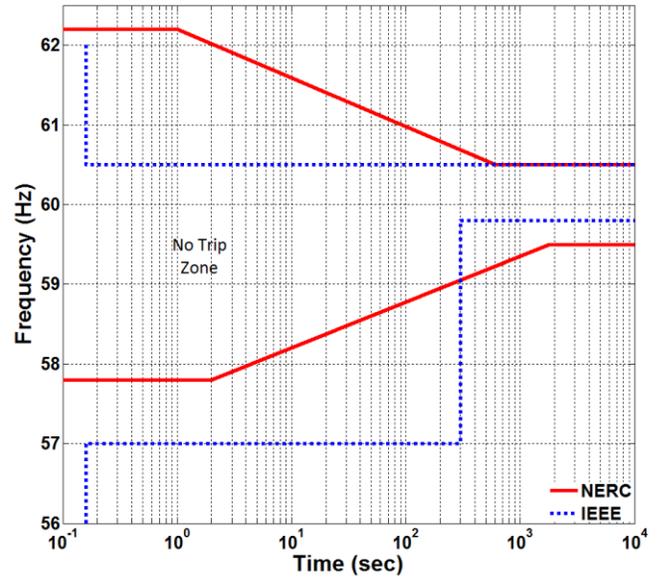
TABLE IV

IEEE Interconnection System Response to Abnormal Frequency	
Frequency Range (Hz)	Default Clearing Times (s)
$f > 60.5$	0.16
$59.8 < f < 60.5$	continuous
$57 < f < 59.8$	0.16 - 300
$f < 57$	0.16

standards for voltage and frequency have been presented. A graphical comparison of NERC voltage and frequency standards with that of IEEE voltage and frequency standards is shown in Fig. 3 (a) and (b). The region between the blue lines for both voltage and frequency is the no trip zone according to IEEE standards. A DG can continue its normal operation provided its voltage and frequency are within the no trip zone. If the frequency and voltage characteristics are beyond the no trip zone, the DG will be disconnected from the grid and cease to operate. The region between the red lines signifies the no trip zone according to NERC standards. Comparing the two standards it can be observed that the frequency standards for IEEE are more stringent than NERC standards, allowing frequency excursion only up to 60.5 Hz compared to 62.2 Hz as in case of NERC. Each DNO has its own standards which are set by them and vary from others.



(a)

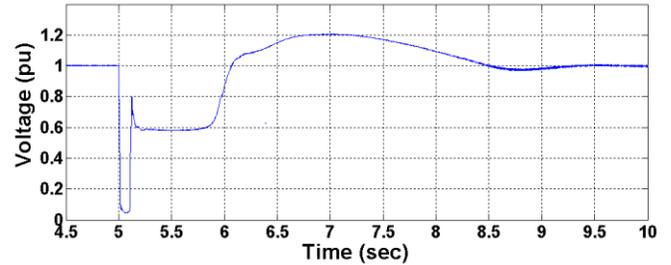


(b)

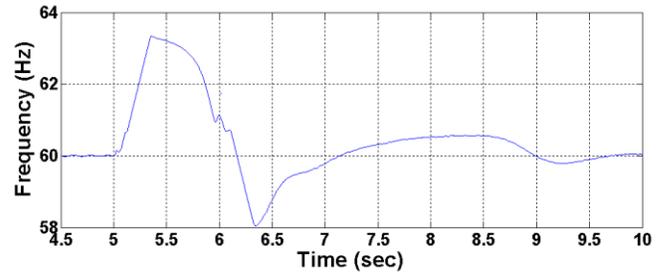
Fig. 3. A review of NERC and IEEE standards (a) for voltage (b) for frequency

IV. HYBRID MICRO-GRID RESPONSE TO GRID FAULT

Fig. 4,5,6 and 7 show the voltage and frequency response of a hybrid micro-grid to 3 phase ground fault, double line to ground fault, single line to ground fault and line to line fault respectively. A permanent fault takes place at bus 1 of the utility grid at $t=5$ s and is cleared by operation of circuit breaker CB 2 (islanding) at $t=104$ ms. For analysis of faults, NERC standards have been chosen in this paper.

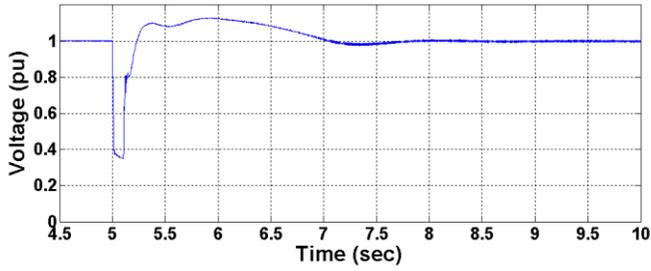


(a)

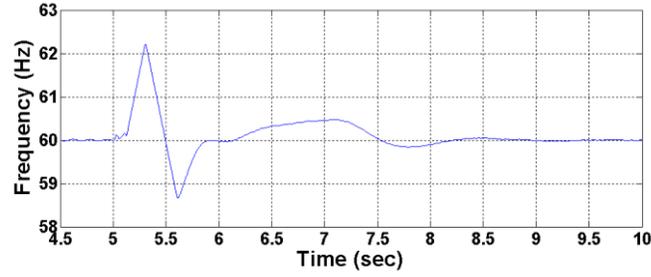


(b)

Fig. 4. Hybrid micro-grid response to 3 phase ground fault; (a),(b) voltage and frequency response.

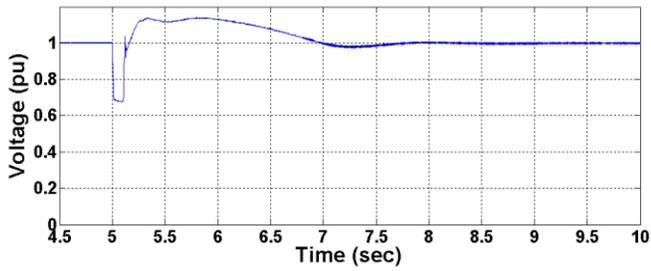


(a)

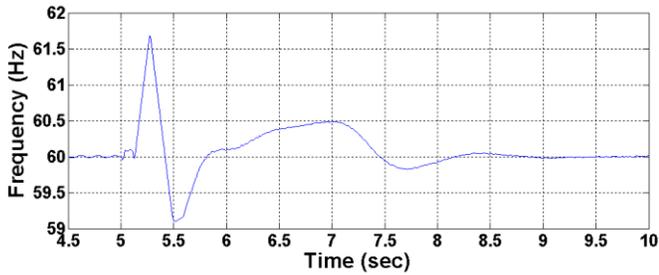


(b)

Fig. 5. Hybrid micro-grid response to double line ground fault; (a),(b) voltage and frequency response.



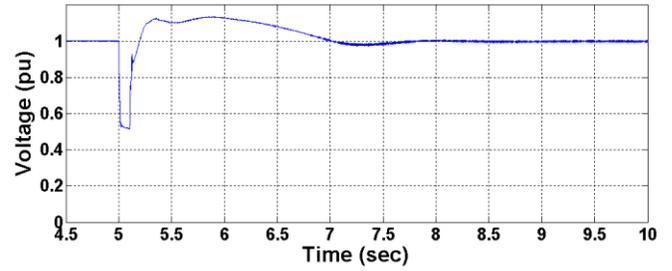
(a)



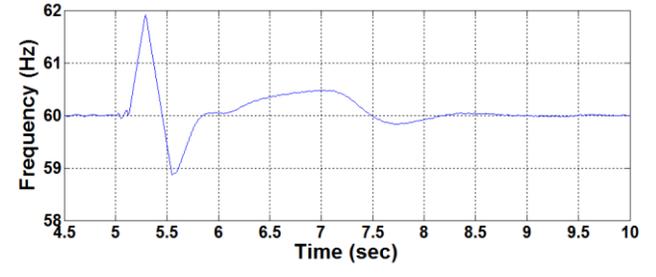
(b)

Fig. 6. Hybrid micro-grid response to single line ground fault; (a),(b) voltage and frequency response.

It can be observed that the frequency for single line to ground fault and line to line fault is within the no trip region. The voltage profile for single line to ground fault and line to line fault is above 1.1 pu but below 1.15 pu. The voltage is above 1.1 pu for one second, which is within the no trip zone. Therefore, the micro-grid can continue its operation. In case of double line to ground fault and 3 phase ground fault, the frequency is no longer within the no trip zone. The voltage for double line to ground is within the no trip zone for three



(a)



(b)

Fig. 7. Hybrid micro-grid response to line to line fault; (a),(b) voltage and frequency response.

phase ground fault lies beyond the no trip zone. In both the cases, i.e. for double line to ground fault and 3 phase ground fault, the over frequency and over voltage relays will be triggered. As a result the DG's will be disconnected and the cease to operate.

V. DYNAMIC VOLTAGE RESTORER FOR SERIES COMPENSATION

For successful transition to islanded mode after a fault, without the DG's being disconnected, the use of dynamic voltage restorer (DVR) is proposed. DVR is a device that detects the sag or swells in voltage and is connected in series for voltage compensation at the point of common coupling as shown in Fig. 8.

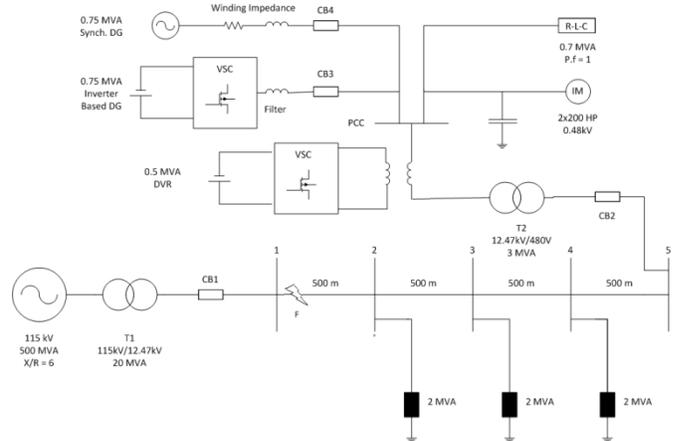


Fig. 8. Single line diagram of system with DVR at PCC

During normal operating condition the DVR operates in a low loss standby mode. During a disturbance, as the voltage is deviated from its operating value, the DVR compensates the voltage sag/swell by means of active and reactive power injection/absorption. It compensates the voltage difference between the pre sag and sag voltage at the point of its connection and maintains the pre sag voltage. As a result the micro-grid is isolated from the fault and does not feel the fault. The control block diagram for the DVR is shown in Fig. 9. The DVR model used in this paper is based on model described in [15]. The design and modeling of DVR is out of scope of this paper and has not been discussed further.

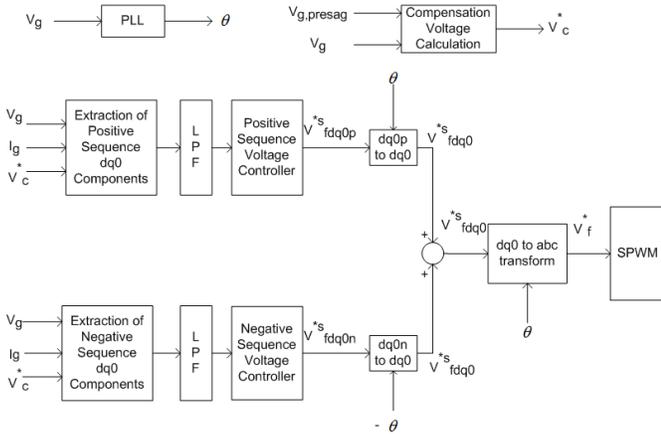


Fig. 9. Control block diagram for DVR

With the DVR in operation, any dip in voltage is compensated. Fig. 7 shows the response of hybrid micro-grid for double line to ground fault and three phase ground fault with DVR connected at PCC. At $t=5$ s a permanent fault at bus 1 happens, there is no dip in voltage of the micro-grid, as it is compensated by the DVR at PCC.

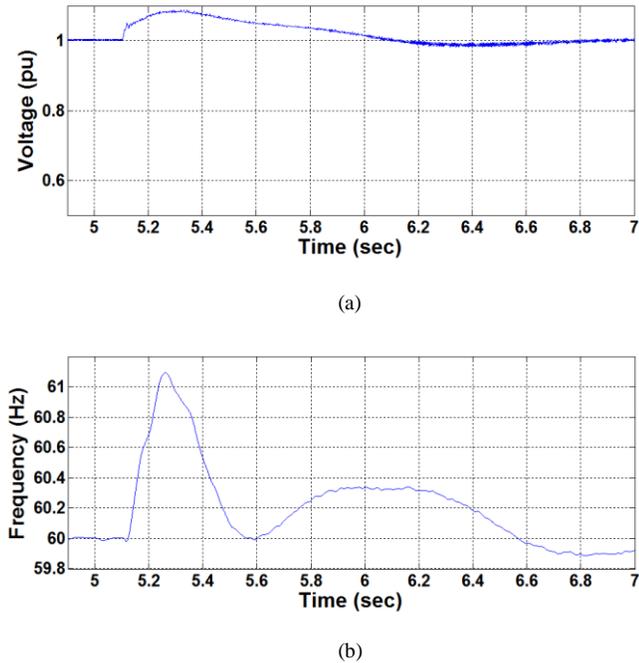


Fig. 10. . Hybrid micro-grid response to 3 phase ground fault with DVR at PCC; (a),(b) voltage and frequency response.

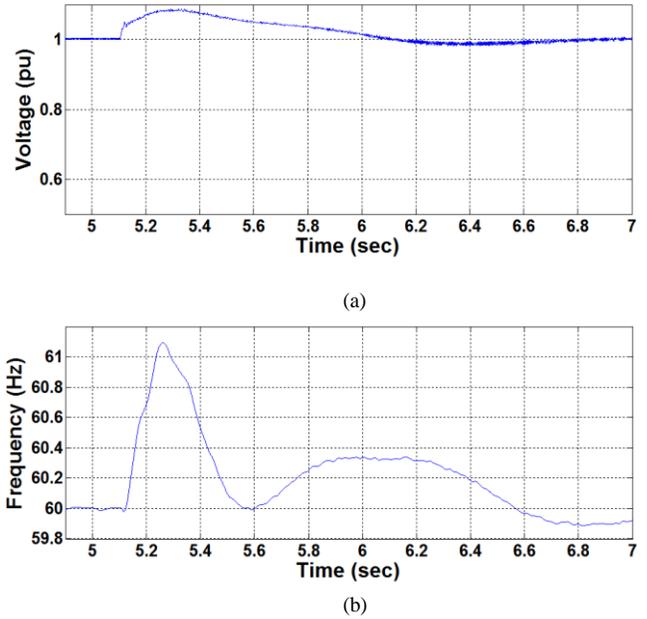


Fig. 11. . Hybrid micro-grid response to double line ground fault with DVR at PCC; (a),(b) voltage and frequency response.

From $t=5$ to $t=5.104$ s the micro-grid is isolated from the fault. At $t=5.104$, to clear the fault circuit breaker CB2 is operated. It can be observed that both, voltage and frequency are within the no trip zone. This leads to successful islanding without unwanted tripping of equipment. The response of hybrid micro-grid to double line to ground fault and three phase to ground fault is identical due to the fact that DVR maintains pre fault condition at the PCC i.e. the voltage and frequency of the hybrid micro-grid are similar to normal operating condition, and when the micro-grid is islanded it is similar to a preplanned islanding when a system is under normal operation. The overvoltage observed in both the cases is below 1.1 pu and lies in the no trip zone. The frequency reaches upto 61.1 Hz, which has a clearing time of 600s up to 10000 s with a slope as can be seen in Fig. 3(b).

VI. DISCUSSION AND CONCLUSION

It is necessary to re-clarify the main objective of this paper. This paper focuses to highlight the voltage and frequency excursions during fault triggered islanding. These excursions in voltage and frequency, if not within the limits of protection standards, may cause the DG's to be disconnected and unsuccessful islanding. The use of DVR as series compensation for successful islanding in case of double line to ground and three phase to ground fault is proposed. It is worthy to mention that the results and discussion are specific for this study and for the model under consideration. One of the major drawbacks of the proposed method is its cost of implementation. In case of critical loads on the system it might be the only viable solution. It can be concluded that for hybrid micro-grids with critical loads, solution to the problem can be expensive. On the other hand, a relaxation in the voltage and frequency standards during transient periods for micro-grid operation can eliminate the problem.

APPENDIX

REFERENCES

Utility Parameters		
Voltage (L-L)		115 kVA
MVA _{sc}		500 MVA
X/R		6
Synchronous Generator		
Nominal power		0.75 MVA
Nominal L-L voltage		480 V
Nominal frequency		60 Hz
No. of poles		4
Stator resistance (R _s)		0.003 pu
Leakage reactance (X _l)		0.18 pu
Direct axis reactance (X _d)		1.305 pu
Transient direct axis reactance (X _{d'})		0.296 pu
Sub-transient direct axis reactance (X _{d''})		10.3 mH
Quadrature axis reactance (X _q)		2.6Kg.m ²
Sub-transient quadrature axis reactance (X _{q'})		0.048 N.m.s
Inertia coefficient		0.5 s
Induction Motor Loads		
Three identical machines Squirrel cage rotor		
Nominal power		149.2 kV
Nominal L-L voltage		480 V
Nominal frequency		60 Hz
No. of poles		4
Stator resistance (R _s)		0.01982 Ω
Stator inductance (L _{ls})		0.207 mH
Rotor resistance (R _r)		0.0109 Ω
Rotor inductance (L _{lr})		0.207 mH
Mutual inductance (L _m)		10.3 mH
Moment of inertia		2.6Kg.m ²
Friction factor		0.048 N.m.s
Brushless Excitation System Parameters : IEEE Type I		
Voltage Regulator	Gain	400
	Time Constant	0.02 s
Exciter	Gain	1
	Time Constant	0.8 s
Damping Filter	Gain	0.03
	Time Constant	1 s
Output Limits	Upper	3.9 pu
	Lower	0 pu

- [1] Krishnamurthy, S.; Jahns, T.M.; Lasseter, R.H.; , "The operation of diesel gensets in a CERTS microgrid," *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE* , vol., no., pp.1-8, 20-24 July 2008
- [2] Katiraei, F.; Iravani, M.R.; Lehn, P.; , "Microgrid autonomous operation during and subsequent to islanding process," *Power Engineering Society General Meeting, 2004. IEEE* , vol., no., pp.2175 Vol.2, 10-10 June 2004
- [3] Katiraei, F.; Iravani, M.R.; , "Power Management Strategies for a Microgrid With Multiple Distributed Generation Units," *Power Systems, IEEE Transactions on* , vol.21, no.4, pp.1821-1831, Nov. 2006
- [4] Katiraei, F.; Iravani, M.R.; Lehn, P.W.; , "Small-signal dynamic model of a micro-grid including conventional and electronically interfaced distributed resources," *Generation, Transmission & Distribution, IET* , vol.1, no.3, pp.369-378, May 2007
- [5] Dong-Jing Lee; Li Wang; , "Small-Signal Stability Analysis of an Autonomous Hybrid Renewable Energy Power Generation/Energy Storage System Part I: Time-Domain Simulations," *Energy Conversion, IEEE Transactions on* , vol.23, no.1, pp.311-320, March 2008
- [6] Zhixin Miao; Domijan, A.; Lingling Fan; , "Investigation of Microgrids With Both Inverter Interfaced and Direct AC-Connected Distributed Energy Resources," *Power Delivery, IEEE Transactions on* , vol.26, no.3, pp.1634-1642, July 2011
- [7] Kasem Alaboudy, A.H.; Zeineldin, H.H.; Kirtley, J.L.; , "Microgrid Stability Characterization Subsequent to Fault-Triggered Islanding Incidents," *Power Delivery, IEEE Transactions on* , vol.27, no.2, pp.658-669, April
- [8] T.K. Abdel-Galil, A.E.B. Abu-Elanien, E.F. El-Saadany, A. Girgis, Y. A.-R. I. Mohamed, M.M.A. Salama and H.H. Zeineldin, "Protection Coordination Planning with Distributed Generation", CETC NO.2007-149/2007-09-14 Sep. 2007
- [9] Recommended Practice for Excitation System Models for Power System Stability Studies, IEEE Standard 421.5, Aug. 1992
- [10] I. C. Report "Excitation system models for power system stability studies", *IEEE Trans. Power App. Syst.*, vol. PAS-100, no. 2, pp.494-509 1981
- [11] Yeager, K.E.; Willis, J.R.; , "Modeling of emergency diesel generators in an 800 megawatt nuclear power plant," *Energy Conversion, IEEE Transactions on* , vol.8, no.3, pp.433-441, Sep 1993
- [12] I. J. Balaguer , L. Qin , Y. Shuitao , U. Supatti and P. F. Zheng "Control for grid-connected and intentional islanding operations of distributed power generation", *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp.147-157 2011
- [13] "IEEE Standard for Interconnecting Distributed Resources With Electric Power Systems," *IEEE Std 1547-2003* , vol., no., pp.0_1-16, 2003
- [14] Standard PRC-024-1 — Generator Frequency and Voltage Protective Relay Settings
- [15] A. O. Ibrahim, N. Thanh Hai, L. Dong-Choon, and K. Su-Chang, "A Fault Ride-Through Technique of DFIG Wind Turbine Systems Using Dynamic Voltage Restorers," *Energy Conversion, IEEE Transactions on*, vol. 26, pp. 871-882, 2011.

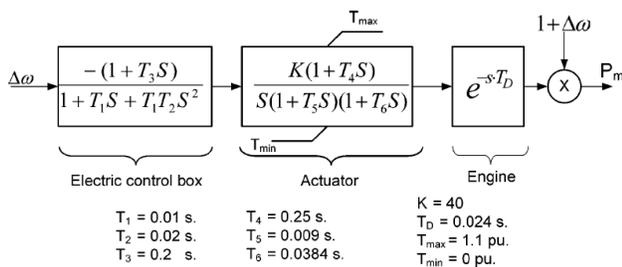


Fig. 8. Governor Parameters