ENHANCEMENT OF MICROGRID DYNAMIC VOLTAGE STABILTY USING MICROGRID VOLTAGE STABILIZER

Amarnath Tamersi
ECE Department
Tennessee Technological University
Cookeville, TN
atamersi42@students.tntech.edu

Ghadir Radman
ECE Department
Tennessee Technological University
Cookeville, TN
GRadman@tntech.edu

Mehriar Aghazadeh
ECE Department
Tennessee Technological University
Cookeville, TN
maghazade42@students.tntech.edu

***Abstract*—The microgrid concept has the potential to solve major problems arising from large penetration of distributed generation in distribution systems. A microgrid is not a robust system when compared to a power system. Therefore, proper control strategies should be implemented for a successful operation of a microgrid. This paper proposes the use of a coordinated control of reactive sources for the improvement of the dynamic voltage stability in a microgrid. The associated controller is termed as a Micro Grid Voltage Stabilizer (MGVS).**

The MGVS is a secondary level voltage controller which takes the weighted average of the voltage deficiencies at the load Buses and generates a control signal. This control signal is divided among the reactive power sources in the microgrid in proportion to their available capacities; thus each source will be required to generate certain amount of reactive power. The MGVS is implemented in a micro grid test system in MATLAB environment. A dynamic simulation of the test system is carried out for the cases of with and without the MGVS for various disturbances. Both grid-connected and islanded modes of operation are considered. Results show that, with the addition of MGVS, the dynamic voltage profile of the microgrid system, especially at the load Buses, improve drastically.

I. INTRODUCTION

The increase in power demand is stressing the transmission and generation system capabilities, leading to frequent power outages. In USA alone, these frequent power outages due to overloaded grid costs the economy $ 104 to $ 164 billion dollars per year. The central plants are at best 35% efficient due to generation and transmission losses. The greenhouse gas emissions have risen owing to the less efficient power system [1]. This led to increased research aiming to meet the growing energy demand without adding the transmission system capabilities. The use of distributed generation (wind turbines, PV arrays, etc) at the distribution system seems to be a viable solution. But, unplanned application of individual distributed generators, while solving some problems, can cause additional problems [1]. The microgrid concept has the potential to solve major problems arising from large penetration of distributed generation in distribution systems. Microgrids are almost 85% efficient as they have very little transmission losses and use the surplus heat to warm or cool buildings [1]. During power outage or disturbance, microgrids can island themselves and retain power availability, avoiding blackouts and lost productivity.

Sufficient amount of dynamic reactive power capabilities are needed to avoid a fast voltage collapse. In principle, a coordinated effort among the reactive sources could result in better effectiveness of these resources. However, in typical power systems, where the electrical distances between the reactive sources and where these reactive powers are needed are long, a coordinated effort may not be suitable due to the excessive voltage drop resulting from the transfer of reactive power within long distances. That is why, in practice, reactive power compensation is usually coming from local sources. In micro-grids, the electrical distances between the sources of the reactive power and the loads, which need the reactive power compensation, is not much; thus a coordinated compensation of reactive power sources for dynamic voltage stability should be desirable. Several blackouts have been associated with voltage stability problems in a power system [2] [3]. The presence of weak microgrids with insufficient amount of dynamic reactive power capabilities can also cause blackouts in microgrids and consequently the main power system.

In this paper, the modeling of a microgrid is presented and a novel coordinated control method for dynamic reactive power sources is proposed. The associated controller is termed as a Micro Grid Voltage Stabilizer (MGVS). MGVS is used to improve the dynamic voltage stability of the microgrid and to prevent voltage collapses. The input to the MGVS is a voltage deficiency of the microgrid in dynamic state and the output of the MGVS is divided between the Distributed Generators (DGs) depending on the nature of DG and its proximity to the voltage sensitive loads. A 21-Bus microgrid test system is used to verify the performance of the proposed controller. The dynamic modeling of the microgrid and the proposed

---

Center for Energy Systems Research, TTU, Cookeville, TN

978-1-61284-738-2/11/$26.00 ©2011 IEEE

controller has been done using MATLAB programming. Simulations are run for various dynamic events and the voltages of the load Buses are compared with and without the presence of MGVS. The effectiveness of MGVS is studied in both grid-connected and islanded modes of microgrid.

In the following section, the modeling of microgrid and its components is discussed. In section III the proposed MGVS is explained. Simulation results and conclusion are explained in the section IV and section V.

II. MODELING OF MICROGRID

In this paper, the modeling of the microgrid includes the modeling of the Diesel Engine Generators, system loads and the transmission system. Following, the dynamic model for Diesel Engine Generators including the dynamic and algebraic equations is presented and discussed. In addition, the network equations including the power flow equations at different buses are presented.

A. Modeling of Diesel Engine Generator

A diesel engine generator (DEG) is widely used in remote locations, household, commercial and industrial applications. The prime-mover is an internal combustion engine which is coupled to a synchronous generator with exciter and a governor. The generator and the prime-mover are mechanically coupled; the dynamics of the SG are not electrically decoupled from dynamics of the output of the generator [4]. The SG is modeled in d-q frame of reference. The sub-transient reactances, saturation, the turbine governor dynamics effecting T_{Mi} and the limit constraints on V_{Ri} are neglected. A linear damping term $T_{FWi} = D_i(\omega_i - \omega_s)$ is assumed. The differential equations for the machine with the IEEE-Type I exciter and a turbine governor are given below in (1)-(7) [5].

$$T'_{doi}\frac{dE'_{qi}}{dt} = -E'_{qi} - (X_{di} - X'_{di})I_{di} + E_{fdi} \tag{1}$$

$$T'_{qoi}\frac{dE'_{di}}{dt} = -E'_{di} + (X_{qi} - X'_{qi})I_{qi} \tag{2}$$

$$\frac{d\delta_i}{dt} = \omega_i - \omega_s \tag{3}$$

$$\begin{aligned}\frac{2H_i}{\omega_s}\frac{d\omega_i}{dt} = T_{Mi} - E'_{qi}I_{qi} - E'_{di}I_{di} \\ - (X_{qi} - X'_{qi})I_{di}I_{qi} \\ - D_i(\omega_i - \omega_s)\end{aligned} \tag{4}$$

$$T_{Ei}\frac{dE_{fdi}}{dt} = -(K_{Ei} + S_{Ei}(E_{fdi}))E_{fdi} + V_{Ri} \tag{5}$$

$$T_{Fi}\frac{dR_{fi}}{dt} = -R_{fi} + \frac{K_{Fi}}{T_{Fi}}E_{fdi} \tag{6}$$

$$\begin{aligned}T_{Ai}\frac{dV_{Ri}}{dt} = -V_{Ri} + K_{Ai}R_{fi} - \frac{K_{Ai}K_{Fi}}{T_{Fi}}E_{fdi} \\ + K_{Ai}(V_{Ref\,i} - |V_i|)\end{aligned} \tag{7}$$

The stator algebraic equations are derived from the dynamic equivalent circuit as shown in Figure 1[5] and are given below in (8)-(9).

$$E'_{di} - |V_i|\sin(\delta_i - \theta_i) - R_{si}I_{di} + X'_{qi}I_{qi} = 0 \tag{8}$$

$$E'_{qi} - |V_i|\cos(\delta_i - \theta_i) - R_{si}I_{qi} - X'_{di}I_{di} = 0 \tag{9}$$

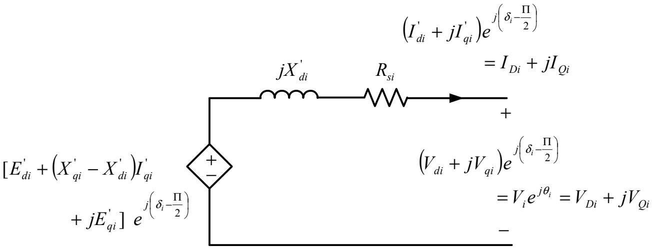

Figure 1. Dynamic equivalent circuit of a synchronous generator

B. Modeling of DEGs and loads Connected to the Microgrid

The loads and DEGS are connected to the distribution network with a known Y-matrix is shown in Figure 2. The overall microgrid system is modeled by writing the power flows equations for all Buses [5] as shown below.

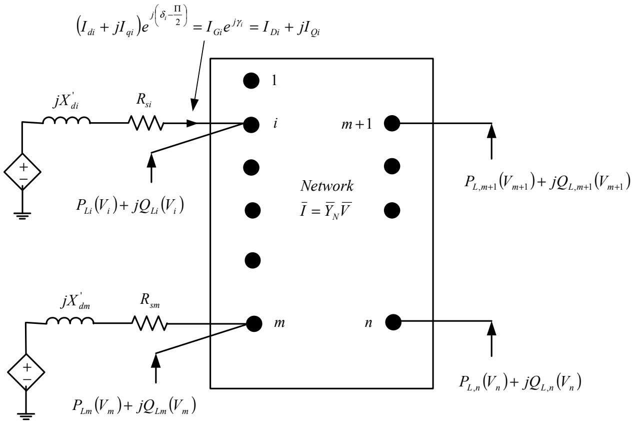

Figure 2. Dynamic equivalent circuit with loads and generators

The power flow equations for generator Buses are given below in (10)-(11)

$$\begin{aligned}I_{di}|V_i|\sin(\delta_i - \theta_i) + I_{qi}|V_i|\cos(\delta_i - \theta_i) + P_{Li} \\ - \sum_{k=1}^{n}|V_i|\,|V_K||Y_{ik}|\cos(\theta_i - \theta_k \\ - \alpha_{ik}) = 0\end{aligned} \tag{10}$$

$$\begin{aligned}I_{di}|V_i|\cos(\delta_i - \theta_i) - I_{qi}|V_i|\sin(\delta_i - \theta_i) + Q_{Li} \\ - \sum_{k=1}^{n}|V_i|\,|V_K||Y_{ik}|\sin(\theta_i - \theta_k \\ - \alpha_{ik}) = 0\end{aligned} \tag{11}$$

The power flow equations for load Buses are given below in (12)-(13).

$$P_{Li}(|V_i|) + \sum_{k=1}^{n} |V_i|\,|V_K||Y_{ik}| \cos(\theta_i - \theta_k - \alpha_{ik}) = 0 \tag{12}$$

$$Q_{Li}(|V_i|) + \sum_{k=1}^{n} |V_i|\,|V_K||Y_{ik}| \sin(\theta_i - \theta_k - \alpha_{ik}) = 0 \tag{13}$$

The above set of differential and algebraic equations from (1)-(13) gives the overall model of the microgrid.

III. MICROGRID VOLTAGE STABILIZER

The MGVS gives an input to the excitation systems or reactive power loops of DGs, which acts to kick in more reactive power into the microgrid to prevent any voltage collapse. Any small increase in reactive load can be met by the DGs, avoiding the use of expensive dynamic reactive sources, such as STATCOM, SVC or capacitor banks. The microgrid voltage stabilizer model and its simplified version are shown in Figure 3 and Figure 4 [6].

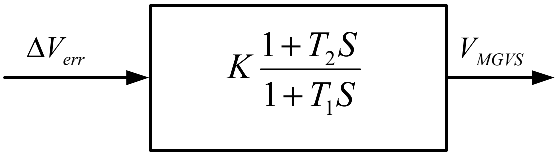

Figure 3. Microgrid voltage stabalizer

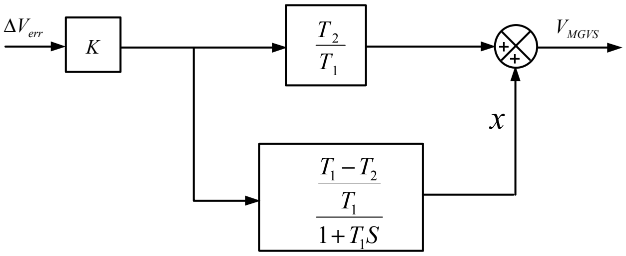

Figure 4. Simplified model of microgrid voltage stabalizer

The input to the MGVS is a measure of the voltage deficiency of the microgrid. The per unit voltage devation ($\Delta V_{err\,i}$) between the desired voltage ($V_{des\,i}$) and the dynamic voltage ($V_{dyn\,i}$) is calculated for all the load Buses (i = 1…l) as shown below in (14).

$$\Delta V_{err\,i} = \frac{V_{des\,i} - V_{dyn\,i}}{V_{des\,i}} \tag{14}$$

Weighting factors for all Buses, based on the importance of the Bus (i.e. induction motor loads are more sensitive to disturbances than the resistive loads) are defined. A weighted average of ΔV_{err} is taken, to get an aggregate voltage deficiency (ΔV_{err}) of the system as shown below in (15). The weighting factors for all the load Buses, i= 1 to l are $\alpha_1, \alpha_2, .. \alpha_l$.

$$\Delta V_{err} = \frac{\alpha_1 \Delta V_{err\,1} + \alpha_2 \Delta V_{err\,2} + \ldots\ldots..\alpha_l \Delta V_{err\,l}}{\alpha_1 + \alpha_2 + \ldots\ldots..\alpha_l} \tag{15}$$

ΔV_{err} is fed through a compensator block with constant gain K and time constant T1 and T2. The output of this MGVS controller is V_{MGVS} , as shown in Figure 3. This block is modified as shown in Figure 4. The differential algebraic equations representing the MGVS are derived from Figure 4 and are given below in (16)-(17).

$$\dot{x}(t) = -\frac{1}{T_1}x(t) + \frac{K(T_1 - T_2)}{T_1{}^2}\Delta V_{err} \tag{16}$$

$$V_{MGVS}(t) = x(t) + K\frac{T_2}{T_1}\Delta V_{err} \tag{17}$$

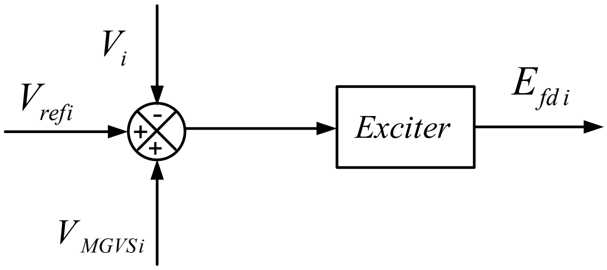

Figure 5. Excitation system of a generator

V_{MGVS} represents the total MGVS correcting signal, which is divided between the DGs depending on the generation reactive reserve, proximity to inductive loads, etc. The weighting factors for the generator Buses (1 to g) are $\beta_1, \beta_2, \ldots\ldots.. \beta_g$. $V_{MGVS\,i}$ is the input to the ith generator's excitation system as shown in Figure 5.

IV. SIMULATION RESULTS

A 21-Bus microgrid test system is used to verify the performance of the proposed controller [7]. The modeling and the simulation of the microgrid system and the MGVS is done in MATLAB environment. In this section, simulation results are presented for dynamic voltage analysis for various dynamic events under both, grid-connected and islanded microgrid modes of operation and also during the islanding process. The dynamic events include line outage, three-phase short circuit fault, and load switching. The results are compared with and without the presence of the proposed MGVS in each case. This will show the effectiveness of the MGVS to use reactive power compensation to improve the voltage profile of the microgrid in case of such different disturbances. The microgrid test case, as shown in Figure 6, have three distributed generators and six constant power loads. The microgrid is connected to the main grid, represented by large synchronous generator. The basic simulation includes, calculating the steady state power flow of the system and the initial value calculation of the state variables of the system. Then, the dynamic case is initialized with the initial values and run for the simulation time. The disturbances are included by

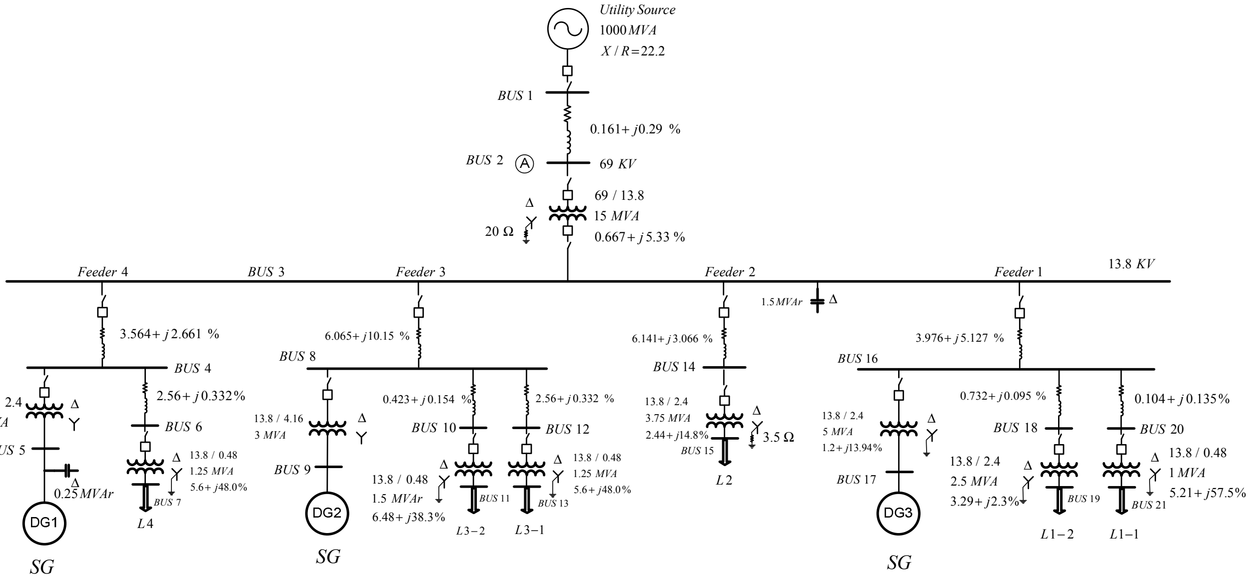

Figure 6. Microgrid test system

changing the corresponding values of the system during simulation period.

A. Voltage Stability Analysis of the Microgrid System in Grid-Connected Mode

In the grid connected mode, the microgrid test system is connected to the main grid. The load at Bus 15 is the largest load in the microgrid. So, the load Bus weighing factor is highest for Bus 15. The MGVS data table consisting of load Bus weighting factors, generator Bus weighing factors and MGVS control parameters are given as follows.

Table I. Load Bus Weighing Factors

α_3	α_7	α_{11}	α_{13}	α_{15}	α_{19}	α_{21}
0.1	0.095	0.119	0.0938	0.302	0.216	0.073

Table II. Weighing Factors for Generator Buses

β_1	β_2	β_3
0.3559	0.3261	0.3180

Table III. MGVS Control Parameters

Gain Constant(K)	T1	T2
10	1	0.1

A three phase short circuit fault is applied at Bus 15. The disturbance starts at 5% of the total time (i.e. 10 sec), and ends after 2 secs. The results show that the load bus voltages improve by more than 10 % in the presence of a MGVS as shown in Figure 7 at Bus 19.

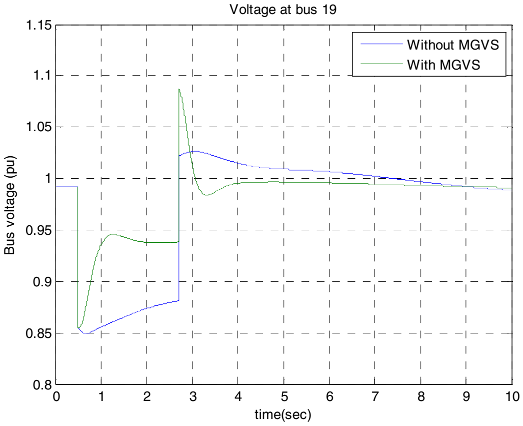

Figure 7. Three phase fault: Comparison of voltage a Bus 19 with and without MGVS in grid connected mode

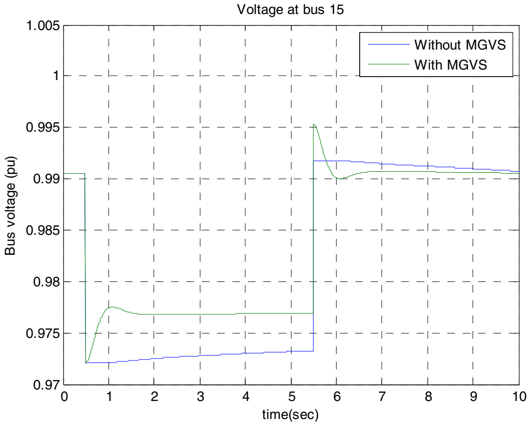

Figure 8. Load Switching: Comparison of voltage of Bus 15 with and without MGVS for 30% increase in load at Bus 15 in grid connected mode

In other case, the load at Bus 15 has been increased by 30%. The disturbance starts at 5% of the total time (i.e. 10 sec), and ends after 5 seconds. The results show that the voltage at Bus 15 improves in the presence of a MGVS as shown in Figure 8.

B. *Voltage Stability Analysis of the Microgrid System during Islanding Operation*

During the islanding operation, the line between Bus 2 and Bus 3 is removed, effectively disconnecting the microgrid from the main grid. Now the total load is supported by DGs at Buses 5, 9 and 17. The load parameters remain unchanged, but the power generation at the generators changes during the dynamic events. The disturbance starts at 5% of the total time (i.e. 10 sec), and ends after 3 seconds. The results show that the voltage at Bus 19 improves by more than 7 % in the presence of a MGVS as shown in Figure 9.

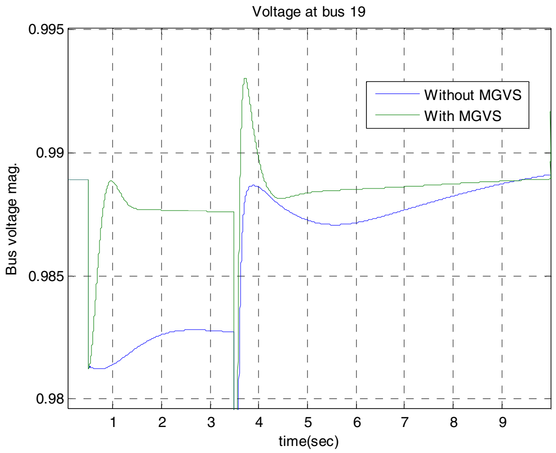

Figure 9. Islanding operation: Comparison of voltages a bus 15 with and without MGVS

C. *Voltage Stability Analysis of the Microgrid System in Islanded Mode*

In the islanded mode of operation, the main grid is removed and the total load is supported by DGs.

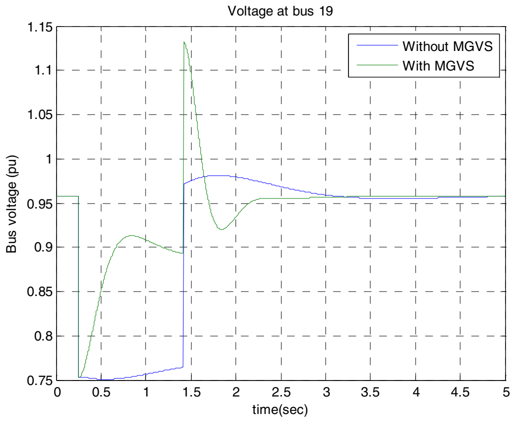

Figure 10. Three phase fault: Comparison of voltage a bus 19 with and without MGVS in islanded mode

A three phase short circuit fault is applied at Bus 15. The disturbance starts at 5% of the total time (i.e. 5 sec), and ends after 70 cycles. The results show that the load bus voltages improve by more than 15 % in the presence of a MGVS as shown in Figure 10 at Bus 19.

A line outage disturbance is applied at between Bus 3 and Bus 16. The disturbance starts at 5% of the total time (i.e. 6 sec), and ends after 2 seconds. The results show that the load bus voltages improve in the presence of a MGVS as shown in Figure 11 at Bus 21.

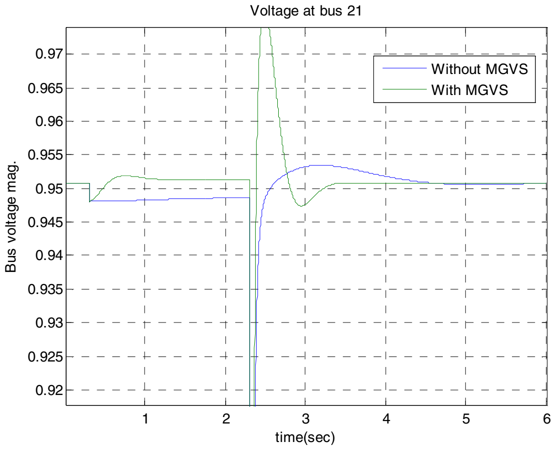

Figure 11. Line outage: Comparison of voltage a Bus 19 with and without MGVS in islanded mode

V. CONCLUSION

In this paper, the concept of the MGVS is introduced. Then, the modeling of a microgrid with DGs and MGVS for voltage stability analysis was studied. The differential algebraic equations (DAEs) related to the microgrid system were derived. Various disturbances and faults like three-phase short circuit fault, load switching, and line outage were simulated with and without MGVS in both grid connected and islanded modes of operation and also during the islanding operation. Simulation results show that the MGVS can significantly improve the voltage profile of the system for various disturbances. During three phase short circuit fault the MGVS improves the voltages at all the un-faulted load Buses. During load switching disturbance, MGVS reduces the reactive power dependence on the main grid by sharing most of the reactive load between the DGs. During line outage and islanding operation, MGVS is effective to coordinate the DGs reactive power generation and supply the lost generation from the grid.

REFERENCES

[1] M.U. Zahnd, "Control Strategies for Load-Following Unbalanced MicroGrids Islanded Operation," Faculté Sciences et Techniques de l'Ingénieur, Lausanne, MS Thesis 2007.

[2] A. Kurita and T. Sakurai, "The power system failure on July 23, 1987 in Tokyo," in *Proceedings of the 27th IEEE*

Conference on Decision and Control, Austin, 1988, pp. 2093 - 2097.

[3] US-Canada power system outage task force, "Final report on the august 14,2003 Blackout in the United States and Canada: Causes and Recommendations," Nautral resources Canada and U.S. department of energy, 18 Pages Report.

[4] L. Robertr, A. Akhil, M. Chris, S. John, D. Jeff, G. Ross, A. S. Sakis, Y. Robert and E. Joe, "Integration of Distributed Energy Resources: The CERTS MicroGrid Concept," U.S. Department of Energy, White Paper LBNL-50829, 2002.

[5] P.W. Sauer and M.A. Pai, *Power System Dynamics and Stability*, 2nd ed. Champaign, USA/Illinois: Stipes Publishing, 2006.

[6] P. L. Jeffrey, "Modeling of Dynamic Loads for Voltage Stability Studies," Tennessee Technological University, Cookeville, MS Thesis 2007.

[7] F. Katiraei, M.R. Iravani and P.W. Lehn, "Micro-grid autonomous operation during and subsequent to islanding process," *IEEE Transactions on Power Delivery*, vol. 20, no. 1, pp. 248-257, Jan 2005.