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Contents :

CONTROL OF A STAND-ALONE MICROGRID WITH ACTIVE MANAGEMENT SCHEME

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Abstract: *This paper presents an optimal load sharing strategy between several generation units in a stand-alone MicroGrid in order to have minimum power loss in the system and with consideration of normal buses voltage and rating of generation units. Simulation results in a typical distribution system show that the proposed method can meet the requirement of the system and DG units rating in stand-alone operations. In this way the system is managed in an optimal and reliable situation that guarantee continuity of power to loads in stand-alone mode of a MicroGrid.*

Key words**:** *MicroGrid, Distributed Generation (DG), Active Management, Control, State Estimation, Optimal, Load Sharing*

1.Introduction

Producing electrical energy from Distributed Generation (DG) is a solution for increased demand of energy, need of high quality and reliable power, environmental pollution, global warming, and rapid decrease in fossil fuel resources [1]-[3]. The concept of MicroGrid can be viewed as a group of DG, loads, and other part of a distribution system that can work in a group and be connected to utility or work in stand-alone [4]. This concept provides a new idea for defining a creative scheme for employing DG resources in a flexible manner with generation units and consumer closely integrated.

A MicroGrid can work in island mode or grid-interconnection to the utility main. Islanding occur when a DG or a group of DG units continue to energize a portion of the distribution system (a MicroGrid) that has been separated from the utility source [5]-[8]. There are two type of islanding, unintentional and intentional. In most cases, unintentional islanding is not desirable because it can cause power quality or safety problem [5], [6]. So in this case all DG units should disconnect from the system. However the implementation of DG sources can increase reliability of the power system in case of utility outage or when a MicroGrid needs to be independent and is called intentional islanding. To meet technical requirements in this case, the DG units in the MicroGrid must have protection, control and communication components enabling safe operation.

The main challenge in operating such DG system is the coordination of the numerous generators for sharing the real and reactive power output and control of system frequency and voltage. In [9]-[13], a concept has been developed and improved using reactive power/voltage and active power/frequency droops for the power control of the inverters. The droops are similar to those in utility grids. This method uses the grid quantities voltage and frequency for coordination of the components. The main advantage of this method is that it use local variable for controlling the generation units. However as frequency will deviate after any load change, a secondary control loop is needed for stable and accurate frequency control. In addition, load sharing between generation units in order to have optimal condition in the network and maintaining all constraints in the system can not be performed. If the optimal working desired, then there is need for communication between all controllable components.

Recently with the increased penetration of DG units in distribution system and in order to have flexible planning and operation of distribution system, new methods are required and intelligent system controller can be used for control and operation of a distribution system consisting of several DG units. This is for implementing maximum capacity of DG units and improve quality of power for the customers. So In this paper an active management system, a form of centralized control of distribution networks, for control and managing a MicroGrid in stand-alone mode will introduce and suitable control strategy for optimal and reliable power sharing between DG units will propose and investigate with simulation.

The paper is organized as follows. Section 2 introduces the active management system for distribution system. Section 3 describes and models all part of a MicroGrid management system. In section 4 the proposed control strategy in the system will explain. System under study will introduce in section 5. Simulation results and discussion presented in section 6. Lastly, section 7 draws the conclusions of the paper.

2. Active Management of Distribution System with MicroGrid

Active management is a form of centralized control for distribution networks and is proposed as a means of enhancing connectable capacity [14]. Taking a similar approach to that used in conventional power systems, a distribution management system controller would be used for wide area voltage and frequency control and also active and reactive power management [15]- [17].

As Figure 1 shows, three control levels are suggested for a distribution system consists of “n” MicroGrids:

- Distribution Management System (DMS) and Market Operator (MO) at the level of the Medium Voltage
- MicroGrid Management System (MGMS) at any MicroGrid system
- Local Controllers (LC), those exist in some controllable part of the distribution system

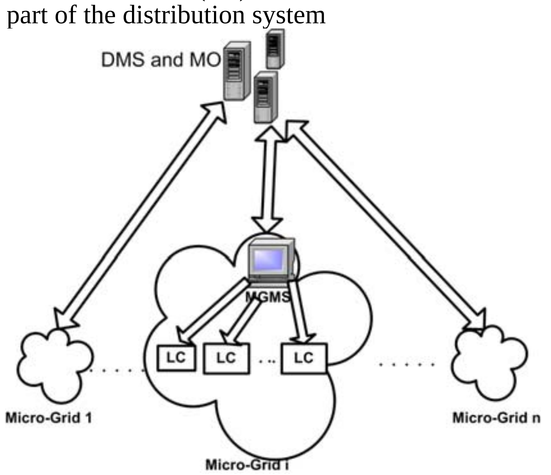

Figure 1: Active management of of a distribution system with several MicroGrids

2.1. DMS and MO

The DMS and MO are responsible for the technical and economical operation in a medium and low voltage area when there are several Microgrids in the system. The DMS control the system in optimize and economical state and with consideration of system acceptable parameters. In addition, MOs are responsible for the market operation of the area in the power system. Both of the systems are in contact with upper voltage controllers and central dispatching in the whole power system.

2.2 MicroGrid Management System (MGMS)

In order to utilize each MicroGrid in the system, it is necessary to control and manage individual MicroGrid in the system. This control functions and interfacing with DMS achieve by MicroGrid Management System (MGMS). The MGMS is responsible for optimal and reliable control of the MicroGrid with aim of controllable part of the system like loads, reactive compensation units, transformer tap position and also available DG units. The MGMS determine and send reference signal for all controllable equipments with the aim of communication links.

2.3 Local Controller (LC)

The lowest level of control consists of equipment control function in order to firstly avoid abnormal condition and fault for each equipment and secondly performing control commands which come from MGMS. The local controller can be active and reactive power control of DG units, tap position of the transformers, amount of reactive power compensation and also command for load shedding in controllable loads.

The main and critical equipment used in this structure is communication devices between all levels of controller. With recent advances in the filed of communication technology, using this structure is applicable and the connection can be reliable enough. Also there are several project all around the world that are investigating the practical and technical issues of applying the active management to distribution networks [17]-[20]. For example, the research cluster on “Integration of renewable energy sources and distributed generation into the European Electricity Grid” – (IRED) [18], with support of European Commission focus on integration of renewable energy and distributed generation with energy management systems in pilot installations. The energy management system has been developed by several companies and implemented in some european countries like germany and spain[18],[19]. It seems that in near future this system will take place in all distribution networks.

3. MGMS Structure

Active management of a MicroGrid now is important because of using several DG units in the system and significance of power supply reliability and quality [16]. Figure 2 shows a possible structure for MGMS.

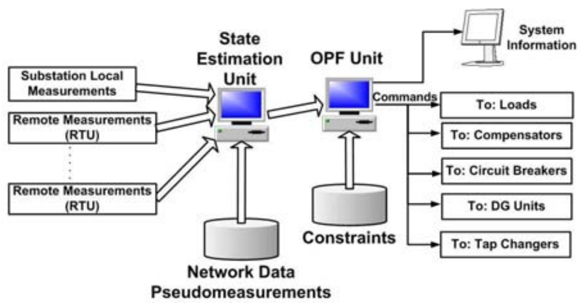

Figure 2: Structure of MGMS

As shown in the figure, MGMS estimates state of the network then evaluates it and takes the proper control actions. The objective of the MGMS is to manage and control the MicroGrid in the grid connected and islanded mode without breaking any limit in system equipments or parameters as well as optimal working of the system. The MGMS can change setting of different devices like transformer taps, capacitors, circuit breakers, loads, and DG units.

The ultimate goal of this paper is to propose a control strategy for stand-alone MicroGrid in order to cause its normal and optimal operation. So any equipment in the system should have a controller and the coordination between all parts and managing the system is performed with MGMS. Following subsections focuses on discussion and modeling of different part of MGMS in an island mode of operation.

3.1 State Estimation Unit

Today with the development of automation in distribution system, SCADA (Supervisory Control And Data Acquisition) has been installed on the distribution system which can measure the voltage magnitude, active power, reactive power and other values at a certain node or line. SCADA can transmit all this data back to the control center [21],[22]. If enough measurements can be obtained accurately, continuously, and reliably the operator can understand the exact status of the system and decide how to most effectively manage it. However, various constraints make it impossible to have a perfect picture of the system. First, because of the economical constraints, measurement instruments can not be installed every place where the measurements are needed, so the data are incomplete. Second, because of the nature of the measurement instruments and the communication problems in transmitting the data back to the control center, the measured data are subject to error or lost communication, so the data may be inaccurate, unreliable, and delayed. State estimation is one effective way to reduce these concerns. The state estimation technique is the process of producing the best possible estimates of the true value of the system states using available information. It tries to smooth out small random errors in meter readings, detect and identify gross measurement errors, fill in meter readings that have failed due to the communication failures, and estimate values in un-metered locations.

As there is very limited number of real time measurements in distribution systems with huge number of nodes, distribution system state estimation is more challenging. So pseudo measurements are necessary for a distribution system state estimator. The load modeling procedure can provide estimates of real-time customer load profiles, which can be treated as the pseudo measurements for state estimation [22]-[24].

The algorithm used in this paper is based on classical power system state estimator algorithms. The best estimate is found by using a weighted least squares formulation [23],[24].

$$Min \quad J(x) = \sum_{i=1}^{M} \frac{[z_i - h_i(x)]^2}{\sigma_i^{\ 2}} \tag{1}$$

where:

x: vector containing all the state variables (Buses voltages amplitude and angle)

M: Number of measurements, pseudo-measurements and virtual measurements

z_i: Measured value of measurement i

h_i: Expression of the measurements in function of state variables

σ_i: variance of the distribution of measurement i

The functions h are not linear, and it is necessary to apply Newton's iterative technique. More precisely, the gradient of J(x) is calculated and then forced to zero using Newton's method. This will lead to the following equation to be solved iteratively:

$$\begin{aligned} x_{k+1} &= x_k + G(x_k)H^T(x_k)W[z - h(x_k)] \\ G(x_k) &= [H^T(x_k)WH(x_k)]^{-1} \\ H(x) &= \frac{\partial h(x)}{\partial x} \end{aligned} \tag{2}$$

The State Estimation Unit uses real time measurements from the system, some pseudo measurement, and system configuration like switch status and then calculate the current state of the system. The state estimation unit output is all buses voltage, values of load demand and line currents.

3.2 Optimal Power Flow Unit

The aim of this unit is to determine each DG unit's values of generation in order to have optimal operation and also normal voltage in all buses, normal current in lines, considering inverters rating, considering DG unit rating and time delay for responding to changed parameter.

In this study the OPF unit in modeled as a problem of finding each DG unit active and reactive power in order to minimize active power loss of the system with constraints of normal voltage magnitude, DG units rating, and lines power rating. The problem formulation is as equation (3).

$$Minimize \quad P_{Losss} = f(|v|, \delta)$$

Subject to:

$$\begin{aligned} &Load\ Flow\ Equation\ (it\ mean \sum_{i=1}^{ngen} P_{G_i} = \sum_{i=1}^{nload} P_{D_i} + Losses) \\ &V_i^{\min} \le V_i \le V_i^{\max} \qquad for\ i = 1\ to\ no.\ of\ Buses \\ &P_{Gi}^{\min} \le P_{Gi} \le P_{Gi}^{\max} \qquad for\ i = 1\ to\ no.\ of\ DG\ units \\ &Q_{Gi}^{\min} \le Q_{Gi} \le Q_{Gi}^{\max} \qquad for\ i = 1\ to\ no.\ of\ DG\ units \\ &S_{Line-i} < S_{Max-i} \qquad for\ i = 1\ to\ no.\ of\ Lines \end{aligned} \tag{3}$$

In this equation the power loss in the system can be found as a function of voltages magnitude and angle and it is derived in appendix A1.

An efficient and accurate solution to this problem depends not only on the size of the problem in terms of the number of constraints and design variables but also on characteristics of the objective function and constraints. The Nonlinear Programming (NP) problem in which the objective function and constraints can be nonlinear functions of the design variables is applicable for the OPF problem in this study. Sequential Quadratic Programming (SQP) methods represent the state of the art in nonlinear programming methods. In this study for simulation the “fmincon” function in optimization toolbox of Matlab software which uses those methods is used for optimization [25].

3.3 Local Controller (LC) of Interface Inverters

There are many controllable equipments in a MicroGrid. This study focuses only on MicroGrid consisting of several inverters interfaced DG units and other controllable equipment like loads, transformers, and compensation units are not considered.

The active and reactive power which is supplied by an inverter interfaced DG unit can be controlled independently with parameter of the interfaced inverter. There are two ways for controlling an inverter in a distributed generation system [11]-[13] , [26]-[28]:

3.3.1 PQ Inverter Control

This type of control is adopted when the DG unit system is connected to an external grid or to an island of loads and more generators. In this situation, the variables controlled by the inverter are the active and reactive power injected into the grid, which have to follow the set-points P_{ref} and Q_{ref} respectively. These set points can be chosen by the customer or by a central controller.

The PQ control of an inverter can be performed using a current control technique in qd reference frame which the inverter current is controlled in amplitude and phase to meet the desired set-points of active and reactive power [28]. The inverter controller block diagram for supplying reference value of P_{ref} and Q_{ref} is as Figure 3.

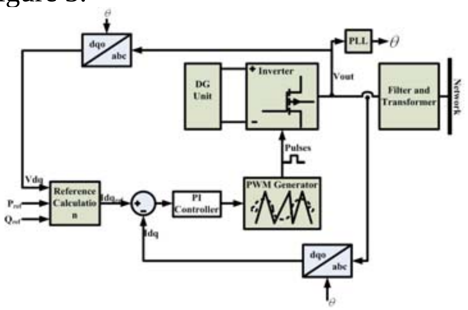

Figure 3: PQ control scheme of inverter with current control loop

For the current controller, two Proportional-Integral (PI) regulators have been chosen in order to meet the requirements of stability of the system and to make the steady state error be zero.

3.3.2 Vf Inverter Control

This controller has to act on the inverter whenever the system is in island mode of operation. In fact in this case, it must regulate the voltage value at a reference bus bar and the frequency of the whole grid. The regulators work in order to keep the measured voltages upon the set-points. Moreover, the frequency is imposed through the modulating signals of the inverter control by mean of an oscillator. A PI controller can regulate bus voltage in reference value with getting feedback of real bus voltage as it is shown in Figure 4.

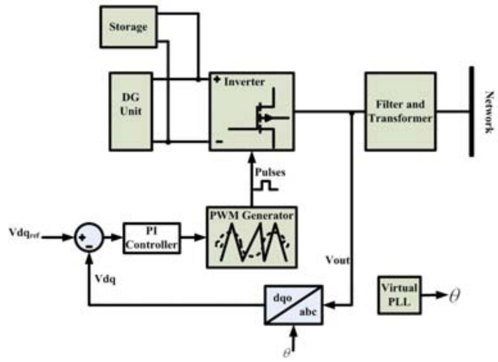

Figure 4: Vf control scheme of inverter

Designing of PI controller in both inverters control loop is done with the method of [28] and with consideration of rating of the inverters and parameter of the circuit.

4. Proposed Control Scheme for a Stand-Alone MicroGrid

In a stand-alone distribution network, there are two main problems. The first problem is the presence of some low response and inertia less generation units which necessitates putting some storage devices on dc link to realize fast load tracking. The second problem is the lack of frequency and voltage reference and so one or perhaps more than one of the DG units should play such a role and being a reference for voltage and frequency. Therefore the reference DG unit should be suitably sized to be able to perform such desired regulation on power and voltage. The suitably sized storage included on the DC bus of this unit insures fast response to any change in power demand (fast load tracking) and stable ac voltage. The other DG units may work in constant power control scheme (PQ mode) to have contribution in stable load balance. Such a reference unit called Master DG unit in this study.

The proposed strategy for controlling power sharing between DG units in this paper is as Figure 5.

At first it is assumed that all the units in the stand-alone system operate below their ratings in order to have selection of power change. When any change in load demand happened, if total power consumption is more than generation, the Master DG unit injects more power to the system to meet the requirement of the loads, whereas the other DG units in the system continue to supply the same power as scheduled. In constant intervals (e.g. 5 seconds), the measurements units measure the system parameters and send them to MGMS. The state estimation unit uses the measured and virtual measurement data and estimates the system state and calculate amount of generation and demand powers and also buses voltage and line current.

Next step will be dividing the power among other units with consideration of their rating and guide system to work in optimal and normal condition and as mentioned this functions will performed with OPF unit. The communication links will transmit new reference of power to the DG units. If the required power is more than the capability of each DG unit, its set point is adjusted to its rating value and then power share between other available DG units. Also load shedding scheme can be used in case of generation outage or voltage deviation from normal values.

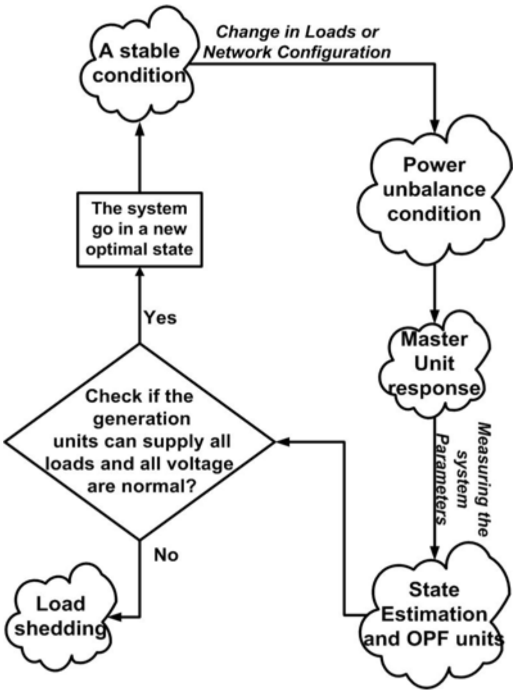

Figure 5: Proposed control for a stand-alone MicroGrid

Figure 6 shows a general overview of the MicroGrid consists of several DG units and the control strategy used for that purpose.

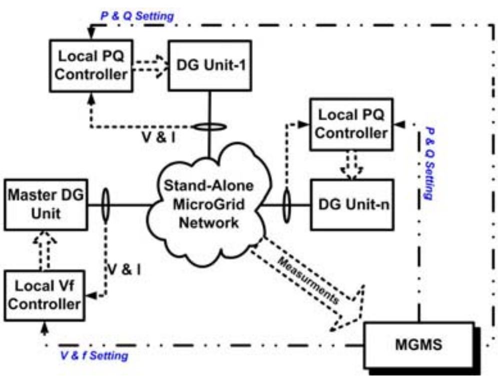

Figure 6: Overview of a MicroGrid and the control strategy

It is obvious that the Master DG unit should be able to produce extra load demand in the interval of load change and receiving new set point to other DG units and so the capacity of storage device should be determined with consideration of maximum load change and delay time of controller and units speed for changing their output. Also any deviation between generation level and demand will compensate by the Master unit.

5. Study System

The proposed control strategy has been experienced on a distribution test system which is shown in Figure 7. The system consists of four feeders that supply from utility via a 20/0.4 KV transformer and data of all component of system can be found in Appendix A2. The important part of system consists of 9 buses and 8 loads in 2 radial feeders.

When the utility is available two Distributed Generation units (DG 1 and DG 2) produce some part of energy needed for the system in order to improve quality and reliability of power and reduce demand charge. The system is considered to become islanded after the fault occurrence in the utility or according to the preplanned disconnection of the system from the utility via turning the main switch off.

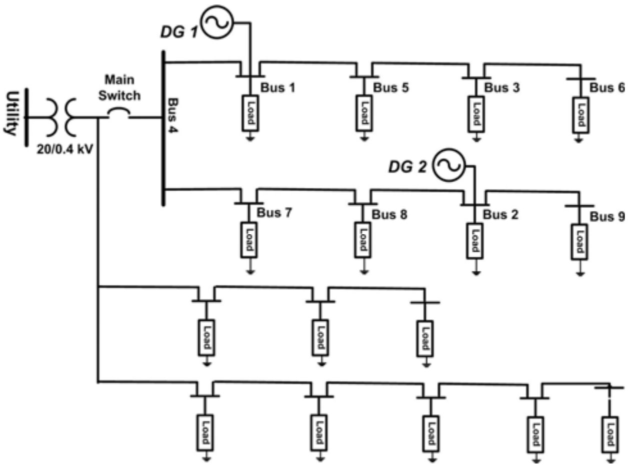

Figure 7: Single line diagram of the system under study

As described before, the master DG unit inverter work in Vf control mode and regulate voltage and frequency of the system and other unit work in PQ mode of operation with amount of active and reactive power that receive from MGMS.

For state estimation, three voltage meters at bus (1,2,6) and two active and reactive power meter in buses with DG unit (buses 1 and 2) is installed. Also pseudo measurement for load estimation of some buses employed for state estimation.

6. Simulation and discussion

The previously discussed concepts are now applied in the study system to explain more effectively the mechanism of MicroGrid control in stand-alone mode of operation. For simplicity, DG units dynamyc is not considered and constant DC voltage is assumed in all units. Also the DG 1 with suitable storage device is considered as Master DG Unit and act like a synchronous generator for producing voltage and frequency reference because it have storage device to overcome load change rapidly. The other unit synchronizes itself with the main unit via PLL and work at PQ mode of operation and its reference power can change with MGMS control commands. The loads are modeled as constant power with initial values of table in the appendix A2. The simulation process is done in four cases and will explain in the following subsections.

6.1 Initiate the system (0<t<1)

Initially it is considered that system work with reference value of load flow calculation. The power reference of DG 2 is set to 230 KW and 60 KVAR. It can be seen from Figure 8 and Figure 9 that in this case the controllers adjusted output power of DG 2 in desired value and as expected remaining needed power supplied by Master unit, DG 1.

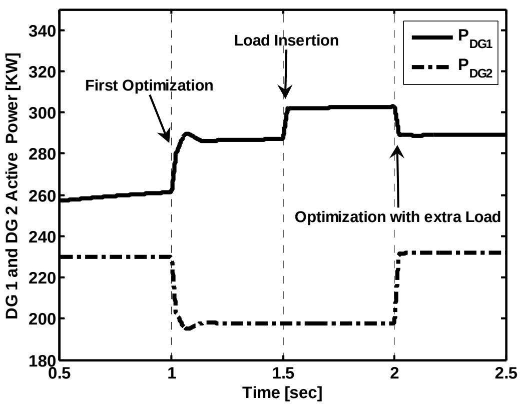

Figure 8: DG 1 and DG 2 active power

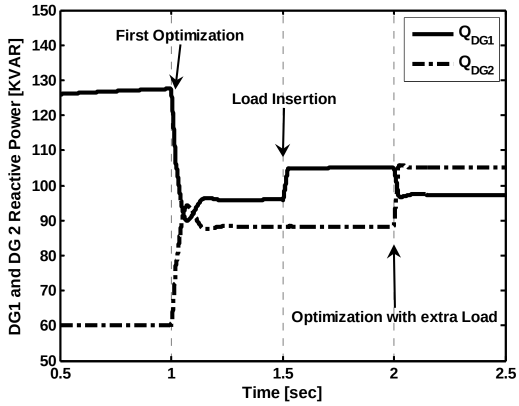

Figure 9: DG 1 and DG 2 reactive power

In this case as Figure 10 shows the voltages are in normal range and total power loss of system is 0.256 per unit (pu) and it is approximately 4% of total system load.

6.2 Optimization of the system (1<t<1.5)

At t=1 second the state estimation unit calculate the system parameters and amount of loads. The results for estimated and real values indicate that the State Estimation Unit has good estimation of the system and the total amount of load as well as voltage of buses after State Estimation process is known. Table 1 shows results of state estimation in this case for some buses voltage and injected powers (it means difference between generated power and demand power).

Table 1: Results of state estimation

Parameter	Measured	Estimated	Error(%)
V_1(pu)	1.0179	1.0198	-0.1877
V_2 (pu)	1.0378	1.0372	0.0561
V_6 (pu)	0.9561	0.9549	0.1325
P_1(kW)	178.915	178.91	0.0009
P_2(kW)	194.015	194.015	-0.0000
Q_1(kVar)	101.77	101.77	0.0007
Q_2(kVar)	48.045	48.045	-0.0000

So the optimal power flow can be done with output of state estimation.The OPF unit in this case calculates optimal value of DG2 as 197 KW and 88 KVAR and sends it to the unit. It is clear from Figure 8 and Figure 9 that local controller perform the command and adjust the powers in desired values. With this optimal value, the system loss will change to 0.2120 pu and it is clear that it is reduced about 25% and also all voltage will remain in normal value as Figure 10 shows.

This new calculated and transmitted reference value for DG units, guide the whole system to work in minimum power loss as well as normal voltage (between 0.95 to 1.05 pu) and normal rating of generation units.

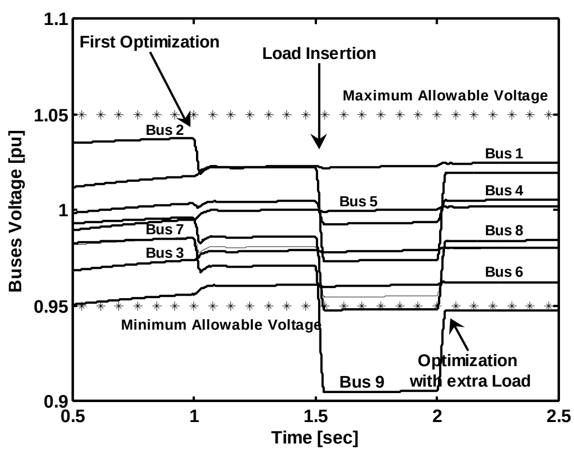

Figure 10: Buses voltage in the system

6.3 Insertion a Load (1.5<t<2)

In third simulation case a perturbed condition happens, for example insertion of a load. At t=1.5 seconds a 40 KW and 20 KVAR load inserted in bus 9 and it can be seen from Figure 8 and Figure 9 that the increased power supplied by master unit DG 1 and the other unit work at predefined reference value.

In this case as Figure 10 shows, some buses voltages exceed from minimum allowable voltage (0.95) and also power loss of system increased to 0.3104 pu.

6.4 Optimization of System with Extra Load (2<t<2.5)

Again in t= 2 seconds the MGMS measure system parameters and estimate the state of the system and determine amount of demand power.

The OPF unit uses information gained from state estimation unit and define new reference power for DG units in order to reduce power loss and also guide system to have normal voltage in all buses. The result of program for reference power of DG 2 in this case is 231 kW and 105 kVAR. After transmitting this signal to DG2, the system will produce this power and as Figure 10 shows the buses voltage goes to normal value and also the power losses will be 0.28 pu and it is obvious that reduced about 10%.

As it is clear from the simulation results, the proposed method for controlling DG units is effective and can reply to the network needs during islanding from main grid and the scheme can guarantee continuity of power to loads. Any change in the system can be observed by MGMS with the aim of real measurement, historical data of system, and state estimation unit. Based on estimated values, appropriate command will produce by OPF unit and sending the command to local controller will guide DG units in optimal situation and the system will work in normal and optimal case. It is worth noted that adding load shedding and protection strategy to proposed load sharing method will cause perfect performance of MicroGrid in island mode of operation.

7. Conclusion

This paper proposed a control and management strategy for optimal and reliable operation of a MicroGrid in stand-alone mode. The scheme uses communication facility to send data of system to central controller and use optimal function to determine suitable generation value of each DG units.

When the utility isn't available in a part of distribution network with some DG sources, the proposed scheme can control the system in such case that the available DG units supply the loads in the system and ensure continuity of power to the loads.

References

[1] W. El-Khattam, M.M.A. Salama, "Distributed generation technologies, definitions and benefits", Electric Power Systems Research, Vol. 71, pp.119–128, 2004

[2] G. Pepermans, J. Driesen, D. Haeseldonckx, R. Belmans, W. D'haeseleer, "Distributed generation: definition, benefits and issues", Energy Policy, Vol. 33, pp. 787–798, 2005

[3] A.A. Ghadimi, A. M. Daryani, H. Rastegar, "Detailed Modeling and analysis of a full bridge PWM DC-DC converter", Proceedings of the Australasian Universities Power Engineering Conference (AUPEC06), December 2006, Melbourne, Australia

[4] R. H. Lasseter and P. Piagi, "Microgrid: A conceptual solution", in Proc. Power Electronics Specialists Conference, Aachen, Germany, June 2004, vol. 6, pages: 4285–4290

[5] H. Zeineldin, E. F. El-Saadany, and M. M. Salama, "Impact of DG interface control on islanding detection", IEEE PES General Meeting, 12-16 June 2005

[6] P.L. Villeneuve, "Concerns generated by islanding", IEEE Power & Energy Magazine, Vol. 2, No. 3, pp. 49-53, May/June 2004

[7] M. N. Marwali and A. Keyhani, "Control of Distributed Generation Systems, Part I: Voltages and Currents Control," IEEE Transaction on Power Electronics, Vol. 19, No. 6, pp. 1541-1550, 2004

[8] M. N. Marwali, J. W. Jung, and A. Keyhani, "Control of Distributed Generation Systems, Part II: Load Sharing Control" IEEE Transaction on Power Electronics, VOL. 19, No. 6, pp. 1551-1561, NOVEMBER 2004

[9] Charles K. Sao, and Peter W. Lehn,"Autonomous Load Sharing of Voltage Source Converters", IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 20, NO. 2, pp. 1009-1016, 2005

[10] Yunwei Li, D. Mahinda Vilathgamuwa, and Poh Chiang Loh, "Design, Analysis, and Real-Time Testing of a Controller for Multibus Microgrid System", IEEE TRANSACTIONS ON POWER ELECTRONICS, VOL. 19, NO. 5, pp. 1195-1204, SEPTEMBER 2004

[11] J. A. Peças Lopes, C. L. Moreira, and A. G. Madureira "Defining Control Strategies for MicroGrids Islanded Operation", IEEE TRANSACTIONS ON POWER SYSTEMS, Vol. 21, No. 2, pp. 916-924, May 2006

[12] F. Katiraei, and M. R. Iravani, "Power Management Strategies for a Microgrid With Multiple Distributed Generation Units", IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 21, NO. 4, pp. 1821-1831, NOVEMBER 2006

[13] A. Engler, "Control of parallel operating battery inverters", Photovoltaic Hybrid Power Systems Conference 2000, Aix-en-Provence

[14] S. N. Liew and G. Strbac, "Maximizing penetration of wind generation in existing distribution networks," Proc. Inst. Elect. Eng., Gen., Transm., Distrib., Vol. 149, No. 3, pp. 256–262, May 2002.

[15] T. Bopp, A. Shafiu, I. Cobelo, I. Chilvers, N. Jenkins, G. Strbac, H. Li, and P. Crossley, "Commercial and technical integration of distributed generation into distribution networks," in Proc. CIRED, 17th Int. Conf. Electricity Distribution, 2003

[16] A. Shafiu, T. Bopp, I. Chilvers, and G. Strbac, "Active management and protection of distribution networks with distributed generation," in Proc. IEEE Power Eng. Soc. General Meeting, Vol. 1, pp. 1098–1103, 2004

[17] Aris L. Dimeas, Nikos D. Hatziargyriou, " Operation of a Multiagent System for Microgrid Control", IEEE TRANSACTIONS ON POWER SYSTEMS, VOL. 20, NO. 3, pp. 1447-1455, AUGUST 2005

[18] B. Buchholz, U. Schluecking, "Energy Management in Distribution Grids: European Cases", IEEE Power Engineering Society General Meeting, June 2006

[19] P. Bresesti, A. Cerretti, "SDNO: Smart Distribution Network Operation Project", IEEE Power Engineering Society General Meeting, June 2007
[20] Okuyama, K.; Kato, T.; Suzuoki, Y.; Funabashi, T.; Wu, K.; Yokomizu, Y.; Okamoto, T, "Improvement of reliability of power distribution system by information exchange between distributed generators- sharing of all DG's information", IEEE Power Engineering Society Summer Meeting, 2001.
[21] A. Shafiu, N. Jenkins and G. Strbac, "Measurement location for state estimation of distribution networks with generation", IEE Proc.-Gener. Transm. Distrib., Vol. 152, No. 2, March 2005
[22] Haibin Wang, and Noel. N. Schulz, "A Load Modeling Algorithm for Distribution System State Estimation", IEEE/PES Transmission and Distribution Conference and Exposition, 2001
[23] K. Li, "State Estimation for Power Distribution System and Measurement Impacts", IEEE Trans. on Power Systems, Vol. 11, No. 2, pp 911-916, May 1996
[24] Inigo Cobelo1, Ahmed Shafiu, Nick Jenkins and Goran Strbac, "State estimation of networks with distributed generation", EUROPEAN TRANSACTIONS ON ELECTRICAL POWER, Vol. 17, pp. 21–36, 2007
[25] "Matlab 2006a user guide", Mathworks, 2006
[26] J. W. Jung, and A. Keyhani, "Modeling and Control of Fuel Cell Based Distributed Generation Systems in a standalone Ac Power System", IAEEE Journal, Vol. 1, No. 1, 2005
[27] Kourosh Sedghisigarchi, and Ali Feliachi, "Impact of Fuel Cells on Load-Frequency Control in Power Distribution Systems", IEEE TRANSACTIONS ON ENERGY CONVERSION, Vol. 21, No. 1, pp. 250-256, MARCH 2006
[28] A. Bertani , C. Bossi, F. Fornari,S. Massucco, S. Spelta, F. Tivegna, "A Microturbine Generation System for Grid Connected and Islanding Operation" IEEE PES Power Systems Conference and Exposition, 2004.

Appendix

A1. Distribution system Loss

In a system with n bus the power loss can be defined as:

$$P_L + jQ_L = \sum_{i=1}^{n} S_i = \sum_{i=1}^{n} V_i I_i^* = [V_1 \quad V_2 \quad \ldots V_n] \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_n \end{bmatrix}^* = V^T I^* \qquad (4)$$

Where V and I are vector of buses voltage and currents respectively and they have simple relation with Zbus matrix of system and substituting in previous equation yield:

$$\begin{aligned} & V = Z_{Bus} I \\ & Therefore: P_L + jQ_L = (Z_{Bus} I)^T I^* = I^T Z_{Bus} I^* \end{aligned} \qquad (5)$$

Let's write buses current and ZBus matrix of the system as real and imaginary parts.

$$\begin{aligned} & Z_{Bus} = R + jX = \begin{bmatrix} r_{11} \cdots r_{1n} \\ \vdots \\ r_{n1} \cdots r_{nn} \end{bmatrix} + j \begin{bmatrix} x_{11} \cdots x_{1n} \\ \vdots \\ x_{n1} \cdots x_{nn} \end{bmatrix} \\ & I = I_a + jI_r = \begin{bmatrix} Ia_1 \\ \vdots \\ Ia_n \end{bmatrix} + j \begin{bmatrix} Ir_1 \\ \vdots \\ Ir_n \end{bmatrix} \end{aligned} \qquad (6)$$

And then substitute the real and reactive part of currents and ZBus matrix into equation (5) yield:

$$\begin{aligned} & P_L + jQ_L = (I_a + jI_r)^T (R + jX)(I_a - jI_r) \\ & so: P_L = I_a^T R I_a + I_r^T R I_r = \sum_{j=1}^{n} \sum_{k=1}^{n} r_{jk} (Ia_j Ia_k + Ir_j Ir_k) \end{aligned} \qquad (7)$$

In order to have power loss formula as a function of buses injected power, we can use relation between power and currents as follow:

$$\begin{aligned} & P_i + jQ_i = V_i I_i^* = \\ & |V_i| (\cos\delta_i + j\sin\delta_i)(Ia_i - jIr_i) \end{aligned} \qquad (8)$$

δ_i is angle of i'th bus voltage in according to reference bus. The real and imaginary part of current can be derived from this equation.

$$\begin{aligned} & Ia_i = \frac{1}{|V_i|} (P_i \cos\delta_i + Q_i \sin\delta_i) \\ & Ir_i = \frac{1}{|V_i|} (P_i \sin\delta_i - Q_i \cos\delta_i) \end{aligned} \qquad (9)$$

Therefore by substituting this equation in equation 5 the power loss can obtain from equation (10):

$$\begin{aligned} & P_L = \sum_{j=1}^{n} \sum_{k=1}^{n} [\alpha_{jk} (P_j P_k + Q_j Q_k) + \beta_{jk} (Q_j P_k - P_j Q_k) \\ & \alpha_{jk} = \frac{r_{jk}}{|V_j||V_k|} \cos(\delta_j - \delta_k) \\ & \beta_{jk} = \frac{r_{jk}}{|V_j||V_k|} \sin(\delta_j - \delta_k) \end{aligned} \qquad (10)$$

A2. Study system Parameter

All lines are similar with the following data:
Cable Resistance: R= 0.164 ohms/km
Cable Inductance: L= 0.26 mH/km

Distribution Line data

From Bus	To Bus	Length (m)
4	1	500
1	5	100
5	3	200
3	6	250
4	7	650
7	8	500
8	2	400
2	9	400

Buses Load data

Bus No.	P (kW)	Q (kVar)
1	80	25
2	36	12
3	25	12
5	90	33
6	60	12
7	36	12
8	56	32
9	96	42

DG Units Data

DG	Nominal Power (kVA)	Control Mode	P-Gain in control loop	I-Gain in control loop
DG 1	390	Vf	1.1	3.23
DG 2	280	P Q	6	0.12

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