Optimal Control and Management of Distributed Generation Units in an Islanded MicroGrid

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ABSTRACT

This paper is concerned with small signal model and the generation control in small islanded MicroGrids consisting of inverter interfaced distributed generation (DG) units. First, the active management strategy of the distribution system is introduced and then its components and corresponding control schemes for active and reactive power control are discussed and implemented. The paper also 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. Simulation results are shown for a typical MicroGrid consists of two DG units. It has been shown that the proposed method can meet the requirement of the system and can operate the system optimally and reliably such that it guarantees continuity of power to loads in stand-alone mode of MicroGrid.

1. INTRODUCTION

Producing electrical energy using distributed generation (DG) units is a solution to meet the increased demand of energy, energy reliability, and reduce environmental pollution. DG units can act as alternative energy sources and can substitute rapidly decreasing fossil fuel resources which contributes to the effect of global warming [1]-[3]. A MicroGrid can be viewed as a group of DG sources connected to the loads. The DG sources can feed to the loads alone and/or they can feed to the utility grid [4]. This concept provides a new idea for defining a creative scheme for employing closely integrated DG units in a flexible manner. As mentioned, 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]-[9]. 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 to have 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 the control of system frequency and voltage. Several methods like droop method, master-slave method have been presented in the literature for controlling an islanded network with multiple DG units [10]-[14]. In order to have flexible planning and operation of distribution system, new methods are required and an intelligent system controller must be used for control and operation of the distribution system consisting of several DG units.

In this paper, an active management system, a form of centralized control of distribution networks, for control and management of a MicroGrid in stand-alone mode is introduced. A control strategy for optimal and reliable power sharing between DG units in the network is proposed and simulation results are shown. The paper is organized as follows: In section 2, the active management system for distribution system in introduced. In section 3, a method for modeling of a distribution system is described, in section 4; model of entire MicroGrid management system is described. In section 5, the control strategy is developed. Simulation results are presented in section 6 and finally, conclusion of this research work is described in section 7.

2. ACTIVE MANAGEMENT OF DISTRIBUTION SYSTEM WITH MICROGRID

Active management is a form of centralized control for distribution networks, which enhances the connecting capacity of DG units [15]. Taking a similar approach to that used in conventional power systems, a distribution management system controller is used for wide area voltage and frequency control and also for active and reactive power management [16]-[17]. Three control levels are suggested for a distribution system consists of ‘n’ MicroGrids [18]:

- Distribution Management System (DMS) and Market Operator (MO) at the level of the Medium Voltage. These systems are responsible for the technical and economical operation of several MicroGrids in the system.
- MicroGrid Management System (MGMS) at any MicroGrid system. The MGMS is responsible for the optimal and reliable control of the MicroGrid. The MGMS determine and send the reference signal to all controllable equipments using available communication links.
- Local Controllers (LC), those exist in some controllable part of the distribution system. 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 critical equipments used in this structure are the communication devices between all levels of controller. With recent advances in the field of communication technology, communication between different parts can be done reliably and efficiently.

3. Modeling of a Distribution Network

As stated, the interest of integrating DG units into the present distribution systems is well recognized. In this section, eigenvalues of the distribution network are determined. The distribution network is modeled in dq0 reference frame, so the developed models and programs can be directly incorporated to other system component models. To build the model of the electrical network under dq0 frame, park transformation is used [19]. The reference frame of park transformation is selected such that q-axis leads the d-axis by 90 degrees and coincides with the system reference phasor.

A. Modeling Lines and Cables in dq0 Reference Frame

In distribution systems having short lengths, the lines/cables can be modeled with serial impedance and two parallel capacitors (PI configuration). Figure 1 shows these basic parts of the lines/cables separately.

\[ V_{abc} \rightarrow R \rightarrow L \rightarrow I_{abc} \rightarrow C \rightarrow V_{abc} \]

Figure 1: Single Line Diagram of Basic Components of Lines/Cables

Model of serial impedance in dq0 frame can be described by equation (1) [20].

\[
\begin{align*}
L \frac{d}{dt} i_d &= -L \omega i_q + R i_d = v_{id} - v_{2d} \\
L \frac{d}{dt} i_q &= L \omega i_d + R i_q = v_{id} - v_{2q} \\
L \frac{d}{dt} i_0 &= R i_0 = v_{10} - v_{20}
\end{align*}
\]

\[ L = L_s - L_m, L_0 = L_s + 2L_m. \] Also R = R_s – R_m, R_0 = R_s + 2R_m, where L_s is the self-inductance, L_m the mutual inductance, R_s is the resistance, and R_m is the mutual resistance.

In addition, model of a parallel capacitor in dq0 frame can be described by equation (2) [20]:

\[
\begin{align*}
C \frac{d}{dt} v_d &= -C \omega i_q = i_{1d} - i_{2d} \\
C \frac{d}{dt} v_q &= C \omega i_d = i_{1q} - i_{2q} \\
C_0 \frac{d}{dt} v_0 &= i_{10} - i_{20}
\end{align*}
\]

Where C = C_s–C_m, C_0 = C_s + 2C_m, C_s is the capacitance and C_m is the mutual capacitance.

B. Establishing the State Matrix of Distribution Networks

The state matrix of a distribution network can be determined as follows:

Step 1: It is assumed that between two nodes there exists only an impedance. The capacitance of the lines/cables is treated as an independent shunt component.

Step 2: The state variables of the network are: a) currents injected into nodes that connect at least two lines/cables as well as other energy sources/sinks such as DG, shunt capacitors, loads and b) Voltages of the nodes that have shunt capacitors.

Step 3: Forming a general outline for writing differential equations of the state variables.

It can be seen from equation (1) that for a serial impedance with current as state variable, the state equation has the following form:

\[
I_t = A_i I_t + B_i V_{aux} + C_i V_{aux}
\]

where:

\[
A_i = \begin{bmatrix}
-\frac{R}{L} & \frac{\omega}{L} \\
-\frac{\omega}{L} & -\frac{R}{L}
\end{bmatrix},
B_i = \begin{bmatrix}
1 & 0 & 1 \\
0 & 0 & 1
\end{bmatrix},
C_i = \begin{bmatrix}
-\frac{1}{L} & 0 \\
0 & -\frac{1}{L}
\end{bmatrix}
\]

(3)

\[
I_t = [i_d \ i_q] T,\ V_{aux} = [v_{aux-d} v_{aux-q}] T, V_{end} = [v_{end-d} v_{end-q}] T.
\]

In addition, for nodes with parallel capacitance, the state matrix with node voltage as state variable can be deduced from equation (2) as:

\[
\dot{V}_t = G V_t + M I_{aux} + N J_{end}
\]

where:

\[
G = \begin{bmatrix}
0 & \omega \\
-\omega & 0
\end{bmatrix}, M = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0
\end{bmatrix}, N = \begin{bmatrix}
-\frac{1}{C} & 0 \\
0 & -\frac{1}{C}
\end{bmatrix}
\]

(4)

\[
V_t = [v_d \ v_q] T, I_{aux} = [i_{aux-d} i_{aux-q}] T, J_{end} = [j_{end-d} j_{end-q}] T.
\]

For a network with ‘n’ independent branch currents and ‘m’ independent node voltages as state variables, the equations can be written in general form as:

\[
\dot{I}_{2n+1} = A_{2n+1} I_{2n+1} + B_{2n+1} V_{2n+1} + C_{2n+1} V_{2n+1}
\]

\[
\dot{V}_{2n+1} = G_{2n+1} V_{2n+1} + M_{2n+1} I_{2n+1} + N_{2n+1} J_{2n+1}
\]

(5)

Where, I and V are the set of the state variables consisting of the dq components of the selected branch currents and node voltages.

Step 4: Elimination of extra variable

The current injecting to a node that connects several lines is function of other currents and can be eliminated from state equations. For example, ‘node 2’ in Figure 2 connects lines and it does not have any load or generation unit.
eliminated with the following load profiles, which can be minimized active

\[ V_2 = D_4 V_1 + E_2 (I_3 + I_4) + F_2 (I_3 + I_4) \]

where:

\[ D_4 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, E = -L(i) \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, F = \begin{bmatrix} -R(i) & L(i) \omega \\ -L(i) \omega & -R(i) \end{bmatrix} \]

Substituting \( V_2 \) from this equation into equation of the nodes 3 and 4 yields a new equation for those nodes with same state variables.

Step 5: If necessary, interfacing the electrical network model with other system components can give the whole system state equations.

C. Results of eigenvalue calculation for distribution networks

With the proposed strategy, the study of authors in several distribution networks in IRAN shows that the eigenvalues of the distribution network have relatively large real part and hence, it is sensible to say that distribution network has short dynamic time constants. Hence, it is proper to adopt the steady state or quasi steady state assumptions to model the distribution network and the admittance matrix representation of the distribution network can be used for modeling of the system.

4. MGMS STRUCTURE

Active management of a MicroGrid is important because of using several DG units in the system and significance of power supply reliability [17]. Figure 4 shows a structure for MGMS.

As shown in the Figure 4, MGMS estimates the states of the network and takes the proper control actions. The objective of the MGMS is to manage and optimally control the MicroGrid in grid connected and islanded mode configurations without breaking any limit in system equipments or system parameters. The MGMS will act on different devices like transformer tap, capacitor banks, circuit breakers, loads and DG units [15].

Figure 3: Structure of MGMS

The ultimate goal of this paper is to propose a control strategy for stand-alone MicroGrid in order to cause its normal and reliable 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 focus on discussion and modeling of different parts of MGMS in an island mode of operation.

A. State Estimation Unit

Today, with the development of automation in distribution system, SCADA (Supervisory Control And Data Acquisition) can be 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 manage it effectively. However, various constraints like economical and technical constraints make it impossible to have a perfect picture of the system. State estimation is one effective way to reduce these concerns.

State estimation technique is the process of producing the best possible estimates of the true value of the system states using available information [23].

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. In order to obtain satisfactory estimates, the addition of new real time measurements, specifically voltage measurements at critical locations and the use of information from the loads (pseudo measurements) are necessary. The state estimation unit uses real time measurements from the system, few pseudo measurements, and system configurations like switch status. It then calculates the current state of the system. The state estimation unit outputs are bus voltages, values of load demand and line currents.

B. Optimal Power Flow (OPF) unit

The aim of this unit is to determine each DG unit’s generation in order to have optimal operation and also determine voltages in all buses, line currents, considering ratings of the inverters, DG units and time delays for responding to a changed parameter. In this study, the optimal power flow unit in modeled as a problem of finding each DG unit’s active and reactive power in order to minimize active
power loss of the system with constraints of normal voltage magnitude, and DG units rating. Mathematically, the problem formulation can be shown by equation (7).

In this equation, the power loss in the system can be found as a function of voltage magnitude and angle and it is derived in appendix. 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 the characteristics of the objective function and constraints. The nonlinear programming problem in which the objective function and constraints can be nonlinear functions of design variables is applicable to the optimal power flow problem in this study.

\[
\text{Minimize} \quad P_{\text{Loss}} = f(\|v\|, \delta)
\]

Subject to:

Load Flow Equation (it mean\( \sum_{i=1}^{\text{ngen}} P_i = \sum_{i=1}^{\text{load}} P_i + \text{Losses} \))

\[V_{\text{min}}^i \leq V_i \leq V_{\text{max}}^i \quad \text{for } i = 1: \text{nbus} \]

\[P_{i_{\text{min}}} \leq P_i \leq P_{i_{\text{max}}} \quad \text{for } i = 1: \text{ngen} \]

\[Q_{i_{\text{min}}} \leq Q_i \leq Q_{i_{\text{max}}} \quad \text{for } i = 1: \text{ngen} \]

Sequential quadratic programming (SQP) methods are the state of the art method in nonlinear programming. In this study, this method is used to solve optimal power flow problem. The method is implemented using “fmincon” function in optimization toolbox of MATLAB/Simulink [25].

C. Local Controller (LC) of Interface Inverters

The active and reactive power which is supplied by an inverter interfaced DG unit can be controlled independently with parameter of the interfaced inverter. PQ, PV, and Vf control schemes are the common schemes which are applied for inverter interfaced DG units [12]-[14], [26]-[28]. This study focuses only on the MicroGrid consisting of several inverters interfaced to DG units and other controllable equipment like loads, transformers, and compensation units are not considered.

5. PROPOSED CONTROL SCHEME FOR A STAND-ALONE MICROGRID

In a stand-alone distribution network, there are two main problems. The first problem is the slow dynamic response of the generation units which necessitates the use of storage devices on dc link to perform fast load tracking. The second problem is the lack of frequency and voltage reference. 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 reference unit called master DG unit in this study.

The proposed strategy for controlling power sharing between DG units in this paper is as follows:

- At first it is assumed that all the units in the islanded system operate below their ratings in order to have selection of power change.
- When any change in load demand happens, the master DG unit changes its output to meet the requirement of the loads, whereas the other DG units in the system continue to supply the power as scheduled.
- Similar to the conventional power system, the measurements units measure the system parameters and send them to MGMS at constant intervals. The state estimation unit uses the measured and the virtually measured data and estimates the system state. It calculates the amount of power generation and power demand along with bus voltages and line currents.
- Then it divides the power among other units according to their ratings and guide the system to work in an optimal and normal condition. As mentioned these functions are performed by optimal power flow unit. The communication links transmit the new power reference to the DG units.

In addition, during outage or when power demand is greater than the generation, system may experience under voltage and hence load shedding scheme should be used. In this study, it is considered that the load and generation are balanced and there is no need for load shedding. It is obvious that the master DG unit should be able to produce extra load demand in the interval of load change. So, the capacity of storage device should be determined taking into account the maximum load change, time delay of controller, and the speed of master DG unit to change its output. In this study, method outlined in [26] is used for designing storage capacity. Like conventional power system, if the master unit fails, other unit should play its role and MGMS must switch the control to new master unit.

6. SIMULATION RESULTS

A distribution system shown in Figure 5 is used for the analysis of this work. The system consists of four feeders that supply from utility via a 20/0.4 KV transformer and the data for all components of the system can be found in Appendix. When the utility is available two DG units produce certain part of energy needed for the system. 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. After that the two important feeders with two DG units act as a stand-alone MicroGrid.
It is assumed that DG 1, with suitable storage device, is the master DG unit and 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 DG1 control loop is as shown in [28]. It has a PI controller with KP=1 and KI=3. The control of voltage and frequency is dictated by the reference signal frequency of PWM. For the PQ control of DG2, two current control loops with simple PI controller with KP=5 and KI=0.1 are designed.

For state estimation, three voltage meters at bus (1,2,6) and two active and reactive power meter in buses with DG units (buses 1 and 2) are installed. Also, pseudo measurement for load estimation of some buses is employed for state estimation. For the system under study, there are seven state variables. The system has seven eigenvalues (-630.63 ± j314.16). Since all lines have equal impedance and capacitance per length, the eigenvalues are same. The eigenvalues have real part value of -630.63. This means that a dynamics caused by a certain disturbance will die down to 5% of its initial value within 0.0063 second. It is reasonable to say that normally the time intervals between two disturbances will be bigger than 0.0063 second. So, as mentioned the admittance matrix can be used for modeling the network.

The simulation is done for four cases. The simulation results are explained in the following subsections.

A. Initiation of the system

Initially, it is considered that system works 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 6 and Figure 7 that in this case the controllers adjusted the output power of DG 2 to desired value and the remaining power needed is supplied by master unit DG 1.

As shown in Figure 8, the voltages are in the normal range. Also total active power loss of system is 0.256 per unit and it is approximately 4% of total system load.

B. Optimization of the system

At t=1 sec, the state estimation unit calculates the system parameters and the amount of loads. The results for estimated and real values indicate that the state estimation unit has good estimate of the system. The total amount of load as well as voltage of buses is known. So, the optimal power flow can be done with this data. The optimal power flow unit calculates optimal value of DG2 as 197 KW and 88 KVAR and sends it to the unit. It is clear from Figure 6 and Figure 7 that local controller receives the command and adjusts the powers as desired. With this optimal value, the system loss will be 0.2120 pu. It is clear that losses are reduced by 25% and also all voltages remain at normal value as shown in Figure 8. Increase in a Load

C. Increase in a Load

The system response to increase in a system load is simulated in third case. At t=1.5 sec, (40 KW+ 20 KVAR) load is added at bus 9 and it can be seen from Figures 6 and 7 that the required power is supplied by master unit DG 1 to this load and the other unit work at predefined reference value.

Figure 8 shows buses voltages on certain buses after load addition. This figure shows that some buses voltage exceed from normal rating (±5%). In addition, power losses of the system are increased to 0.3104 pu.
8. APPENDIX

A. Distribution system Loss

In a system with “n” buses the power loss can be defined as:

$$P_L + jQ_L = \sum_{i=1}^{n} V_i^* I_i = \begin{bmatrix} V_1^* & V_2^* & \ldots & V_n^* \end{bmatrix} \begin{bmatrix} I_1 \end{bmatrix} = V^* I$$  \hspace{1cm} (8)

Where “V” and “I” are vector of buses voltage and current respectively. They have simple relation with Zbus matrix of system and substituting in previous equation yield:

$$V = Z_{bus} I$$

Therefore:

$$P_L + jQ_L = (Z_{bus} I)^* I' = I' Z_{bus} I'$$  \hspace{1cm} (9)

Let’s write buses current and Zbus matrix of the system as real and imaginary parts.

$$Z_{bus} = R + jX = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nn} \end{bmatrix} + j \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nn} \end{bmatrix}$$ \hspace{1cm} (10)

And then substitute the real and reactive part of currents and Zbus matrix into equation (9) yield:

$$P_L + jQ_L = (I_a + jI_r)^* (R + jX) (I_a - jI_r)$$

so:

$$P_L = I_a^T R I_a + I_r^T R I_r = \sum_{j=1}^{n} \sum_{i=1}^{n} r_{jk} (I_{ja} I_{aj} + I_{jr} I_{rij})$$ \hspace{1cm} (11)

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

$$P + jQ = V I' = \begin{bmatrix} V_1 \end{bmatrix} (\cos \delta + j \sin \delta) (I_a - jI_r)$$ \hspace{1cm} (12)

where \( \delta_i \) 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.

$$I_{aj} = \frac{1}{|V|} (P \cos \delta + Q \sin \delta)$$ \hspace{1cm} (1)

$$I_{jr} = \frac{1}{|V|} (P \sin \delta - Q \cos \delta)$$ \hspace{1cm} (3)

Therefore, by substituting this equation in equation 3 the
power loss can be obtained from equation (14):

\[
P_L = \sum_{j=1}^{m} \alpha_\delta(P_j P_i + Q_j Q_i) + \beta_\delta(Q_j P_i - P_j Q_i)
\]

where:

\[
\alpha_\delta = \frac{r_k}{|V_j| |V_i|} \cos(\delta_j - \delta_i)
\]

\[
\beta_\delta = \frac{r_k}{|V_j| |V_i|} \sin(\delta_j - \delta_i)
\]

B. Study system Parameter

All lines are similar with the following data:
Cable Resistance: \( R = 0.164 \text{ ohms/km} \)
Cable Inductance: \( L = 0.26 \text{ mH/km} \)

Distribution Line data

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Buses Load data

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DG Units Data

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REFERENCES