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SEQUENTIAL POWER FLOW ANALYSIS OF AN AUTONOMOUS MICROGRID WITH VARIOUS DISTRIBUTED ENERGY RESOURCES

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Abstract. *The main purpose of this paper is to analyze the sequential power flow of an autonomous microgrid (MG) with various distributed energy resources (DERs). This system consists of five different types of DERs and loads. These DERs include two 1.5 MW diesel engine generators, two 1.79 MW gas turbine generators, two 1.0 MW fuel cell generation systems, a 1.5 MW wind turbine generator, and a 0.5 MW photovoltaic generation system. In this paper, based on the Newton-Raphson method, a sequential power flow program was developed in Matlab environment and its accuracy is verified. And the program was used to simulate and analyze the daily power flow of the MG under the autonomous operating mode. The simulation results demonstrate that the developed approach is suitable for the daily power flow analysis of the autonomous MGs.*

Keywords: Microgrid, Distributed energy resources, Power flow, Steady-state analysis, Autonomous operation

1. **Introduction.** The history of development of traditional electrical power systems is over one century; this vertical structure system contains generation, transmission, and distribution. The electric power must be transmitted from the transmission and distribution systems to the customers. Therefore, the transmission losses are considerable. Besides, the CO_2 emission of thermal power plants cause global warming to become increasingly worse. Consequently, one of the major tasks of mitigating the global warming phenomenon is reducing the power generation of such thermal power plants. On the basis of this objective, the development of distributed energy resources (DERs) is an unavoidable trend in past decades. DERs are usually connected to distribution systems directly supplying power to the local network to satisfy customer demands. Thus, the incorporation of DERs reduces total power system loss because no transmission losses are incurred, and DERs usually offer the advantages of low environmental effects and high efficiency. Generally, distribution systems integrated with various DERs and loads to form a micro power system are called microgrids (MGs); these systems are designed to be operated in grid-connected and autonomous modes [1], some researches have discussed the system structure [2], operations [3], implementation [4], and management of the MGs [5]. Given that MGs have become a new development trend in power systems, realizing solid system structures, as well as operating and control technologies, among others, is a necessary requirement. For this reason, the sequential power flow analysis of an MG with five different types of DERs under autonomous operating mode is evaluated in this paper. This paper has five sections. Section 1 provides an introduction. Section 2 describes the proposed microgrid. Section 3 explains the proposed approach. Section 4 demonstrates and discusses the simulation results and Section 5 concludes the paper.

2. **Description of the Proposed Microgrid.** Figure 1 shows the MG, modified from a 11.4 kV primary distribution system of Taipower (Taiwan Power Company). This system

consists of a main transformer rated at 25 MVA, 69 kV/11.4 kV, and 60 Hz, and five primary feeders. Two feeders form an MG through a point of common coupling (PCC) of the static switch that enables connection and disconnection from the upstream utility grid; the other feeders are the normal feeders without DERs. The left feeder consists of two gas turbine generators (GT#1, GT#2), two fuel cell generation systems (FC#1, FC#2), a photovoltaic cell generation system (PV), and three types of equivalent lumped loads, which are residential, office, and commercial loads. The right feeder comprises two diesel

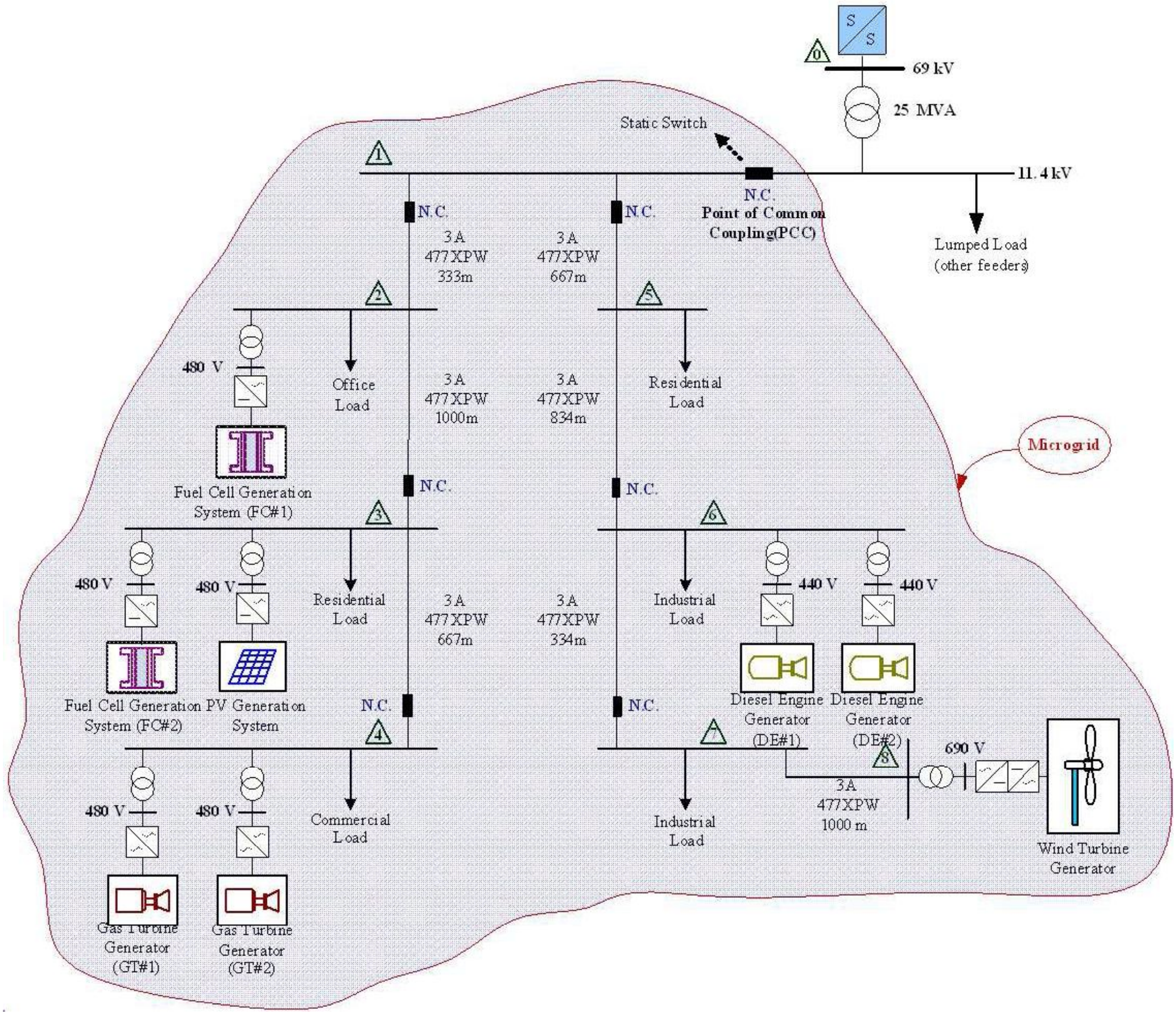


FIGURE 1. Microgrid architecture

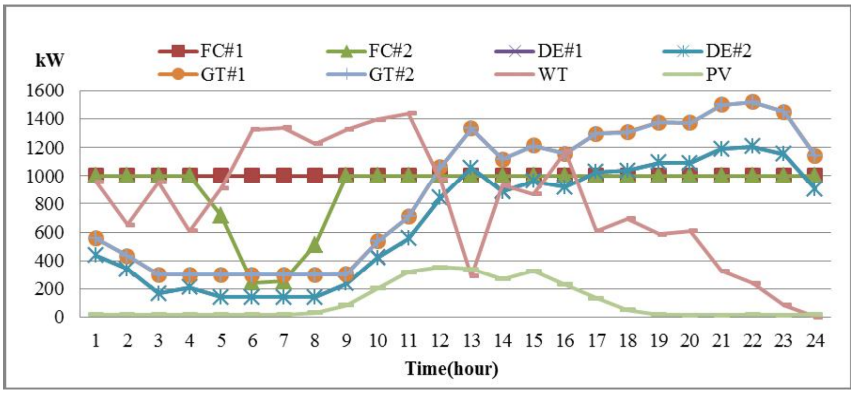
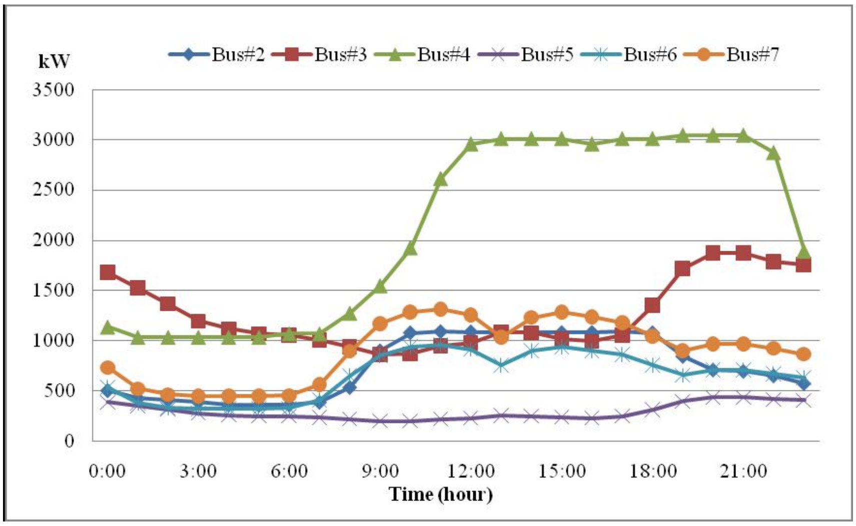
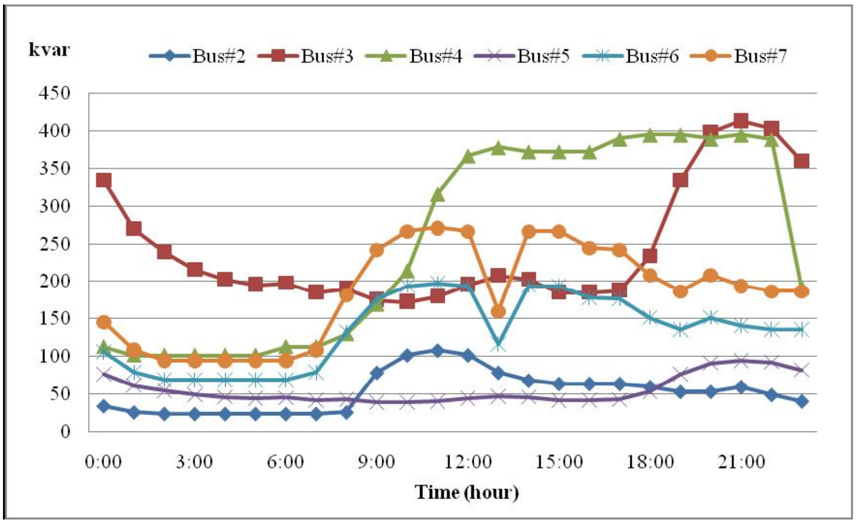


FIGURE 2. Optimal real power output curves for the DERs



(a) Real power



(b) Reactive power

Figure 3. Equivalent lumped load curves of real and reactive powers at load buses

engine generators (DE#1, DE#2), a wind turbine generator (WT), as well as residential and industrial loads. In this paper, the MG is assumed to operate in autonomous mode; therefore, the load demands are supplied only by the DERs. The principle of the MG optimal dispatch is the minimization of fuel cost and subject to power balance. The detailed procedure is not described here. The results of optimal real power output of each DER are shown in Figure 2. In addition, the equivalent lumped load curves for the real and reactive powers of each load types are shown in Figure 3.

3. **The Proposed Approach.** In order to realize the daily characteristics of the power systems, a sequential power flow analysis is essential. Huang and Chen [6] proposed Three-Phase Z-Bus Distribution Factor to solve this problem; however, the Newton-Raphson method is one of the most commonly used techniques for solving nonlinear algebraic equations, and presents better convergence than does the Gauss-Seidel method [7-10]. Therefore, it is popularly applied in power flow analysis. The iteration number of the Newton-Raphson approach is independent of the scale of system and can solve the problem through a few iterations. In this paper, the loads and DERs are assumed to be equivalent injected powers in power flow analysis. Equations (1) and (2) are the power mismatches

for bus i, in which $P_i^{(k),spec}$ and $Q_i^{(k),spec}$ represent the equivalent real and reactive power injections of the bus, and $P_i^{(k),cal}$ and $Q_i^{(k),cal}$ denote the calculated values of the injected real and reactive powers of the bus, respectively. These can be calculated using Equations (3) and (4).

$$\Delta P_i^{(k)} = P_i^{(k),spec} - P_i^{(k),cal} \tag{1}$$

$$\Delta Q_i^{(k)} = Q_i^{(k),spec} - Q_i^{(k),cal} \tag{2}$$

$$P_i^{(k),cal} = \sum_{j=1}^{n} \left|V_i^{(k)}\right| \left|V_j^{(k)}\right| |Y_{ij}| \cos\left(\theta_{ij} + \delta_j^{(k)} - \delta_i^{(k)}\right) \tag{3}$$

$$Q_i^{(k),cal} = -\sum_{j=1}^{n} \left|V_i^{(k)}\right| \left|V_j^{(k)}\right| |Y_{ij}| \sin\left(\theta_{ij} + \delta_j^{(k)} - \delta_i^{(k)}\right) \tag{4}$$

Collecting all mismatch equations into vector-matrix form yields

$$\begin{bmatrix} \Delta P_i^{(k)} \\ \Delta Q_i^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_i}{\partial \delta_i^{(k)}} & \frac{\partial P_i}{\partial \left|V_i^{(k)}\right|} \\ \frac{\partial Q_i}{\partial \delta_i^{(k)}} & \frac{\partial Q_i}{\partial \left|V_i^{(k)}\right|} \end{bmatrix} \begin{bmatrix} \Delta \delta_i^{(k)} \\ \Delta \left|V_i^{(k)}\right| \end{bmatrix} \tag{5}$$

Equation (5), which is the formula for the correction of phase angle and magnitude of bus voltages $\Delta\delta_i^{(k)}$ and $\Delta\left|V_i^{(k)}\right|$, is solved using Equation (6), and the solved corrections are added to update all buses voltages using Equations (7) and (8). The power flow equations are solved until the power mismatches at all buses fall within the specified tolerance levels.

$$\begin{bmatrix} \Delta \delta_i^{(k)} \\ \Delta \left|V_i^{(k)}\right| \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1} \begin{bmatrix} \Delta P_i^{(k)} \\ \Delta Q_i^{(k)} \end{bmatrix} \tag{6}$$

$$\delta_i^{(k+1)} = \delta_i^{(k)} + \Delta\delta_i^{(k)} \tag{7}$$

$$\left|V_i^{(k+1)}\right| = \left|V_i^{(k)}\right| + \Delta\left|V_i^{(k)}\right| \tag{8}$$

4. Simulation Results and Discussion.

The Newton-Raphson method was applied to solve the sequential power flow of the MG under autonomous operating mode with the assumption of three-phase balanced. A daily power flow analysis was explored in detail in this section, after the rigorous engineering analyses on the voltage profiles, line flow profiles, and system losses by the proposed approach. The simulation results are illustrated as follows.

4.1. Voltage profiles.

The results of the bus voltage profiles along the feeders of the MG are shown in Figure 4. Since the system is operated under autonomous mode, the power was fed only from DERs connected to the network without the upstream utility grid. Therefore, no power fed from the upstream grid through the main transformer. The voltage drops are slight due to the DERs supply the power to nearby loads by short delivering distance, and the average daily voltages at each bus are near nominal voltage. Consequently, the voltage at the end of the relatively heavier loading feeder is greater than 0.97 p.u.; the voltage at Bus#4 is 0.990 p.u. during the peak loading period. The DERs interconnected to the distribution network to form a MG is clearly helpful to the system voltage profiles under suitable control constraints, especially during autonomous operating mode.

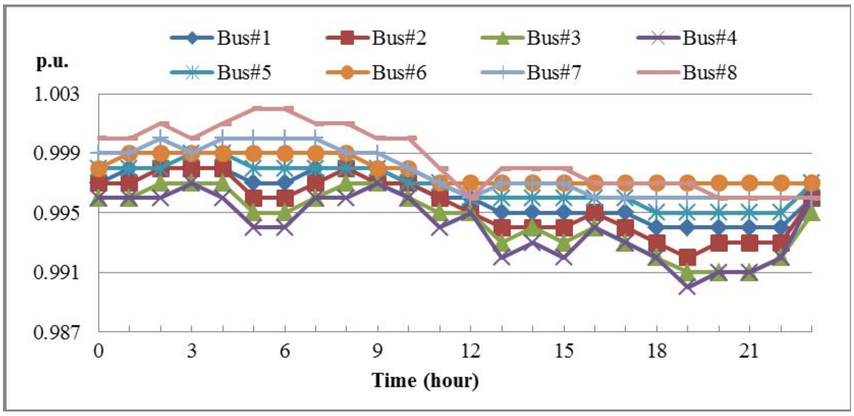


Figure 4. Simulation results of the bus voltage

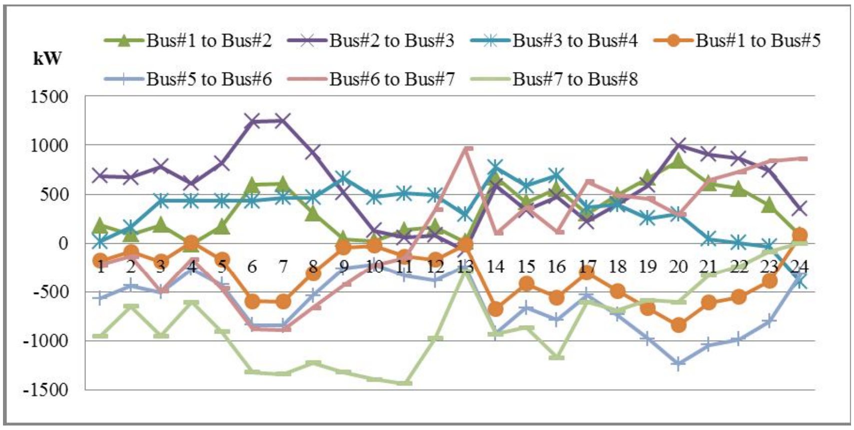


Figure 5. Simulation results of the real power flow

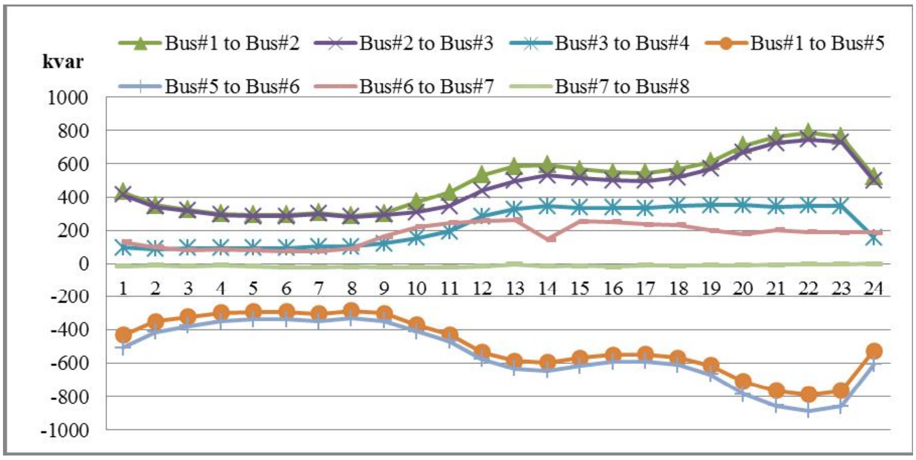


Figure 6. Simulation results of the reactive power flow

4.2. **Line flow profiles.** Figure 5 and Figure 6 illustrate the simulation results of daily real and reactive power flows in each feeder section. The peak loading period of the MG occurs around 18:00 to 23:00; by contrast, the off-peak loading period occurs around 00:00 to 08:00. The simulation results of the voltage profiles and line flows clearly reflect these phenomena. The variations in the real and reactive power flows are significant in each feeder segment at different times in one day. The directions of power flows in some feeder segments are reversed, especially in right feeder. The reversed real and reactive powers flowing in the primary feeder between buses 7 and 8 is the largest among all the feeder sections because Bus#8 is a generator bus connected to a wind turbine generator. The

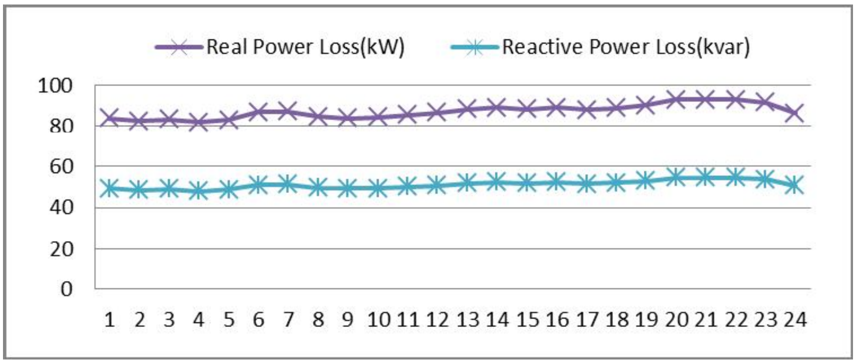


Figure 7. Simulation results of the system losses

power supply from this bus is a function of wind velocity. Similarly, the PV generation system is connected to Bus#3; the power output of this bus is directly proportional to solar irradiation and cell temperature. The simulation results depict that the power supply by PV is approximately between 07:00 to 15:00. The power supply from the above-mentioned buses is highly dependent on weather conditions. To sum up, the DERs are the only power supply to the loads and maintain power balance to keep voltage and frequency stable without the upstream utility grid under autonomous operating mode.

4.3. **System losses.** The daily system losses of the MG is shown in Figure 7. According to the simulation results, it is concluded that the power loss is directly proportional to the loading. Therefore, the more load used, the higher the increase in losses.

5. **Conclusions.** In this paper, a sequential power flow analysis of a MG with various DERs and loads under autonomous operating mode is evaluated. The daily voltage profiles, line flow profiles, and total system losses are explored via a sequential power flow program using the Newton-Raphson method. This program is developed in Matlab environment. The simulation results demonstrate that the interconnected of DERs is helpful in enhancing system operation performance and efficiency.

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