Real-Time Frequency and Voltage Control of an Islanded Mode Microgrid

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Abstract :

In this paper, we investigated the necessity and effects of optimal control methods in the stability and performance of a micro-grid that operates in islanded mode. The micro-gird is consisted of a combine heat and power (CHP), a capacitor bank (CB), photovoltaic panel (PV) as power generation sources. In addition, battery and the building electricity and thermal load are placed on the load side. A simple comprehensive model is assumed for each component of the micro-gird and the dynamic behavior of micro-grid voltage and frequency is studied in details. Since the micro-grid operates in islanded mode, the fluctuations in the building load act as disturbances and could cause the instability in the voltage and frequency. So it is necessary to design a controller to regulate the voltage and frequency. Particle swarm optimization (PSO) is used as a method to realize the optimal controller in the micro-grid. Simulation results showed the effects of proposed controller on the reduction of voltage and frequency fluctuations.

Keywords: Micro-grid, Dynamic loads, Integrated building control, Optimal control

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CB, and battery. Also different loads considered for the building are shown.

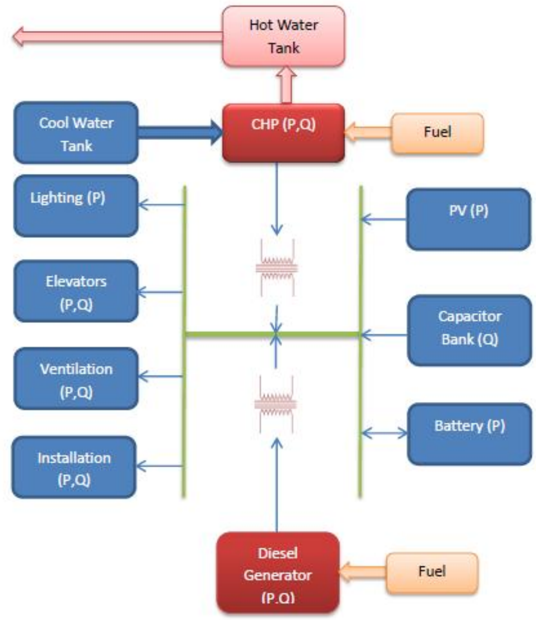

Fig. 1. Micro-grid structure

1. Introduction

Micro-grids are getting more popular recently all around the world due to their vast abilities such as integrating different kinds of power generators, generating power locally, easy to manage, and etc. Micro-grids encompass a wide range of prime mover technologies, such as combined heat and power (CHP), internal combustion (IC) engines, gas turbines, micro-turbines, photovoltaic, fuel cells and wind-power. This feature let us change the major power generator when it is necessary or economical [1].

By constructing smart grids such as smart structures for buildings, the possibility of energy management, enhancement of reliability, and network stability could be reached. The voltage and frequency of the micro-grids which operate in islanded mode are subjected to exceed their permissible limit. In fact, the voltage and frequency of the network in the islanded mode are sensitive to the variation and fluctuation of consuming load. The main reason of frequency variation in the islanded micro-grid is the difference between active power generation and consumption. Moreover the difference between reactive power consumption and generation could cause major fluctuation in the voltage. The load consumption can be considered as summation of macroscopic and microscopic consumption. The macroscopic consumption is equal to the average of the load consumption in long-term (approximately in the range of minute). On the other hand the short-term variations of the load (often in a range of msec.) are referred as microscopic consumption. CHP and Diesel Generator are regularly used to provide the necessary macroscopic power consumption of a micro-grid. Since CHPs spend long time to track the load changes, they are used to supply the macroscopic load consumption and the need for alternative equipment to track microscopic changes is undeniable. The electrical battery unit is used to follow the microscopic (real-time) load consumption in the micro-grid. Although electrical batteries have low response latency, their capacities are not enough to cover the macroscopic power consumption. The CHP has the ability to track the microscopic and macroscopic reactive power consumption. Therefore it is suitable for providing reactive power consumption [2, 3].

The organization of this paper is as follows. In section 2 the structure of the micro-grid and its components are define. In section 3 problem formulation is explained, and the results are presented in section 4. Finally the conclusion can be found in section 5.

2. Micro-grid Structure

This section introduces the different concepts employed in the micro-grid structure. As illustrated in Fig.1, the main parts in the micro-grid are CHP, PV, CB, and battery. Also different loads considered for the building are shown.

2.1. Photovoltaic Panels

One of the most important problems that our world has been facing recently is environmental issue due to the enormous production of greenhouse gases. So scientists have been researching to find new and renewable kinds of energy. One of the most efficient and common kinds of renewable energy systems are Photovoltaic Panels (PV) systems. PV systems are known as a clean power electricity source to meet future electricity demands.

The power that a PV system generates depends on the weather conditions, season, and geographic location, and any changes in the weather conditions cause fluctuation in its output power. This power output fluctuation results in major frequency and voltage deviation in electric power systems when PV systems are connected to the grids. In order to have safe and reliable grid, before connecting PV systems to the other utilities suitable measures must be applied to the PV systems. One useful and common method of reducing the effect of power output fluctuation of PV systems is to add energy devices like batteries one the PV system side [4-6].

In this paper we assume that we have a PV system in the micro-grid that can generate 1 kW in the most desirable weather conditions. Due to variable weather conditions we considered the PV system to have a turbulence behavior. In addition, this PV system is connected to the grid through an inverter which can control (reduce) the output power of this PV system.

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2.2. Combine Heat and Power (CHP)

Distributed generator (DG) play an increasing role in the electricity markets [10]. There are lots of reason why DG are getting popular every day: deregulation of power system, increasing difficulty faced in installing new transmission and distribution infrastructure and recent technological advances in the area of DG energy sources. The services that a DG can provide include standby generation, peak chopping capability and base load generation. DGs are one the most common devices in the electrical grids due to their vast applications such as backup generation, loss reduction, power quality improvement, grid expansion postponement, peak load services, urban and remote application, CHP generation and financial and trading benefits.

The most form of DG is Combined Heat and Power (CHP) generation since it provides numerous advantages to both distribution and electricity users. This kind of generators can provide both electrical power and thermal energy. Other benefits of CHP projects include: reduction of greenhouse gas emission, increase in SME business reliability, improved electrical power quality, increased energy efficiency, resulting in significant financial and environmental benefits [7, 11].

In this paper to simulate the micro-grid we approximate CHP equations with two first-order transfer functions. The transfer functions we have considered are:

$$\frac{dP}{dt} = \frac{P_{max}}{\tau_p}\left(U_p - \frac{P}{P_{max}}\right) \quad (1)$$

$$\frac{dQ}{dt} = \frac{Q_{max}}{\tau_q}\left(U_q - \frac{Q}{Q_{max}}\right) \quad (2)$$

In these equations Up is the input signal for the active power that the CHP generates (P) relative to its maximum active power generation (P_{max}), and Uq is the input signal for the reactive power that the CHP generates (Q) relative to its maximum reactive power generation (Q_{max}). τ_p and τ_q are time constant of system. Based on the consumption profile we had, we assumed the maximum active and reactive power that this CHP can generate, are 70 kW and 40 kVAr respectively.

Since the time constant of inverters which connect DG or CHP to the grid, is too small, we ignore the dynamic equations of inverters.

2.3. Electrical Storage

One of the advantages of micro-grids is using renewable energy such as wind turbines and photovoltaic panels. The output power that these kinds of generators provide depends on the weather conditions, and since weather conditions are not stable and show variable behavior, significant frequency variations and voltage drops may happen in the micro-grid. Fluctuation in voltage and frequency of the micro-grid not only decrease the reliability and power quality of the micro-grid but also may cause damage in equipment. As a result, micro-grids are well positioned to benefit from battery-based storage systems for maintaining reliability and power quality.

As it is explained batteries beside wind turbines and photovoltaic panels can play an important and safe role in micro-grids. Batteries can reduce the fluctuations in micro-girds, by generating and consuming (saving) power when it is necessary. Batteries only generate direct current, and in order to use them in alternative current micro-grids we have to use an inverter that connects batteries to the micro-grid.

One important feature of a battery is its state of charge (SOC). SOC is an expression of the present battery capacity as a percentage of maximum capacity. SOC is generally calculated using current integration to determine the change in battery capacity over time. Like CHP we simplified the equations of the battery in order to simulate the micro-grid. The equations that we assumed for the battery are:

$$\frac{dP_{bat}}{dt} = \frac{Pmax_{bat}}{\tau_{bat}}\left(U_{bat} - \frac{P_{bat}}{Pmax_{bat}}\right) \quad (3)$$

$$\frac{dSOC}{dt} - bP_{bat} \quad (4)$$

In the first equation U_{bat} is the input signal for the power that the battery generates relative to its maximum power generation ($Pmax_{bat}$). Based on the consumption profile we had, we assumed the maximum power that this battery can generate, is 10 kW.

2.4. Capacitor Bank

In the micro-grid there are some loads that consume both active and reactive power, on the other hand, in order to simplify our grid we assume that only CHP can generate reactive power. In order to have a better voltage profile throughout the network and, additionally, to provide sufficient reactive power to balance reactive generation and reactive load under islanded operation, we used capacitor banks in the micro-grid [8]. Like other generators we simplified the equations of the capacitor banks in order to simulate the micro-grid. The equation that we assumed for the capacitor bank is:

$$\frac{dQ_c}{dt} = \frac{Qmax_c}{\tau_c}\left(U_c - \frac{Q_c}{Qmax_c}\right) \quad (5)$$

In this equation U_c is the input signal for the reactive power that the capacitor banks generates relative to its maximum reactive power generation (Q_{max}). Based on the consumption profile we had, we assumed the maximum reactive power that these capacitor banks can generate is 20 kVAr.

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3. Problem Formulation

As described before, CHP and DG are used to generate necessary power for the micro-grid. These two power generators are connected to the terminal bus as shown in Fig.2.

Using the Kirchhoff voltage law, voltage of the terminal can be computed.

$$V_t = V_{s1} - \frac{|z1|S1}{V_{s1}} = V_{s2} - \frac{|z2|S2}{V_{s2}} \quad (6)$$

$$S_i = \sqrt{(P_i)^2 + (Q_i)^2} \quad (7)$$

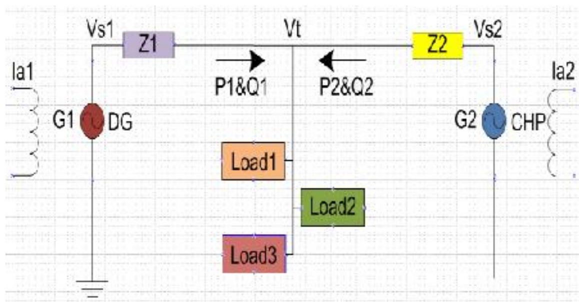

Fig. 2. Terminal Bus

In above equations, V_{s1} and V_{s2} indicate the output voltages of diesel generator and CHP. The values of Z_1 and Z_2 represented the impedances of lines. Also S_1 and S_2 are referred to the complex powers that are produced by power generators. Output voltage of generators depends on the frequency of operating point (ω) and shunt drive current (I_a). Equation 3 declared the relationship between these variables. The second term in (7) represented the voltage droop control between DG and CHP.

$$V_{si} = k_i I_{ai} \omega - \gamma_i Q_i \quad (8)$$

The parameter k_i is a constant value which is determined using the generators structure [3].

Difference between generated power (P_{Gen}) and consumed power (P_{Cons}) could cause the variation in the frequency. The relation is described as:

$$\frac{d\omega}{dt} = \lambda(P_{Gen} - P_{Cons}) + (\omega_{max} - \alpha P - \omega) \quad (9)$$

$$P_{Gen} = P_{pv} + P_{Bat} + P_{DG} + P_{CHP} \quad (10)$$

$$P_{Cons} = \sum_{i=1}^{number\ of\ loads} P_{load_i} \quad (11)$$

In (9), λ is generator shaft rotational inertia that defines the relation between frequency changes and power production and consumption differences.

The second term describes frequency droop control of generators' synchronized operation as shown in the Fig.3. The parameter α is the slope of frequency droop.

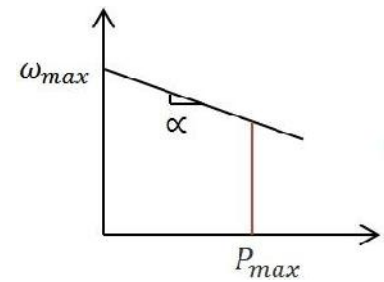

Fig. 3. Frequency droop characteristic

$$P_{max} = P_{max1} + P_{max2} \quad (12)$$

4. Controller Design

The main goal in the islanded micro-grid is frequency and voltage regulation. Based on the micro-grid component models described in previous sections, we have to solve a non-linear problem. It could be modeled as a nonlinear optimal control problem.

Based on the aim of control frequency and voltage, a proper cost function could be defined as:

$$J = \int_{t_0}^{t_f} (\xi_\omega |\omega - \omega_{ref}|^2 + \xi_V |V_t - V_{ref}|^2) dt \quad (13)$$

The controller assigns inputs so that this cost function takes its minimum amount. By minimizing such cost function, the voltage and frequency remain unchanged around their reference values (ω_{ref}, V_{ref}). By adjusting the parameters ξ_V and ξ_ω the importance weights of frequency and voltage regulation could be changed.

In order to control voltage of the grid we have to control both generating active and reactive power. Since there are some constrains on generating active power, voltage of the grid is mostly controlled by controlling reactive power produced by capacitor bank.

In addition to system constraints, power balance in terminal bus should be considered as below:

$$P_1 + P_2 = P_{Cons} - P_{Pv} - P_{Batt} \quad (14)$$

The control actions and the related constraints that should be taken into account about them are listed as:

$$0 < U_{DG} < 1 \quad (15)$$

$$0 < U_{CHP} < 1 \quad (16)$$

$$0 < U_{ai} < 1 \quad (17)$$

$$Umin_{bat} < U_{bat} < Umax_{bat} \quad (18)$$

Since the DG and CHP have significant role in supplying the macroscopic power consumption, it is assumed that these components should track the macroscopic power consumption, in other words, CHP and DG compensate large fluctuations of demand. So a new constraint forces DG and CHP to track the average of last 15 load consumption steps. This is useful when the variation of power consumption is more than the capacity of the electrical storage (Battery). Based on the sizing of the battery, these variations could be occurred

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in macroscopic changes. This constraint has two main advantages:

1) Force the DG and CHP to track the macroscopic changes and let the battery tracks microscopic changes.
2) Prevent the battery from working in the maximum power and increase the battery performance.

The nonlinear optimal control problem could be solved using evolutionary optimization methods such as PSO, GA, etc.

5. Simulation Results

5.1. Case Study

The case study investigated in this paper is a university building. Mentioned building has laboratories, computer rooms, elevators, lighting, installations, etc. The active and reactive power consumption data for April [9] is used as a macroscopic power consumption in the micro-grid. The microscopic power consumption is modeled as a normal distribution. This power is added to macroscopic power consumption to form the total power consumption. Fig. 4 and 5 illustrate the total active and reactive power consumption used in this paper.

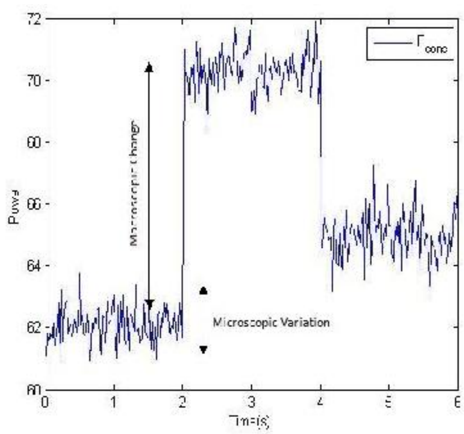

Fig. 4. Load active power consumption [kW]

5.2. Results

The real time optimization control has been done in Matlab-Simulink using PSO algorithm. The simulation time consists of 300 steps of 20 miliseconds which is equal to 6 sec. In each iteration, the best control actions are selected using PSO algorithm and are applied to the micro-grid. After applying the optimal control inputs, the next optimization step is repeated using the new states.

Fig. 6 is output active power of photovoltaic panels. In this diagram we assume that when the active power consumption increases, the output power of photovoltaic panels decrease simultaneously. This assumption makes the situation harder for controller to control the grid.

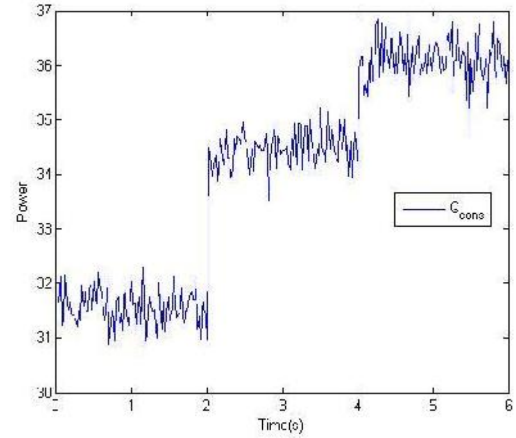

Fig. 5. Load reactive power consumption [kVar]

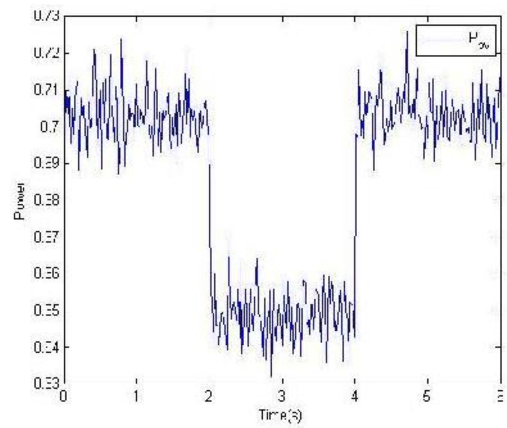

Fig. 6. Power generation of the PV [kW]

Fig. 7 and Fig. 8 show the terminal voltage and frequency of the micro-grid respectively.

In Fig.9 and 10 the percentage errors of voltage and frequency are shown. As you can see the error of this micro-grid is 1% which is acceptable for the micro-grid and these fluctuations in voltage and frequency will not affect the performance of the utilities which are connected to the micro-grid.

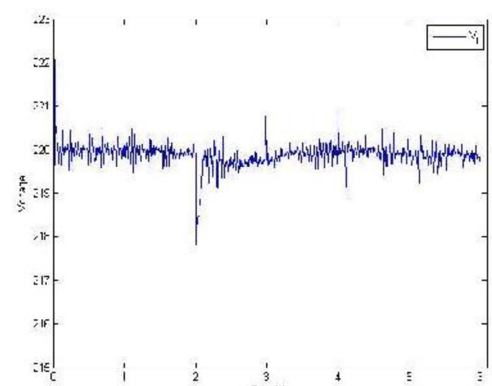

Fig. 7. Terminal voltage of the micro-grid.

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6. Conclusion

A set of components and a new optimal control strategy for controlling the variation of the voltage and frequency is proposed in this paper. Also a simple and efficient model is developed for describing the behavior of the micro-grids components. The strategy relies on the trajectory of the monitoring and applying the proper controller inputs. Moreover the power consumption in the micro-grid is divided into macroscopic and microscopic power consumption. Related to the different nature of these two power consumption, different control strategies are designed for regulation in each case. For instance the battery is used to regulate the voltage and frequency confront to microscopic variations. Also CHP and DG are used for macroscopic variations.

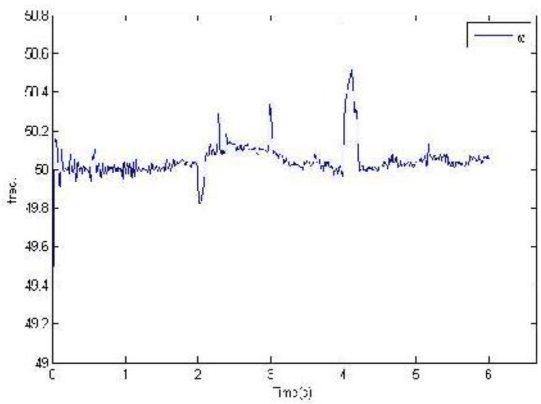

Fig. 8. Frequency of the micro-grid.

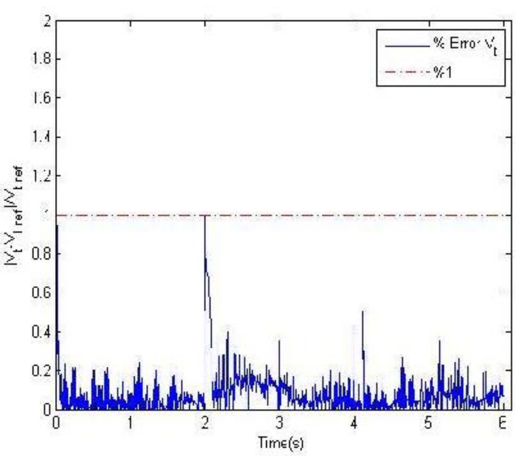

Fig. 9. Percentage errors of voltage

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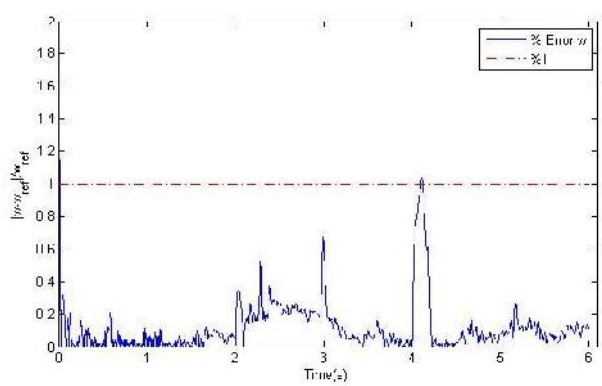

Fig. 10. Percentage errors of frequency

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