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A Hierarchical Power Management Strategy for Multiple Single-Phase Roadway Microgrids

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***Abstract*—This paper proposes a centralized hierarchical power management strategy for multiple single-phase wind/solar generation-based roadway microgrids integrated into a three-phase utility distribution grid. The proposed power management strategy consists of a Central Power Management Controller (CPMC) operating at the distribution grid level to regulate the power flow between the distribution grid and the microgrids, a Supervisory Power Management Controller (SPMC) operating at the microgrid level for voltage and frequency control of each microgrid under the coordination of the CPMC, and a Local Power Management Controller operating at the unit level for power management of each individual unit under the coordination of the SPMC. An adaptive droop control is designed to precisely control the voltages and frequency of each microgrid. Simulation studies are carried out in MATLAB/Simulink to validate the proposed power management strategy for controlling multiple roadway microgrids in both grid-connected and island modes as well as the transition between different modes.**

***Index Terms*--Closed-loop droop control, hierarchical power management strategy, roadway microgrid, solar generation, wind generation**

I. Introduction

In recent years, there has been an interest in using the highway right-of-way and roadway infrastructure for renewable electric power generation and distribution [1]-[3]. For example, reference [3] presented a novel concept and design of wind/solar hybrid generation-based roadway microgrid. The fundamental unit of the roadway microgrid is the energy-plus roadway/traffic-signal light (EPRTL). One EPRTL unit contains a wind/solar hybrid generation system installed on the pole(s) of traffic-signal and/or street lights and an optional battery system. The electric power generated by the wind turbines and solar panels supplies the local loads, which are the traffic-signal and/or street lights, and the surplus is delivered through the roadway microgrid to supply other loads in the microgrid or the utility distribution grid to which the microgrid is connected.

Many microgrid architectures, either in single phase [4] or three phases [5], have been proposed since the concept was introduced. However, no work has been reported on integrating multiple single-phase microgrids into a three-phase distribution grid. The aforementioned roadway microgrid represents a new AC microgrid architecture, where one roadway microgrid is typically connected to one phase of the local utility distribution grid; and in a certain power distribution area, multiple single-phase roadway microgrids are connected to different phases of the local three-phase distribution grid.

Power management is the key issue for the operation of the roadway microgrids and their interactions with the utility distribution grid. Power management strategies have been proposed for AC microgrids [6], DC microgrids [7], and AC/DC hybrid microgrids [8]. In these strategies the operating command for each power source was assumed to be known. However, there was no explanation on how to generate these commands.

Droop controls have been widely used to control inverters in microgrids. Much effort has gone into using droop control to optimize the power sharing and minimize the circulating current of parallel-connected inverter systems [9], [10]. However, the conventional droop controls were based on open-loop control principles because they only used locally measured information for controlling each local plant. An adaptive droop control method was proposed in [11] to operate multiple voltage-source inverters of a microgrid in both grid-connected and island modes.

This paper proposes a centralized hierarchical multilayer power management strategy for multiple single-phase roadway microgrids connected to a three-phase utility distribution grid. Computer simulations are conducted to validate the proposed power management strategy for controlling multiple roadway microgrids connected to a local utility distribution grid in Lincoln, Nebraska in different operating modes.

II. Architecture of Roadway Microgrids and Power Management System

Traffic-signal lights and street lights are usually connected to one phase of the local three-phase distribution grid. Therefore, the EPRTL units that are geographically close and connected to the same phase of the local distribution grid form a single-phase roadway microgrid. In a certain power distribution area, multiple single-phase roadway microgrids can be connected to different phases of the local distribution

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grid. To properly operate the roadway microgrids, an appropriate power management strategy is needed to handle issues at all different layers, including power generation sharing among different EPRTL units within a microgrid, three phase power balance among different microgrids, and control of bidirectional power flow.

A. Roadway Microgrid and Its Power Management System

Fig. 1 shows a typical configuration of a single-phase roadway microgrid. It consists of multiple (three in this example) EPRTL units connected to the same phase of the local distribution grid. Each EPRTL unit has a wind/solar hybrid generation system and an optional energy storage system, e.g., a battery [3]. The hybrid generation system consists of a WTG and one or more PV panels mounted on the top of the pole of a traffic-signal or street light. The energy storage system is used as a source or sink of the electric power to control the power exchanged between the EPRTL unit and the microgrid. Each microgrid is connected to the local distribution grid through a single-phase transformer and a circuit breaker, e.g., a Static Transfer Switch (STS). The power generated by the EPRTL units is consumed by local loads, which are traffic-signal lights and/or street lights; the surplus power can be delivered to other loads in the microgrid or the local distribution grid. On the other hand, the power can also be delivered from the utility distribution grid to the microgrid when the power generated by the EPRTL units is not sufficient to supply their local loads.

Many roadway traffic control systems have communication infrastructure for closed-loop traffic signal operation. Such infrastructure can be utilized to develop a hierarchical power management strategy to control the electric power production, distribution, storage, and consumption within the microgrid, as shown in Fig. 1. The power management strategy consists of a high-layer Supervisory Power Management Controller (SPMC) for the microgrid and a low-layer Local Power Management Controller (LPMC) for each EPRTL unit. The SPMC communicates with each LPMC and the STS to collect information from them, and then make decisions and send out commands and information, such as active power reference and control mode, to each LPMC to coordinate the actions of the EPRTL units. The LMPC then determines the desired power outputs for the WTG, PV panels, and battery storage of each EPRTL unit in different operating modes.

B. Multiple Single-Phase Roadway Microgrids Integrated into a Three-Phase Distribution Grid

In a certain power distribution area, multiple single-phase roadway microgrids are usually connected to different phases of the local distribution grid, as shown in Fig. 2. The numbers of the microgrids in phases A, B and C are *a*, *b* and *c*, respectively.

The operations of the multiple single-phase microgrids are coordinated by a CPMC located at the distribution grid level. The CPMC collects the information, such as the number of microgrids in each phase and the maximum power that can be sent to the distribution grid from each microgrid, and makes

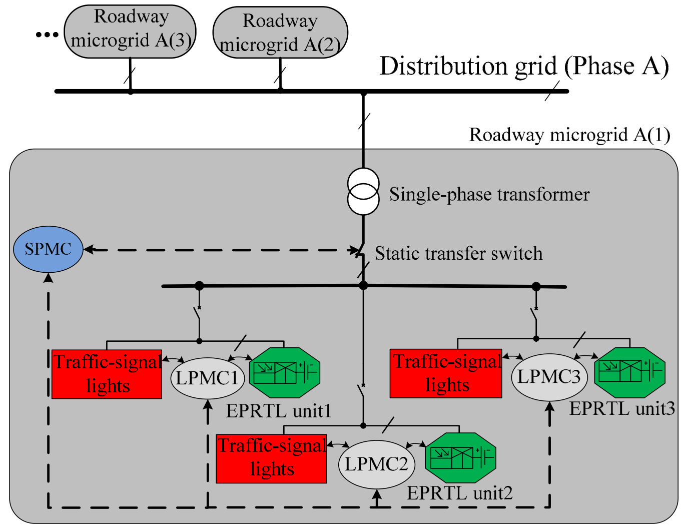

Fig. 1. Typical configuration of a single-phase roadway microgrid.

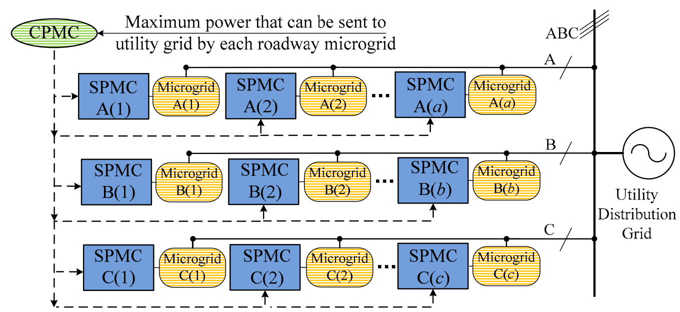

Fig. 2. The architecture of multiple single-phase roadway microgrids integrated into a three-phase distribution grid.

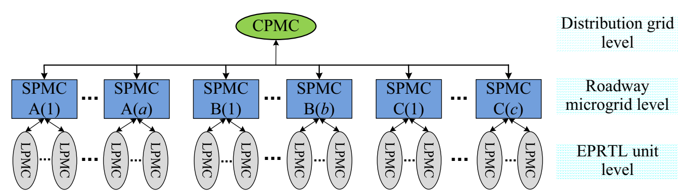

Fig. 3. Proposed hierarchical power management system.

decisions on how much power is to be sent by each microgrid to the distribution grid while ensuring the balance of the power of the three phases. The SPMC in each microgrid then makes decisions according to the commands received from the CPMC. The overall hierarchical power management system is shown in Fig. 3.

III. Power Management for a Single-Phase Roadway Microgrid

Each single-phase roadway microgrid has two operating modes: the grid-connected mode and the island mode. The power management system acts as the brain and the sensing and neutral system to optimally manage power production, storage, distribution and consumption of the microgrid in different modes using the existing roadway communication infrastructure.

Fig. 4 illustrates a typical configuration of a microgrid consisting of three equivalent EPRTL units. An SPMC

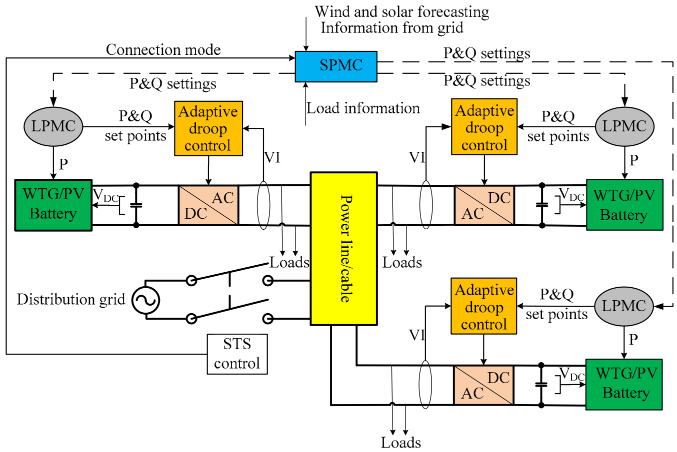

Fig. 4. A roadway microgrid with three EPRTL units and power management system.

communicates with each EPRTL unit. Each LPMC uses a droop control to regulate the active power P and reactive power Q of the inverter of each EPRTL unit to achieve appropriate power sharing among different EPRTL units. This droop control-based power sharing is coordinated by the SPMC at the microgrid level, which generates the set points of the active power P and reactive power Q for each LPMC. This leads to an adaptive droop control [11] for more accurate power control in the island mode of operation.

A fixed frequency is always desired for microgrid operation. The adaptive P/f droop control is implemented by the following equation, which can be regarded as a closed-loop control to regulate the active power output to the reference point. Each droop controller receives a new P setting from the SPMC continuously to minimize the frequency deviation in the island mode. Below is the adaptive P/f droop control equation.

$$\omega = \omega_0 + M_P\left(P_{ref} - P\right) \tag{1}$$

where w_0 is the desired frequency, M_p is the droop coefficient, P_{ref} is the active power reference, P is the active power exchange between the inverter and the microgrid. P_{ref} is updated by the SPMC, based on which the adaptive droop control of the LPMC of each EPRTL unit regulates the active power of the inverter to maintain the frequency of the microgrid at the desired value. A closed-loop reactive power-voltage droop control can be implemented in a similar way.

IV. Power Management Strategy for Multiple Single-Phase Roadway Microgrids

In a certain power distribution area, multiple roadway microgrids might be integrated into the utility distribution grid. As one microgrid is connected to one phase of the distribution grid, these microgrids should be distributed evenly among the three phases. When the roadway microgrids are connected to the distribution grid, it is operating in grid-connected mode. When there is some fault in the distribution grid, all the roadway microgrids have to be disconnected from the distribution grid out of safety reason. So, this operation mode is called single microgrid island mode.

Grid-Connected Mode

In an ideal condition the microgrids in Phase A of the utility distribution grid are designed to have the same total power generation capacity as those in Phases B and C. In the grid-connected mode, all the WTGs and PV panels in every microgrid work in the MPPT mode. Since the weather condition is usually approximately the same within a certain power distribution area, the power generated by the microgrids in the three phases should be maximum and approximately balanced.

However, sometimes the total capacity or generation of the microgrids in one phase is not equal to that in another phase because e.g., some microgrids are under maintenance or some microgrids have operational problems. In this case, the power exchanged between the microgrids and the distribution grid should be controlled to ensure a power balance among the three phases.

The CPMC is located at the utility distribution grid level. It collects the information of the total maximum wind power and solar power that can be generated by the microgrids in each phase and then calculates the maximum power that can be sent to the utility distribution grid while keeping a power balance among the three phases. The maximum power that can be sent to the distribution grid from each microgrid may not be equal to the maximum power that can be generated by the microgrid.

Consider that there are a, b and c microgrids connected to Phases A, B and C circuits of a utility distribution grid, respectively. The target of the CPMC is to maximize the total power that can be sent to the distribution grid by the microgrids, as described by (5).

$$\max \sum_{i=1}^{a} P(i,t) + \sum_{j=1}^{b} P(j,t) + \sum_{k=1}^{c} P(k,t) \tag{2}$$

where $P(i, t)$ is the power sent to the distribution grid from the ith microgrid in Phase A, $P(j, t)$ is the power sent to the distribution grid from the jth microgrid in Phase B, and $P(k, t)$ is the power sent to the distribution grid from the kth microgrid in Phase C. The objective function (2) is subject to the following constraints.

$$\begin{cases} -P_L(i,t) \le P(i,t) \le P_{(W+S)\max}(i,t) - P_L(i,t) \\ -P_L(j,t) \le P(j,t) \le P_{(W+S)\max}(j,t) - P_L(j,t) \\ -P_L(k,t) \le P(k,t) \le P_{(W+S)\max}(k,t) - P_L(k,t) \end{cases} \tag{3}$$

$$\sum_{i=1}^{a} P(i,t) = \sum_{j=1}^{b} P(j,t) = \sum_{k=1}^{c} P(k,t) \tag{4}$$

In (3), P_L stands for the total power consumption of the loads, e.g., the traffic-signal lights and street lights, within a microgrid, which is usually a constant; $P_{(W+S)max}$ is the total maximum power that can be generated by the WTGs and PV panels in the microgrid. Equation (4) ensures that the power sent to the three phases of the distribution grid should be balanced.

A. Single Microgrid Island Mode

When a fault occurs in the distribution substation or the upper-level power grid, the local utility distribution grid will be disconnected from the upper-level power grid. For safety consideration, in this circumstance each roadway microgrid is disconnected from the utility distribution grid and operates independently. The wind and solar power only supplies the traffic-signal/street lights in the microgrid. When there is little wind and solar power that can be generated, the battery will supply power to the traffic-signal/street lights for a certain time, e.g., four hours.

V. Simulation Results

Simulation studies are carried out for multiple microgrids operating in the grid-connected mode as well as for one of the microgrids operating in the island mode to verify the control algorithms proposed in Sections III and VI.

A. Multiple Microgrids Operating in Grid-Connected Mode

In this case study, the installed capacities of WTGs and PV panels in one microgrid are 12 kW and 3 kW, respectively. The maximum power that can be generated in one day by WTGs and PV panels is obtained by using the wind and solar power data provided by [12].

Supposed that there are six microgrids connected to Phase A (a = 6), seven microgrids connected to Phase B (b = 7), and eight microgrids connected to Phase C (c = 8).

By using the CPMC, the amount of power that can be sent to the distribution grid is determined for each microgrid. Due to some reason the total capacity or generation of the microgrids in one phase may not be equal to that in another phase. Fig. 5 shows the maximum power that can be sent to the distribution grid by one microgrid in Phases A, B and C in each hour of a day, respectively. The total maximum powers that can be generated by different phases are different. The optimization algorithm (2)-(4) uses the smallest value of the total maximum power among the three phases as a base for power sharing so that the power can be balanced among the three phases. The WTGs and PV panels in the microgrids of that base phase operate at their maximum power points; while the WTGs and PV panels in the microgrids of other two phases are regulated to generate the same amount of total output power as the base phase with the smallest microgrid capacities, instead of working at the maximum power points. In this case study, the microgrids in phase A will operate at the maximum power point as the total capacity of the microgrids in phase A is the smallest. Different microgrids in different phases generate different amounts of active power, as shown in Fig. 5.

B. Single Microgrid Island Mode

Suppose that there are three EPRTL units in one roadway microgrid, which has enough power to supply the load in the island mode. The roadway microgrid model is built in MATLAB/Simulink using the Automated State Model Generation algorithm [13]. The parameters of the microgrid are listed in Table I.

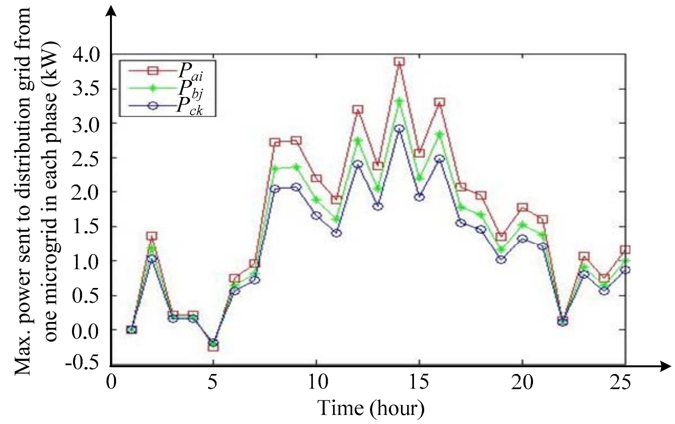

Fig. 5. The maximum power sent to the distribution grid by each microgrid in Phases A, B and C in each hour of a day.

TABLE I
PARAMETERS OF THE MICROGRID USED IN THE SIMULATION

Symbol	Description	Value
S_{base}	Base power	5 kW
f_{base}	Base frequency	60 Hz
P_{ref}	Reference power for one EPRTL	
P	Active power exchanged between one EPRTL and the microgrid	

The total load in the roadway microgrid is 1.2 pu. When the three EPRTL units have the same capacity and same droop function, the output powers of the three units are the same, as shown from 0 s to 3 s in Figs. 6 and 7. From 0 s to 3 s, the microgrid is operated in the grid-connected mode. The output powers of all the EPRTL units follow their references perfectly and the frequency is kept at the desired value of 60 Hz when the power references are changed.

At 3 s, the microgrid switches to the island mode. From 3 s to 4 s, the reference power in the droop control has no update, which is still 0.55 pu for each EPRTL unit. The overall load of the roadway microgrid is kept at 1.2 pu. Suppose that the three EPRTL units are identical. Thus, each EPRTL unit should share one third of the load, which is 0.4 pu. Since the power reference does not match the load, there is a frequency deviation of 0.7 Hz from 60 Hz, as shown in Fig. 6. When the load changes from 1.2 pu to 1.5 pu at 4 s, each EPRTL unit should supply one third of the load, which is 0.5 pu. However, the power reference of each EPRTL unit is still 0.55 pu. As a result, the frequency deviation becomes 0.3 Hz from 4 s onwards due to the load change. The magnitude of the frequency deviation depends on the difference between the total reference power and the load.

In Fig. 7, P_{ref} is updated by the closed-loop droop control of the SPMC of the microgrid according to the operating mode and load. From 3 s to 4 s, the reference is updated to be 0.4 pu; and from 4 s to 5 s, as the load changes, the reference is updated to be 0.5 pu. As a consequence, the frequency is

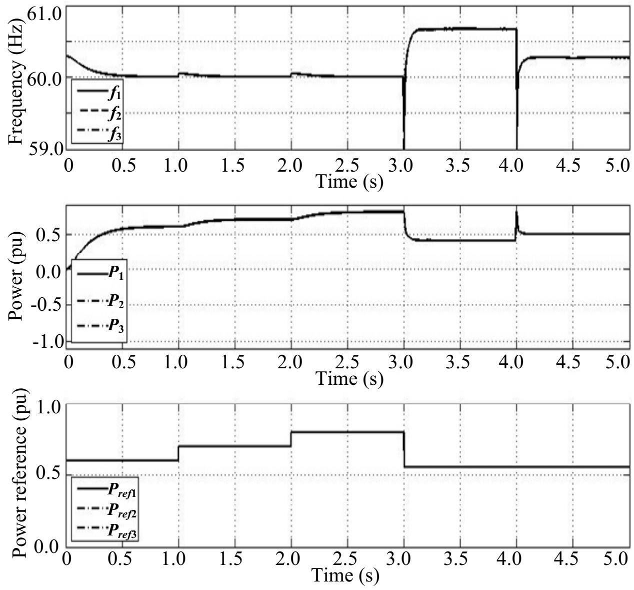

Fig. 6. Load changes from 1.2 pu to 1.5 pu but the reference power has no change at 3 s and 4 s

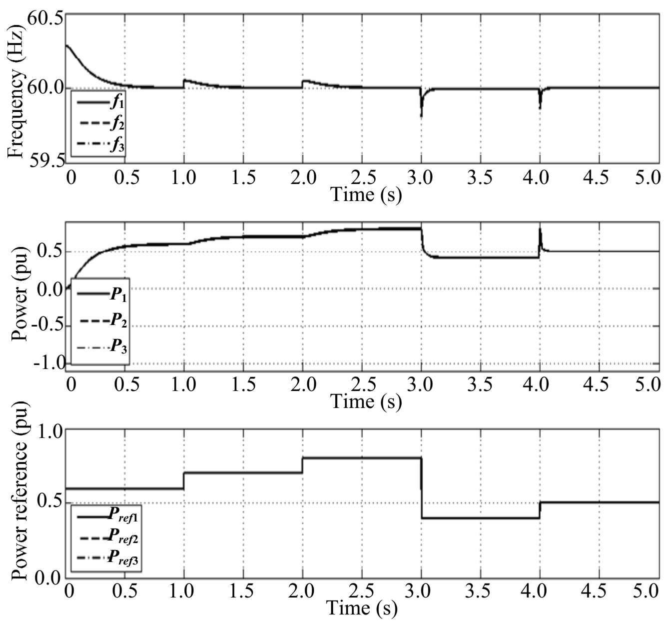

Fig. 7. Load changes from 1.2 pu to 1.5 pu and the reference power updates accordingly at 3 s and 4 s

always maintained at 60 Hz by using the closed-loop droop control.

VI. Conclusion

This paper has presented the concept and architecture of a wind/ solar generation-based single-phase roadway microgrid. A comprehensive hierarchical power management strategy has been proposed for power management of multiple roadway microgrids integrated into a local three-phase utility distribution grid in different operating modes. In the grid-connected mode the microgrids are controlled by a CPMC to generate as much power as possible while maintaining the power balance among the three phases. An adaptive droop control is used to obtain tight regulation for the power and frequency in the island mode so that there is little voltage and frequency deviation. Simulations results have shown that the proposed power management strategy is effective for operating the microgrids to achieve the desired objectives in different modes.

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