

# Construction, Operation and Control of a Laboratory-Scale Microgrid

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**Abstract** – To provide a test facility for possible demonstrations of advanced distributed generation system integration strategies, a single-phase laboratory-scale Microgrid system is set up. Two distributed generators are included in this Microgrid, a photovoltaic simulator and a wind turbine simulator. Both of them are connected to the AC grid via flexible power electronic interface respectively. For stable collaborative operation, a battery energy storage interfaced with a bi-directional inverter is necessary in this Microgrid. In the grid-connected mode, both the distributed generators converters and the bi-directional inverter are the grid-following unit. While switching from grid-connected mode to islanded mode, the bi-directional inverter is setting the voltage and frequency of the Microgrid through absorbing or releasing energy. The operation experimental results show that the laboratory-scale Microgrid system can operate in grid-connected or islanded mode, with a seamless transfer from one mode to the other, and hence increase the reliability of energy supplies.

**Keywords** – Bi-directional inverter, distributed generation, islanded-mode, grid-connected mode, Microgrid

## I. INTRODUCTION

In recent years, distributed generation (DG) technologies such as micro-turbines, photovoltaics (PV) and fuel cells are gaining wide interest due to the benefits such as highly reliable and good quality power supply, environmental preservation and energy cost reduction [1],[2]. But increasing amounts of individual distributed generators can cause as many problems as it may solve [3],[4]. A better way to realize the emerging potential of distributed generation is to take a system approach which views generation and associated loads as a microgrid [5]. A microgrid can operate in grid-connected mode (Mode-G) or islanded mode (Mode-I) and hence increase the reliability of energy supplies by disconnecting from the grid in the case of network faults. Now a considerable research has been undertaken on the control strategy of the microgrid [6]-[7], as part of this research, a series of microgrid test facilities, such as CERTS microgrid test bed, GE microgrid in America [8],[9], Aichi, Kyoto, Sendai microgrid in Japan [10],[11], Labein, Kythnos, CESI microgrid in Europe [12],[13], have been built for possible demonstrations of advanced distributed generation system integration strategies.

But as a newly-emerged thing, the practical applications of the microgrid is still in the initial stage, and further research in developing a hardware test bed to implement the control strategies and verify the operation of the microgrid is still necessary. In this paper, a single-phase laboratory-scale microgrid system was set up, experimental results from the laboratory-scale microgrid system was used to refine the control algorithms.

## II. LABORATORY-SCALE MICROGRID SYSTEM

### A. System description

The structure of the microgrid system is shown in Fig. 1. It is a single phase system, with 230V, 50Hz, comprising PV simulator, wind simulator and battery storage. Both of them are connected to the AC grid via flexible power electronic interface [14]. Also there is a Microgrid Central Controller (MGCC) which is responsible for the optimization of the microgrid operation.

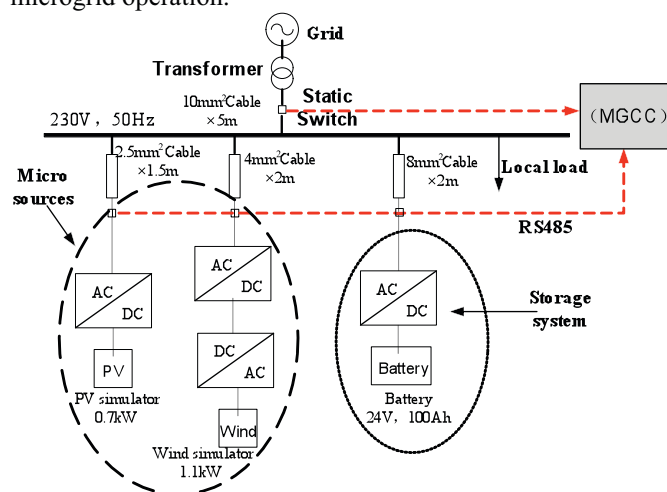
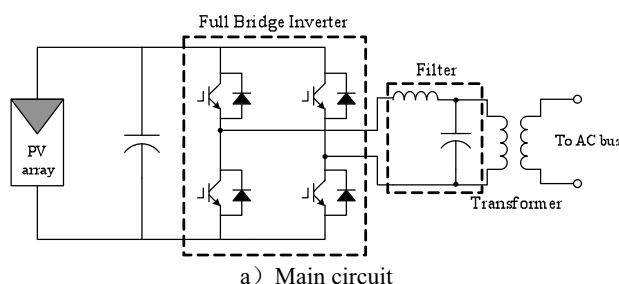


Fig.1: Schematic diagram of a Laboratory-Scale Microgrid

### B. Distributed generators simulator (PV simulator)

Based on the I-V curves of a PV module, a PV simulator was implemented by regulate the output of a DC Regulated Power Supply [15].

The PV simulator is actually a DC voltage source, which is connected to the AC-grid by means of a DC-AC inverter. The topology for the PV inverter is a single-phase, self commutated PV system, as shown in Fig. 2. The main circuit of the inverter includes a filter capacitor, a full-bridge converter and a LC filter which is limiting the high frequency harmonics injected into the AC system. The inverter can work in MPPT or V-constant mode, and a synthesized AC output voltage is produced by appropriately controlling the switches of the full-bridge converter.



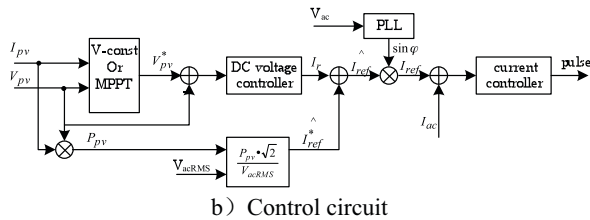


Fig. 2: Single-stage Grid-connected Photovoltaic System

C. Distributed generators simulator (Wind simulator)

In order to examine and to test the behavior of the wind turbine, a simulator for wind turbine was installed in the laboratory-scale microgrid system. As we know, the torque of wind turbine can be calculated by [16],[17]:

$$T_f = \frac{1}{2} \rho \pi C_T(\lambda) v^2 R^3 \quad (1)$$

Where  $\rho$  is the air density,  $v$  is wind speed, R is the rotor radius of wind turbine,  $\lambda$  is the tip speed ratio,  $C_T(\lambda)$  is the torque coefficient which can be calculated by:

$$C_T(\lambda) = a_0 + \sum_{i=1}^6 a_i \lambda^i \quad (2)$$

So the wind turbine can be simulated by a driving motor which is controlled by a frequency converter in torque mode, as shown in Fig. 3. The motor is driving a three-phase induction generator with an output of 1kW [18].

Comparing to the PV inverter, there is another “Turbine” operating mode, as shown in Fig.4. The diagram shows the ramp function of a typical power/voltage curve. The feed-in AC power depending on the DC input voltage of the inverter is shown here. The adjustable parameters  $U_{DCstart}$  and  $U_{DCMax}$  are used to adapt the power/voltage curve of the wind turbine inverter being used.

D. Energy storage system

For the fluctuating energy generation by solar or wind energy and the fluctuating energy demand, a battery storage unit with a bi-directional inverter can be applied to ensure the power balance and stable operation of the microgrid system.

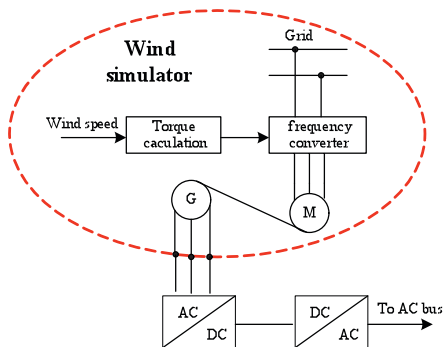


Fig.3: Wind Turbine Simulator configuration

The structure of the bi-directional inverter, which is the key component of the laboratory-scale microgrid, is shown in Fig.5. It is a two-stage topology consists of a DC-AC voltage source PWM inverter with a CUK DC-DC converter. The DC-AC full bridge inverter can operate in four-quadrant by means of pulse width modulation., while

the CUK DC/DC converter, can provide the constant DC voltage to the DC/AC converter input, The HF transformer provides electrical isolation between battery and the grid.

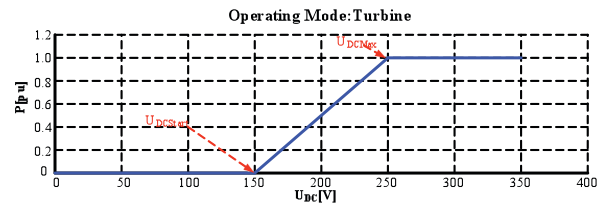


Fig.4: Turbine operation mode of the inverter

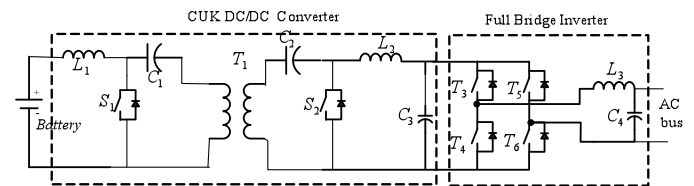


Fig.5: Power section of the battery inverter

E. Microgrid Central Controller

The functions of Microgrid Central Controller range from monitoring the actual active and reactive power of the distributed resources, voltage and frequency of the AC bus. Also it is responsible for the maximization of the microgrid value and the optimization of its operation by sending control signal settings to the distributed resources and controllable loads via communication lines [19]. In this paper, RS485 communication lines are used to realize this function.

III. CONTROL OF THE LABORATORY-SCALE MICROGRID SYSTEM

In microgrid, there are two steady states of operation, Mode-G and Mode-I. Also there are two transient modes of operation, transfer from Mode-G to Mode-I and transfer from Mode-I to Mode-G. The key issue of the control is how to maintain the voltage and frequency stability of the laboratory-scale microgrid.

A. Control of steady states mode

During Mode-G operation, the voltage and frequency of the microgrid is set by the main grid, the PV simulator and wind simulator, are non controllable distributed generators, supplies constant active power output, none of them contributes to the control of the microgrid voltage and frequency. The bi-directional inverter become “grid-following unit”, also has a constant power output. The aim of the battery inverter control is to obtain energy backup as much as possible, so during Mode-G operation, the main grid, the microgrid or both of them, will charge the battery.

While switched from Mode-G to Mode-I, the bi-directional inverter operates in voltage control mode, is setting the voltage and frequency of the microgrid through absorbing or releasing energy. During Mode-I operation, a special case should be considered, when the batteries are fully charged and the power available from the distributed

generators exceeds the power required by the connected loads, to prevent the excess energy from overcharging the batteries, the battery inverter recognizes this situation and changes the frequency of the AC output. As soon as the grid frequency increases beyond the value specified by “ $F_{Start}$ ”, the distributed generators limits its output power accordingly, as shown in Fig. 6.

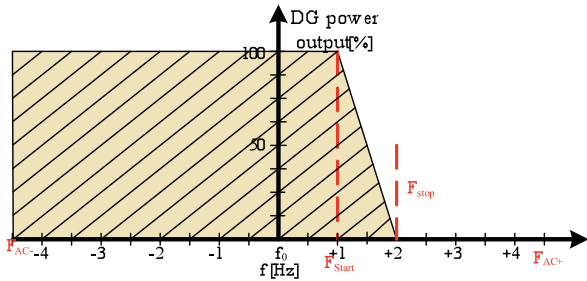


Fig.6: MICROGRID frequency control in Mode-I

*B. Transition between Mode-G and Mode-I*

As mentioned above, there is a different control strategy when the laboratory-scale microgrid system operates in Mode-G or Mode-I. If there is a transition between these two modes, the control mode of the battery inverter will change. A switching circuit, as shown in Fig.7, is designed to realize this transition [20].

The basic idea of the configuration shown in Fig. 7 is to switch the microgrid between the Mode-G and Mode-I. For this purpose, the “AC input” detected the absence or fault of grid voltage and ordered the switch K to open, then the normal open relay contact open, disconnecting the microgrid from the grid. After the grid restoration, the battery inverter detected the voltage presence and switch K closed, then the normal open relay contact close, interconnecting the microgrid to the grid.

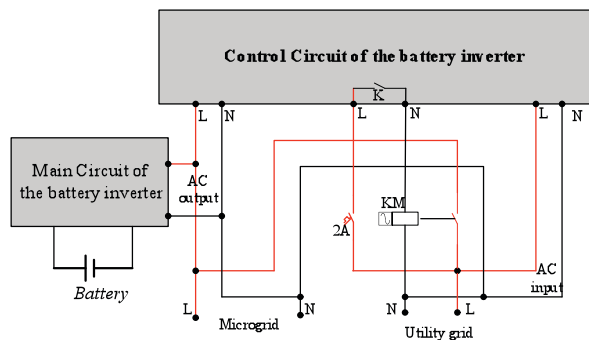


Fig.7: Transition between Mode-I and Mode-G

IV. EXPERIMENTAL RESULTS

For the laboratory-scale microgrid, based on the control strategies of the micro sources and the battery energy storage, a series of experiments were carried out, the power output of the distributed generators and battery, voltage and frequency of the AC bus were real-time measured and analyzed by the Power Quality Analyzer.

*A. Mode-I operation experiment*

Fig.8 gives the Mode-I operation curve of different operating conditions.

Initially, the PV simulator and the battery inverter are paralleling operation, feeding a local load of 0.2kW. In this phase, the PV simulator has a constant power output, and the battery inverter, which is working in constant V/f control, is setting the voltage and frequency of the microgrid. As shown in Fig. 8, the voltage and frequency of the microgrid is 230V, 50Hz.

At  $t_1$ , the wind simulator is connecting to the microgrid. With gradually increasing of the wind simulator power output, there is no change of the PV simulator power output. However the battery will decrease its output for the balance of the power. Due to the excessive power generation, the microgrid will charge the battery, as shown in Fig.9. However, the voltage and frequency of the microgrid is still constant.

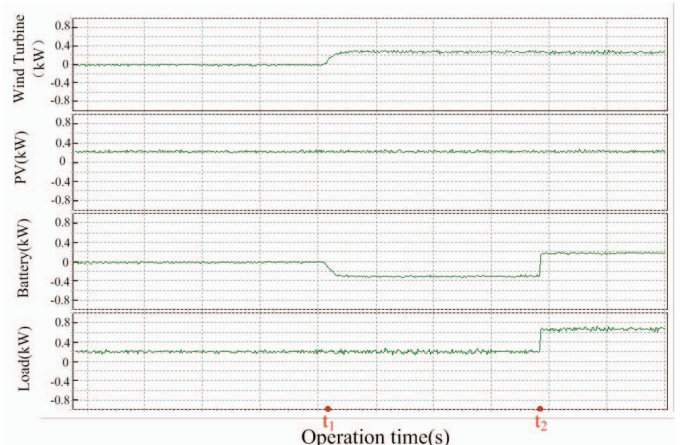
At  $t_2$ , there is a suddenly change of the local load, from 0.2kW to 0.7kW. Because of the constant output of the distributed generators simulator, the battery power output will increase from -0.3kW to 0.2kW correspondingly. This means that the battery inverter will change its operation mode from charging to discharging.

In the Mode-I experiment, whether the suddenly change of distributed generators or local load, the energy requirement will be supplied immediately by the battery and the constant voltage and frequency will be maintained.

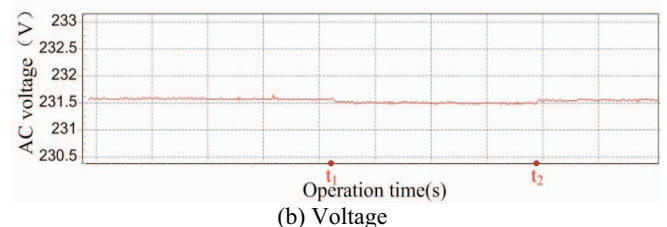
*B. Transfer from Mode-I to Mode-G*

While switching from Mode-I to Mode-G, the voltage and frequency should be maintained within acceptable limits. The dynamic response process is shown in Fig. 9.

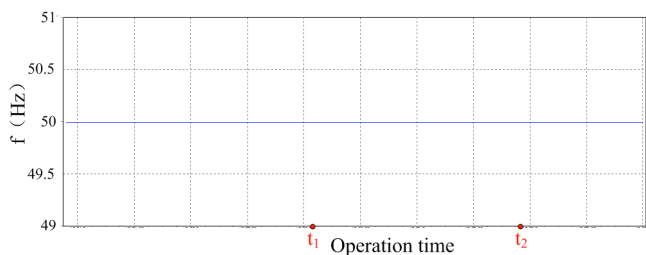
At  $t_3$ , the microgrid is synchronized to the grid and its voltage and frequency become equal to the values of the network. The PV simulator and wind simulator maintain constant power output and the battery will be charged by the grid. As shown in Fig.9, the voltage and frequency will fluctuate accordingly with the grid.



(a) Active power



(b) Voltage



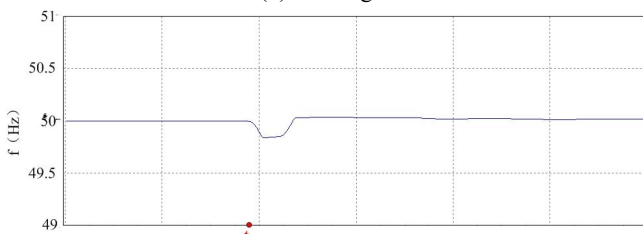
(c) Frequency  
Fig.8: MICROGRID Mode-I operation



(a) Active power



(b) Voltage

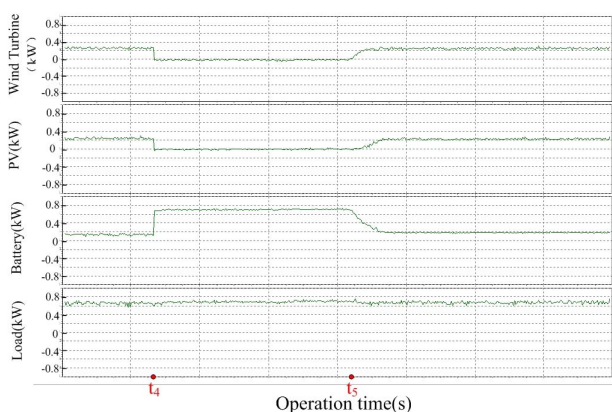


(c) Frequency

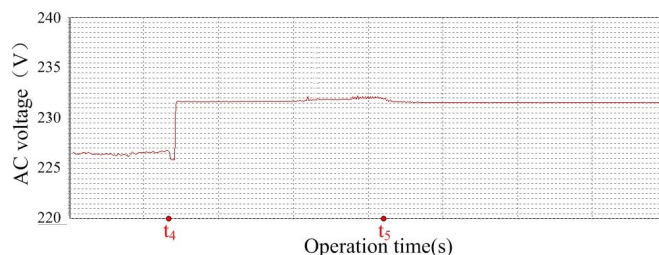
Fig.9: Transition from Mode-I to Mode-G

C. Transfer from Mode-G to Mode-I

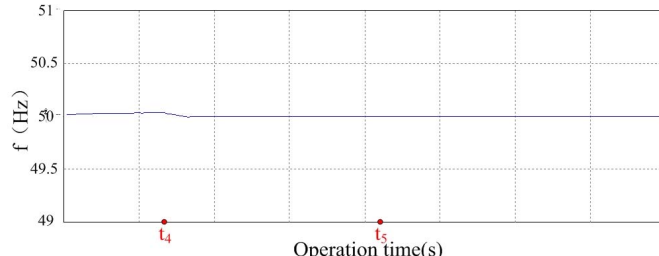
Also the voltage and frequency should be maintained within acceptable limits when switching from Mode-G to Mode-I. The dynamic response process is shown in Fig. 10.



(a) Active power



(b) Voltage



(c) Frequency

Fig.10: Transition from Mode-G to Mode-I

At  $t_4$ , the microgrid is disconnected from the grid and returns to Mode-I operation. During this transition, the voltage and frequency will decrease slightly. For the safe operation, the distributed generators will disconnect from the microgrid (the output power become zero), the battery will increase its power output accordingly for the power balance of the system. Due to the voltage/frequency control of the battery inverter, the voltage and frequency of the microgrid are restored to the nominal value. Then at  $t_5$ , the distributed generators will connect to the microgrid again and return to its initial operating state.

From the voltage and frequency behaviors in Fig. 9 and Fig. 10, it may be observed that microgrid stability is not lost when facing transition between Mode-G and Mode-I.

V. CONCLUSION

In this paper, a laboratory-scale microgrid system has been set up, two generators, PV generator and wind generator, are simulated successfully, and the storage devices are absolutely essential to implement successful control strategies for microgrid Mode-I operation. The operation experimental results show that the laboratory-scale microgrid system can operate in Mode-G or Mode-I and hence increase the reliability of energy supplies, with a seamless transfer from the one mode to the other.

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