

# Multiple-Time-Scales Hierarchical Frequency Stability Control Strategy of Medium-Voltage Isolated Microgrid

Zhuoli Zhao, Ping Yang, Josep M. Guerrero, Zhirong Xu, and Timothy C. Green

**Abstract**—In this paper, an islanded medium-voltage (MV) microgrid placed in Dongao Island is presented, which integrates renewable-energy-based distributed generations (DGs), energy storage system (ESS), and local loads. In an isolated microgrid without connection to the main grid to support the frequency, it is more complex to control and manage. Thus in order to maintain the frequency stability in multiple-time-scales, a hierarchical control strategy is proposed. The proposed control architecture divides the system frequency in three zones: (A) stable zone, (B) precautionary zone and (C) emergency zone. In this way, dynamic stability control that cope with disturbances in short-time scale is implemented by microgrid central controller (MGCC) within Zone B and Zone C. Meanwhile, steady-state stability control to solve the peaks and valleys problem of loads and DGs in long-time scale is executed by microgrid energy management system (MEMS) within Zone A. Furthermore, based on the developed complete small-signal state-space model, sensitivity analysis of the eigenvalues is conducted in order to reveal the dynamic stability margin of the MV microgrid, and to identify the proper range of the control parameters of Zone B. Theoretical analysis, time-domain simulation and field test results under various conditions and scenarios in the Dongao Island microgrid are presented to prove the validity of the introduced control strategy.

**Index Terms**—Microgrid, frequency stability, multiple-time-scales, microgrid central controller (MGCC), microgrid energy management system (MEMS), stability analysis.

## I. INTRODUCTION

The increasing penetration of renewable-energy-based distributed generations (DGs) in distribution networks promotes the emergence of new changes in power generation, transmission and distribution. Integrated DGs, energy storage systems (ESS), and local loads within a certain area, microgrid is an effective way to achieve active distribution networks, which can reduce the impact

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of large penetration of intermittent renewable energy integrated into the electrical grid, making the power system more reliable, safe, clean, and economical [1]–[3]. Microgrids combined with coordinated control, relaying protections, and intelligent dispatching systems, can operate in either grid-connected mode to exchange power with the main grid [4], or in islanded mode when applied in remote areas, islands or faults occur in the external power grid. Isolated microgrids, often named minigrids, are autonomous systems that can achieve self-control, protection and management [5], [6].

In recent years, many related technologies on islanded operation of microgrid have been developed, such as energy management [7]–[8], decentralized and hierarchical control [9]–[11], power quality compensation [12]–[13], and protection schemes [14]–[15], applied to laboratory systems or demonstration projects [16]–[20]. During islanded operation, without a fast and effective power balance strategy, frequency may present high fluctuations and instabilities due to the high penetration of intermittent renewable energy [21]. Power electronic converters based DGs play a significant role in maintaining the stability of microgrids, since they show faster transient response and higher controllability than conventional rotating machines interfaced DGs [22]–[24]. Normally, power electronic converters based DGs can be connected to the microgrid through three major kinds of interfaces: grid-forming, grid-feeding, and grid-supporting power converters [22], [25]. Grid-forming power converters are utilized as voltage source in the absent of master unit in a microgrid. Actually, most of the renewable-energy-based DGs are controlled in grid-feeding mode as current source, thus they cannot directly control the frequency and voltage in microgrid. On the other hand, grid supporting power converters can be controlled as voltage source or current source based on droop concept. Generally, the major purpose is to participate in the regulation of the frequency and voltage amplitude of the microgrid through controlling the active and reactive power injection or absorption.

Originally applied in line-interactive UPS systems, voltage-source-based grid supporting approach have been widely extended to parallel inverters control in inverter-based microgrid [4]. Frequency and voltage magnitude droop control architectures are proposed to stabilize the frequency and voltage of microgrids, and to achieve power sharing in a decentralized manner during islanded operation [6], [26], [27]. However, it is shown that frequency and voltage deviations are inevitable, and accurate reactive power sharing are challenged due to the impact of mismatched feeder impedance [28], [29]. Also, system stability and dynamic are highly affected by the selected droop gains [6]. Furthermore, to obtain accurate power-sharing performance with a high droop gain, the microgrid may experience oscillations and instabilities [30]–[32]. To solve the power control problems, secondary control has been recently addressed based on extra communication system [9], [33], [34]. However, the proposed methods exist fundamental conflict that the secondary voltage control can worsen the already poor sharing of reactive power, while enforcing reactive power sharing can result in poorer voltage profiles than with only primary control conversely [35]. Moreover, most of the microgrid control structures reported in the current literature are proposed for particular microgrids only formed by ideal parallel inverters, which neglect the dynamic of the primary sources, thus being inappropriate to integrate the diversity of DGs in a certain area.

Recently, a few coordinated methods have been proposed to support the frequency and voltage in a multi-source microgrid that includes renewable-energy-based DGs and ESS. In [36], an improved grid-forming control scheme is developed, which can keep the charging voltage of battery banks under control without physical communication. A coordinated control architecture for power management of islanded microgrids is proposed in [37] where the flexible power control of each DG unit can be achieved with seamless modes changes. However, experimental results in [36] and [37] show that the steady-state frequency deviates from the nominal value seriously. In [38], the novel grid-feeding control (GFC) scheme is presented in ESS. It can be also observed that this control method is only capable of dealing with the disturbance of wind-speed variations. Incorporating the current-source-based grid supporting control (GSC) approach, the control concept in [5] includes load-frequency primary control and secondary control, which mimics the frequency control method in interconnected power systems. Furthermore, [39] extends the primary and secondary control from frequency to voltage. In regards to dynamic stability control in short-time scale, the aforementioned control schemes are not sufficient to guarantee the microgrid frequency stability for large transients, such as sudden huge load demands or faults. In the case of multi-source microgrids, a damping method to mitigate the underlying oscillation due to the introduction of GSC approach is not reported in the current literature. On the other hand, the power reserve management is a vital task for microgrid operation in long-time scale. Optimizing microgrid operation using model predictive control approach is presented in [40]–[41] where operation constraints and time-varying request are satisfied. In [42]–[43], multiagent system for real-time operation of a microgrid is studied to maximize the power production of DGs while maintaining the stability. However, the existing control strategies greatly increase the complexity of microgrid energy management, and are only verified in simulation or laboratory test beds. Therefore, it is necessary to develop effective steady-state stability control approach in long-time scale with high applicability and reliability, where the operation modes and the power supply scheduling of microgrid can be optimized or regulated according to the availability of renewable resources, load conditions, and state of charge (SoC) of the ESS.

Motivated by the above-mentioned difficulties, this paper introduces a multiple-time-scales hierarchical frequency stability control architecture with the capability to operate stably and reliably at different conditions. The control architecture is implemented in the medium-voltage (MV) microgrid demonstration project of Dongao Island in China. By using the proposed control strategy, the system frequency is divided into three zones: (A) stable zone, (B) precautionary zone, and (C) emergency zone. The dynamic stability control for short-time scale is implemented by the microgrid central controller (MGCC) within Zone B and Zone C, while steady-state stability control for long-time scale is executed by the microgrid energy management system (MEMS) within Zone A. In order to analyze and ensure stability of the MV isolated microgrid system, a complete small-signal state-space model of the microgrid which containing diesel generator set (DGS), battery energy storage system (BESS), squirrel cage induction generator (SCIG) wind turbine (WT), network and loads is established. The developed state-space model is adopted to analyze the dynamic stability margin of the microgrid and to identify the proper range of key control parameters. Theoretical analysis, simulation and

site experimental results are used to verify the effectiveness of the proposed control strategy.

This paper is organized as follows. Section II illustrates the system configuration and control structure of the isolated MV microgrid. Section III describes the proposed frequency stability control strategy. The detailed small-signal dynamic model of the MV microgrid and corresponding stability analysis are presented in Section IV. In Section V, simulation and experimental results in the Dongao Island microgrid are presented. Finally, conclusion is given in Section VI.

## II. MV ISOLATED MICROGRID SYSTEM IN DONGAO ISLAND

### A. System Configuration

Fig. 1 shows the hierarchically controlled MV microgrid in Dongao Island. This microgrid includes four 10-kV busbars, i.e., BUS-1, BUS-2, BUS-3 and BUS-4, three DGSs, four SCIG WTs, one BESS, six distribution substations (DSs), and several load banks. Interconnection of these components is achieved through 10-kV MV lines. The BESS is connected to BUS-2 via a 380 V/10 kV step-up transformer, which is located geographically near to the point of common coupling (PCC) of the SCIG WTs and residential loads. Besides, the load is composed of six DSs (DS1–DS6: unconnected in this work for the sake of safety) and adjustable load banks. These 10-kV adjustable load banks consist of RLC (resistance, inductance, and capacitor) branches, which are specially used in the field test and can be controlled automatically by remote signals. Details about the component parameters of the MV microgrid system are listed in Tables II and III.

### B. Microgrid Control Architecture

Microgrid unified control system uses a hierarchical control structure, which comprises three control levels: (i) the local control layer, (ii) the centralized control layer, and (iii) the main station energy management layer, as presented in Fig. 1. The communication among the devices, the MGCC and the main station is performed by using the IEC61850 standard protocol. High-speed Ethernet data communication channel is implemented by using fiber optic ring network between the local control layer and the centralized control layer, which rapidly transmits the wide-area measurement sampled-value (SV) messaging, the device event data based on generic object-oriented substation event (GOOSE) network and the clock synchronization data based on the IEEE1588 standard. Thus, the data in these three networks achieved interconnectivity. Furthermore, Global Positioning System (GPS) devices provide a unified synchronization service for all apparatus in the different levels. Details of the three control levels

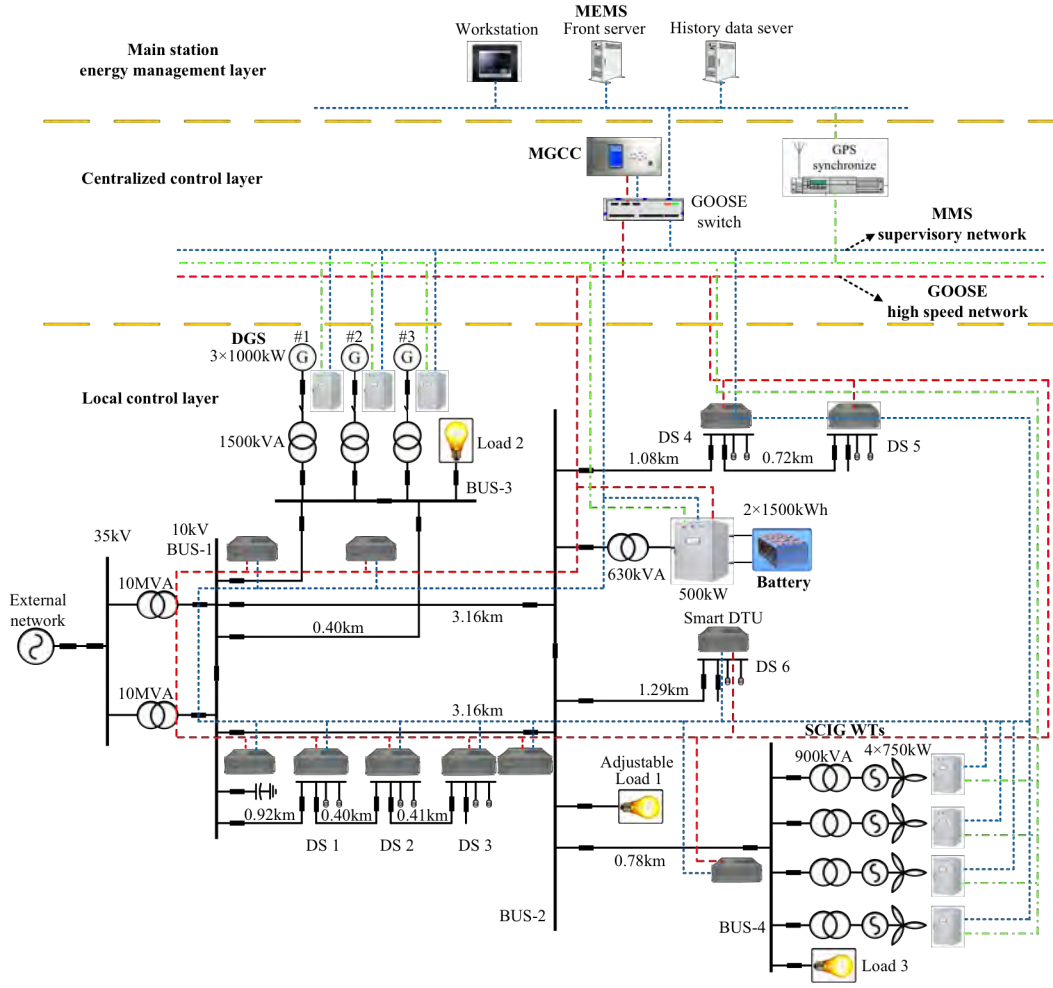


Fig. 1. Single-line diagram and hierarchical control structure of the Donggao Island MV microgrid.

are described as follows:

1) Local control layer is mainly composed of local intelligent terminals, i.e., smart distribution terminal unit (DTU), SCIG WT control system, DGS control system and BESS power conversion system. This layer automatically completes the wide-area data measurement, collection, and the operating conditions identification for the devices. The devices in the local control layer are required to provide two types of communication:

(a) High-speed GOOSE/SV for transmitting data between local control, protection units and MGCC. Moreover, the data must be transmitted with a 5-ms transmission interval.

(b) IEC61850 Manufacturing Message Service (MMS) layer for transmitting the steady-state data from field measurement and control devices to the main station, with a data refresh interval that cannot exceed two seconds.

2) Centralized control layer is responsible for the dynamic stability control, which is implemented by the MGCC.

3) Main station energy management layer is the top layer, equipped with MEMS that provides functionalities such as monitoring, comprehensive data acquisition and processing, steady-state stability control, and optimal dispatch.

### III. MULTIPLE-TIME-SCALES HIERARCHICAL FREQUENCY STABILITY CONTROL STRATEGY IMPLEMENTATION

The objective of the frequency stability control strategy is to maintain the system frequency within the allowed range. Therefore, to mitigate frequency fluctuations due to the variations or switch on/off of distributed renewable resources and loads, additional control measures should be taken to remain the active power balance in the multiple-time-scales. Based on the frequency dynamic behaviors characteristic and the real-time values, the frequency stability control strategy of the microgrid system is divided into three zones, including stable zone, precautionary zone and emergency zone, which is referred in this paper as Zones A, B and C, respectively, as shown in Fig. 2. These proposed three zones reflect the level of frequency stability and are organized as follows.

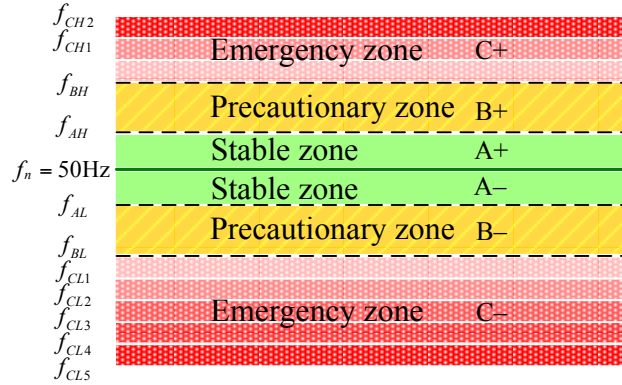


Fig. 2. Hierarchical frequency control strategy for the isolated microgrid.

- 1) **Zone A:** The frequency range in the frequency stable zone is  $f_{AL} < f < f_{AH}$ . Frequency deviation is minimal in this zone and frequency stable zone preventive control (FSZPC) is required to execute in long-time scale. Note that the allowable limit of the frequency deviation in interconnected grid is  $\pm 0.2$  Hz in UCTE (Continental Europe) or  $\pm 0.1$  Hz in North America [44]. The normal frequency fluctuation range of an isolated microgrid is greater than that of interconnected power systems since the capacity of a microgrid is comparatively small. Thus the allowable frequency deviation is set to  $\pm 0.3$  Hz, which is less strict than in conventional power systems.
- 2) **Zone B:** The frequency range in the frequency precautionary zone is  $f_{BL} < f \leq f_{AL} \ \& \ f_{AH} \leq f < f_{BH}$ . When the frequency deviates from permissible frequency fluctuation range, frequency precautionary zone preventive control (FPZPC) that uses the buffering and regulating effect of the BESS has the responsibility to restore the frequency to Zone A. The selection of the border of Zone B ( $f_{BL}, f_{BH}$ ) is discussed in Section V-A.
- 3) **Zone C:** The frequency range in the frequency emergency zone is  $f_{CL} \leq f \leq f_{BL} \ \& \ f_{BH} \leq f \leq f_{CH}$ . When the frequency is deviated dramatically and is unavoidable to fall into Zone C, BESS is unable to restore the frequency back to Zone B effectively as the unbalanced power in the microgrid might have exceeded the charging/discharging limits of the BESS. Meanwhile, the DG units will trip off because of individual under/over-frequency protection. Therefore, in this case, frequency emergency zone preventive control (FEZPC) that results in sequential under-frequency load shedding (UFLS) and over-frequency generator tripping (OFGT)

is supposed to restore the system frequency and protect the microgrid against a blackout.

Consequently, frequency stability control strategy of isolated microgrid comprises the dynamic stability control and steady-state stability control based on different requirement of time scales. Dynamic stability control is composed of FPZPC in Zone B and FEZPC in Zone C, which is implemented by the MGCC within 65 ms through the high-speed GOOSE network. The MGCC is the last line of defense to ensure the safe and stable operation of the microgrid. On the other hand, steady-state stability control refers to the FSZPC in Zone A, which is executed by MEMS every 5 s through MMS supervisory network. It can be concluded that the hierarchical stability control strategy works in a status switching flowchart, as shown in Fig. 3.

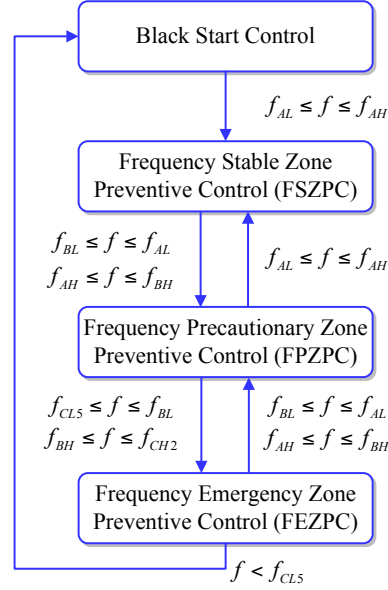


Fig. 3. Status switching flowchart for the hierarchical stability control strategy.

#### A. Frequency Stable Zone Preventive Control in MEMS

When the microgrid is operating in isolated mode, it is essential to monitor for frequency of the system, generated power of the DG units, SoC of the BESS and the load condition in real time. If relevant variables exceed the limits, appropriate means of regulation must be implemented. For instance, regulation of dispatchable DG units, start-up/shutdown of DG units, interruption/recovery of loads, and so forth. FSZPC in MEMS can solve the operation problem of frequency deviation in long-time scale caused by peaks and valleys of load consumption and wind power generation. The control objective of FSZPC is to maintain the microgrid system with sufficient spare capacity, which can guarantee the system to cope with large fluctuations in wind power and equipment failures. Meanwhile, the SCIG WTs power generation should be maximized. The flowchart representing the FSZPC in MEMS is depicted in Fig. 4.

Initially, the load rate of the DGS  $\eta$  is detected. When  $\eta$  is higher than the load rate upper limit  $\eta_H$ , the program determines whether the condition is satisfied to turn on the WT first. If *Criterion 1* is satisfied, the command of WT start-up will be issued. Nevertheless, if the conditions are not met, the discharging conditions of BESS is checked: “if  $P_{BESS}$  is less than discharging power

limit  $P_{Bd\max}$  and SoC is greater than  $SoC_{MEMS\min}$ , then the discharging power of BESS is increased; otherwise the DGS will be turned on afterwards". On the other hand, when  $\eta$  is below the load rate low limit  $\eta_L$ , the charging conditions of BESS is checked: "if  $P_{BESS}$  is less than charging power limit  $P_{Bc\max}$  and SoC is less than  $SoC_{MEMS\max}$ , then the charging power of BESS is raised; if the conditions are unsatisfied, then the DGS or WT will be shut down according to Criterion 2". Otherwise, when  $\eta$  is inside the limits ( $\eta_L \leq \eta \leq \eta_H$ ),  $P_{BESS}$  will be restored to zero if  $\eta_L \leq \eta \cdot P_{DGS} - P_{BESS} \leq \eta_H$  is satisfied. Then, the BESS performs maintenance program once SoC is out of the range of low/upper threshold for MEMS, i.e.,  $SoC_{MEMS\min}$  and  $SoC_{MEMS\max}$ . The detailed description of the commands and criteria in the flowchart are as follows:

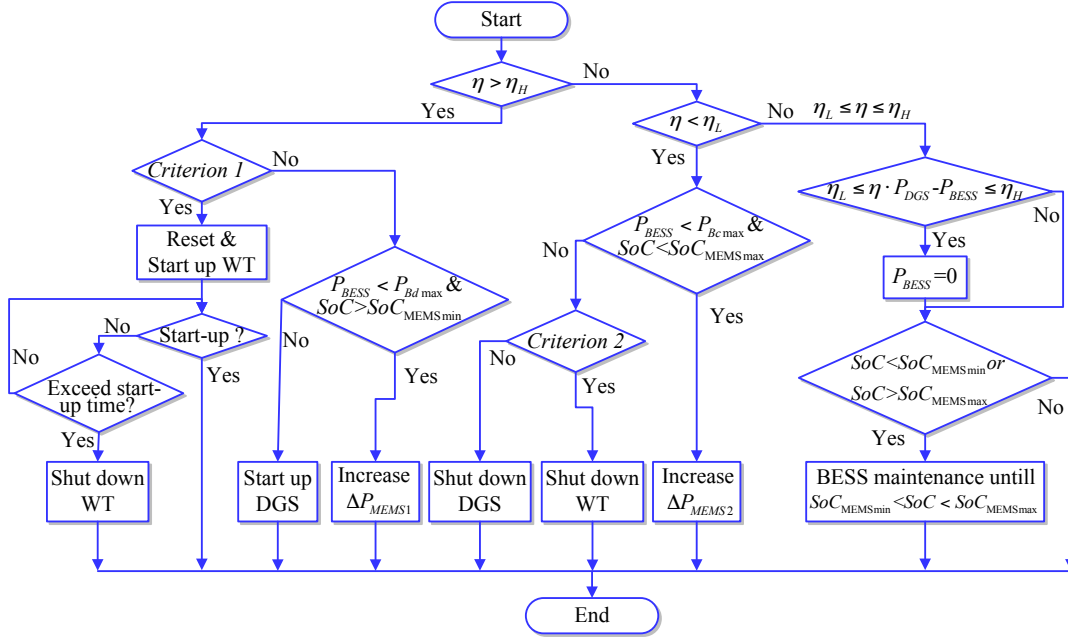


Fig. 4. FSZPC flowchart of MEMS.

1) *BESS commands*: The adjusting commands of the BESS are designed as follows:

$$\begin{aligned} \Delta P_{MEMS1} &= P_{DGS} - \Delta P_{aim\_up} \\ &= P_{DGS} - (P_{upper\_limit} - (P_{upper\_limit} - P_{low\_limit}) \times K_{osc}) \end{aligned} \quad (1)$$

$$\begin{aligned} \Delta P_{MEMS2} &= P_{DGS} - \Delta P_{aim\_down} \\ &= P_{DGS} - (P_{low\_limit} + (P_{upper\_limit} - P_{low\_limit}) \times K_{osc}) \end{aligned} \quad (2)$$

subjected to:

$$\text{power constraints} \quad \Delta P_{MEMS1}, \Delta P_{MEMS2} < K_{reg} \cdot P_{DG\text{Rate}} \quad (3)$$

$$\text{sensitivity constraint} \quad P_{BESS} - P_{MEMS} > K_{sen} \quad (4)$$

where  $\Delta P_{MEMS1}$  and  $\Delta P_{MEMS2}$  are the commands corresponding with load rate exceeding  $\eta_H$  and  $\eta_L$ ,  $P_{upper\_limit}$  and  $P_{low\_limit}$  are the upper limit and the low limit of the DGS output power,  $K_{osc}$  is the oscillation coefficient,  $K_{reg}$  is the regulating coefficient,  $P_{BESS}$

is the measured active power value of BESS,  $P_{MEMS}$  is the power command for the BESS and  $K_{sen}$  is the sensitivity coefficient, respectively. Note that the purpose of introducing the coefficient  $K_{osc}$  is to prevent the oscillation due to repetitively regulating BESS nearby the limits. Thus, the regulating objective is narrowed. Besides,  $\Delta P_{MEMS}$  is restricted with power constraints; no repetitive instruction is issued if sensitivity constraint is not satisfied.

2) *Criteria of start-up/shutdown of WTs*: First, the penetration rate of wind power in the microgrid can be defined as follows:

$$S_{pr} = \frac{P_{WT\_T}}{P_{DGS\_T} + P_{WT\_T}} \quad (5)$$

where  $P_{DGS\_T}$  and  $P_{WT\_T}$  are the total capacity of the DGS and WTs in operation, respectively. Thus, the condition of starting up a WT (*Criterion 1*):

$$\begin{cases} \text{a) } \eta > \eta_H \\ \text{b) } S_{su} \leq S_{pr1} \\ \text{c) } \Delta P_{sc} \geq k_{WT} \cdot P_{WTrate} \end{cases} \quad (6)$$

where  $S_{su}$  is the penetration rate after starting up a WT,  $\Delta P_{sc}$  is the spare capacity of the DGS,  $k_{WT}$  is the impact coefficient of WT start-up, and  $P_{WTrate}$  is the rated power of the SCIG WT. Note that the regulating and impact resistance capability of the MV microgrid system improves with the increasing of the DGS in operation. Therefore, to upgrade the utilization rate of the WTs in the microgrid,  $\eta_H$  should be reduced reasonably based on the quantity of DGS  $N$ . The condition of shutting down a WT (*Criterion 2*):

$$\begin{cases} \text{a) } \eta < \eta_L \\ \text{b) } S_{rt} > S_{pr2} \end{cases} \quad (7)$$

where  $S_{rt}$  is the real-time penetration rate.

### B. Frequency Precautionary Zone Preventive Control in MGCC

When the system frequency is inside the precautionary zone, first, the shortage or the surplus of the active/reactive power in the microgrid system is calculated by the MGCC based on  $f/P$  and  $V/Q$  droop approaches [6], [39]. Then the power commands of the BESS are issued by MGCC through GOOSE channel with a communication delay  $\tau_{cd}$ . The primary objective is to stabilize the system frequency fluctuations caused by the variations of the loads and renewable DGs in short-time scale. Note that by using centralized control schemes for BESS management can ensure the optimum operation of multi BESS easily when integrating more distributed BESS units into the MV microgrid, which is also the case for the future plans in Dongao pilot project. To be mentioned that the time delay of the high-speed GOOSE/SV network is usually considered to be in the order of 60 ms [45]. Therefore, the communication delay is normally negligible in such low-delay network [46]. Detailed analysis about the communication delay

issue is given in Subsections IV-A-6 and IV-B-3.

$$P_{Bref} = P_{MEMS} + K_{fp}(\Delta P) - K_{scl} \cdot \frac{df}{dt} \quad (8)$$

where  $K_{fp}$  is the frequency-active power droop gain,  $f$  is the monitored microgrid frequency,  $f_n$  is the reference frequency of the microgrid,  $K_{scl}$  is the coefficient of the supplementary control loop,  $K_{vQ}$  is the voltage-reactive power droop gain,  $V_{rms}$  is the rms value of the voltage of BUS-2,  $V_n$  is the reference voltage of BUS-2.  $f$  can be obtained by a low-pass filter as follows:

$$f = \frac{\omega_c}{s + \omega_c} f \quad (10)$$

where  $\omega_c$  is the filter cutoff frequency. On this basis, considering the constraints of maximum power limits of charging/discharging, if  $P_{Bref}$  exceeds the charging limit  $P_{Bcmax}$  or discharging limit  $P_{Bdmax}$ , then the reference power command is set to the limit values.

### C. Frequency Emergency Zone Preventive Control in MGCC

If the frequency cannot be effectively controlled by the FPZPC scheme under large disturbances and falling into Zone C, UFLS or OFGT of MGCC is implemented to avoid frequency collapse.

1) *UFLS*: When the frequency of the microgrid decreases to  $f_{CL} \leq f \leq f_{BL}$  region of Zone C, it is necessary to shed some of loads sequentially in accordance with the load levels. UFLS function in FEZPC has five basic stages, as presented in Table I.

TABLE I  
EXECUTION CONDITIONS OF UFLS

| UFLS Stage | Frequency range                          | Delay time       | Shedding load |
|------------|------------------------------------------|------------------|---------------|
| 1st stage  | $\downarrow 48.5\text{--}49.0\text{ Hz}$ | $t \geq t_{uf1}$ | DS6           |
| 2nd stage  | $\downarrow 48.0\text{--}48.5\text{ Hz}$ | $t \geq t_{uf2}$ | DS5           |
| 3rd stage  | $\downarrow 47.7\text{--}48.0\text{ Hz}$ | $t \geq t_{uf3}$ | DS4           |
| 4th stage  | $\downarrow 47.5\text{--}47.7\text{ Hz}$ | $t \geq t_{uf4}$ | DS3           |
| 5th stage  | $\downarrow 45.0\text{--}47.5\text{ Hz}$ | $t \geq t_{uf5}$ | DS2           |

2) *OFGT*: The flowchart of OFGT is illustrated in Fig. 6. It can be seen that when the frequency increases to  $f_{BH} \leq f \leq f_{CH}$  region of Zone C, there are two stages of OFGT configured in FPZPC scheme. To guarantee the system stability under emergency conditions, uncontrollable microsources such as WTs should be disconnected in priority, and controllable microsources DGS may trip from the microgrid afterwards. Nevertheless, note that unreasonable OFGT scheme causes large impact on the frequency since the spare capacity is relatively low in a microgrid. Therefore, OFGT platen that can be used to enable/disable the tripping function of specific DG units is integrated into the sequential logic, which can be configured based on the field test results.

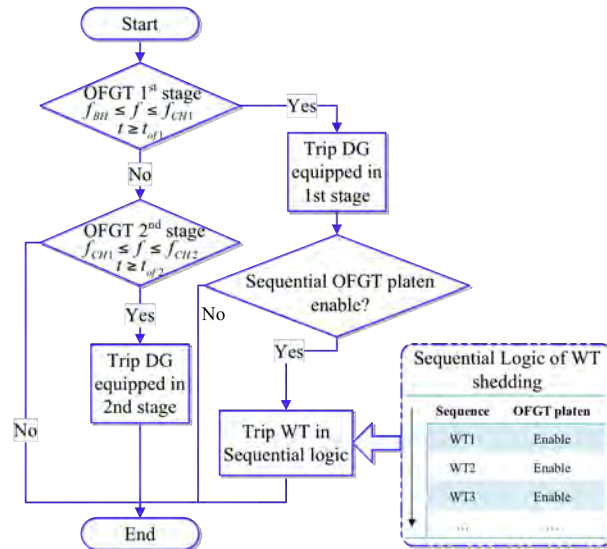


Fig. 6. Flowchart of OFGT.

#### IV. MODELING AND STABILITY ANALYSIS OF THE MV ISOLATED MICROGRID SYSTEM

In order to analyze and ensure system stability, as well as to select the parameters of the FPZPC in Zone B properly, a small-signal state-space model of the MV microgrid is established and presented in Section IV-A. The systematic modeling approach can be readily extended to include more DG units and loads.

##### A. Modeling of the MV Isolated Microgrid System

Fig. 7 shows the equivalent circuit of the microgrid system. The whole dynamic model consists of four major subsystems, i.e., BESS, DGS, SCIG WT and network including loads. Each subsystem is modeled based on its local reference frame. Since the microgrid includes more than one DG units, all interfaced state variables of the subsystems should be transformed to a global reference frame, based on the transformation defined in (11) [48]. The global reference frame of the microgrid ( $dq$ -frame) rotates at the angular frequency of  $\omega_e$ , which is defined on the voltage vector of BUS-3.  $d_D q_D$ -frame,  $d_B q_B$ -frame and  $d_I q_I$ -frame are the local reference frame of DGS, BESS, SCIG WT locked to the rotor of DGS, BUS-2 and BUS-4, respectively; and the corresponding rotating speed is  $\omega_D$ ,  $\omega_B$  and  $\omega_I$ .

$$\begin{bmatrix} \Delta f_q^n \\ \Delta f_d^n \end{bmatrix} = \begin{bmatrix} \cos \delta_n^o & -\sin \delta_n^o \\ \sin \delta_n^o & \cos \delta_n^o \end{bmatrix} \begin{bmatrix} \Delta f_q^g \\ \Delta f_d^g \end{bmatrix} + \begin{bmatrix} -f_d^{no} \\ f_q^{no} \end{bmatrix} \Delta \delta_n \quad (11)$$

In (11),  $\delta_n$  ( $n = D, B, I$ ) is the angle between the local reference frame of the  $n$ th subsystem and the global reference frame;  $\begin{bmatrix} \Delta f_q^n & \Delta f_d^n \end{bmatrix}^T$  and  $\begin{bmatrix} \Delta f_q^g & \Delta f_d^g \end{bmatrix}^T$  are the state variables in the aforementioned frames, respectively. Note that superscript “ $o$ ” denotes the steady-state operating values in the equations of the following subsections.

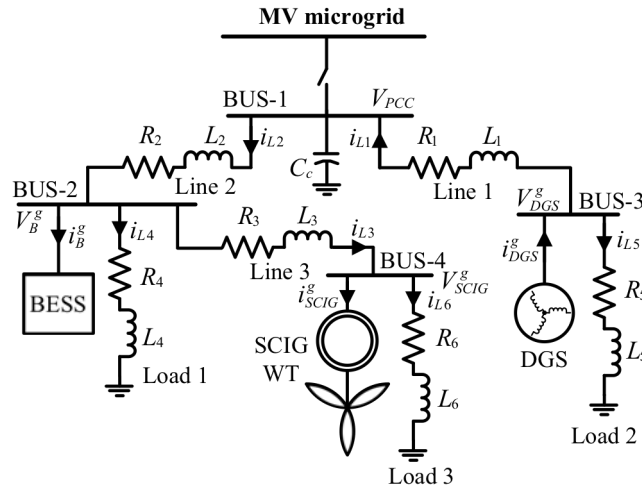


Fig. 7. Equivalent single-line diagram of the microgrid used for stability analysis.

### 1) Dynamic model of BESS

BESS unit is composed of a battery bank, bidirectional conversion system and power circuit, as shown in Fig. 5. The control system is composed of: 1) droop control loop, which is responsible for setting the values of active and reactive power to contribute to the regulation of the microgrid frequency and voltage; 2) power control loop to yield close control dynamic characteristics of the output power; and 3) inner current control loop, which has responsibility to control the current of the filter inductor and limit the inverter fault current.

As illustrated in Fig. 5, the power and current control are achieved with conventional PI controllers (with gains  $K_{pp}$ ,  $K_{ip}$ ,  $K_{pq}$ ,  $K_{iq}$ ,  $K_{p1}$ ,  $K_{i1}$ ,  $K_{p2}$  and  $K_{i2}$ ), including feed-forward terms. Therefore, the dynamic model of the power and current control loop can be derived as:

$$i_{odref}^B = K_{pp}(P_{Bref} - P_{Bout}) + K_{ip} \int (P_{Bref} - P_{Bout}) dt \quad (12)$$

$$i_{oqref}^B = K_{pq}(Q_{Bref} - Q_{Bout}) + K_{iq} \int (Q_{Bref} - Q_{Bout}) dt \quad (13)$$

$$V_{cdref}^B = -K_{p1}(i_{odref}^B - \bar{i}_{od}^B) - K_{i1} \int (i_{odref}^B - \bar{i}_{od}^B) dt + \omega_B L_{Bf} \bar{i}_{oq}^B + \bar{V}_{od}^B \quad (14)$$

$$V_{cqref}^B = -K_{p2}(i_{oqref}^B - \bar{i}_{oq}^B) - K_{i2} \int (i_{oqref}^B - \bar{i}_{oq}^B) dt - \omega_B L_{Bf} \bar{i}_{od}^B + \bar{V}_{oq}^B \quad (15)$$

where  $\bar{i}_{od}^B$ ,  $\bar{i}_{oq}^B$  are the filtered values of the current,  $\bar{V}_{od}^B$  and  $\bar{V}_{oq}^B$  are filtered voltage of BUS-2,  $i_{odref}^B$  and  $i_{oqref}^B$  are the reference values of the converter output current,  $V_{cdref}^B$  and  $V_{cqref}^B$  are the reference values of the converter output voltage. As seen from Fig. 5, the phase lock loop (PLL) is mainly used for microgrid synchronization. And the mathematical model of the PLL is given by

$$\omega_B = (\delta_{ref} - \delta_B)(K_{Bp} + \frac{K_{Bi}}{s}) \quad (16)$$

where  $K_{Bp}$  and  $K_{Bi}$  are the gains of the PI controller.

The power circuit consists of the equivalent resistor  $R_{Bf}$  and inductance  $L_{Bf}$ , which represents the lumped elements of the series filter and the interface transformer. The equations depicted the dynamic of the power circuit are written as

$$\frac{di_{od}^B}{dt} = -\frac{R_{Bf}}{L_{Bf}} i_{od}^B + \omega i_{oq}^B + \frac{1}{L_{Bf}} (V_{od}^B - V_{cd}^B) \quad (17)$$

$$\frac{di_{oq}^B}{dt} = -\frac{R_{Bf}}{L_{Bf}} i_{oq}^B - \omega i_{od}^B + \frac{1}{L_{Bf}} (V_{oq}^B - V_{cq}^B) \quad (18)$$

Thus, the state-space model of the BESS unit consists of the submodules of the control loop and power circuit, which can be established by linearizing the equations of (8)–(10) and (12)–(18). Furthermore, the model of the submodules transferred to the global reference frame using (11) can be derived as (19) and (20), respectively:

$$\Delta x_{B,c}^g = A_{B,c} \Delta x_{B,c}^g + B_{B,c} \Delta x_{B,p}^g + B_{B,c}^u \Delta u_B + B_{B,c}^V \Delta V_B^g \quad (19)$$

$$\Delta x_{B,p}^g = A_{B,p} \Delta x_{B,p}^g + B_{B,p} \Delta x_{B,c}^g + B_{B,p}^u \Delta u_B + B_{B,p}^V \Delta V_B^g + B_B^\omega \Delta \omega_B \quad (20)$$

In (19) and (20)

$$\Delta x_{B,c}^g = \begin{bmatrix} \Delta \bar{V}_{oq}^B & \Delta \bar{V}_{od}^B & \Delta \bar{V}_{cq}^B & \Delta \bar{V}_{cd}^B & \Delta i_{qq} & \Delta i_{pd} & \Delta i_{oq}^B & \Delta i_{od}^B & \Delta V_{qq} & \Delta V_{pd} & \Delta \omega_B \end{bmatrix}^T, \Delta x_{B,p}^g = \begin{bmatrix} \Delta i_{oq}^g & \Delta i_{od}^g \end{bmatrix}^T,$$

$$\Delta u_B = \begin{bmatrix} \Delta Q_{MEMS} & \Delta P_{MEMS} & \Delta V_n & \Delta \omega_n \end{bmatrix}^T, \Delta V_B^g = \begin{bmatrix} \Delta V_{oq}^g & \Delta V_{od}^g \end{bmatrix}^T.$$

Note that  $\Delta i_{qq}$ ,  $\Delta i_{pd}$ ,  $\Delta V_{qq}$  and  $\Delta V_{pd}$  are the state variables represented the integrator states of the power and current controllers.

## 2) Dynamic model of DGS

DGS is composed of three blocks: (i) electrical system of the three-phase salient-pole synchronous generator; (ii) rotating mechanical system; (iii) governor and excitation systems. The mathematic model of the electrical system of DGS in the rotor reference frame  $d_d q_d$  can be expressed as follows:

$$M \frac{d}{dt}(i^D) = Ni^D + v^D \quad (21)$$

where

$$i^D = \begin{bmatrix} i_{Sqs}^D & i_{Sds}^D & i_{kq1}^D & i_{fd}^D & i_{kd}^D \end{bmatrix}^T, v^D = \begin{bmatrix} v_{Sqs}^D & v_{Sds}^D & v_{kq1}^D & e_{fd}^D & v_{kd}^D \end{bmatrix}^T$$

are the current and voltage vectors of the stator windings ( $Sqs, Sds$ ), field winding ( $fd$ ) and the damper windings ( $kq1, kd$ ). The method of deriving matrices  $M$  and  $N$  is presented in [48].

The model of motion of the synchronous generator can be described by:

$$\frac{2H_S}{\omega_b} \frac{d\omega_{Dr}}{dt} + \frac{K_{DS}}{\omega_b} \frac{d\delta_D}{dt} = T_{mS} - T_{eS} \quad (22)$$

where  $H_S$ ,  $K_{DS}$  are the inertia constant and damping factor, respectively.  $\omega_{Dr}$  is the angular velocity of the rotor.  $T_{mS}$  and  $T_{eS}$  are the mechanical and electromagnetic torque, respectively, and

$$T_{eS} = -i_{Sds}^D (-i_{Sqs}^D + i_{kq1}^D) X_{mq} i_{Sqs}^D + (-i_{Sds}^D + i_{kd}^D + i_{fd}^D) X_{md} \quad (23)$$

where  $X_{mq}$  and  $X_{md}$  are the magnetizing reactance.

Please note that  $T_{mS}$  and  $e_{fd}^D$  are the output of the governor and excitation systems, respectively, and can be obtained from IEEE working group [49], [50]. A state-space model of DGS can be constructed by linearizing the equations of (21)–(23). Further, the model transferred to the global reference frame using (11) can be incorporated as follows:

$$\Delta x_{DGS}^g = A_{DGS} \Delta x_{DGS}^g + B_{DGS}^u \Delta u_{DGS} + B_{DGS}^V \Delta V_{DGS}^g \quad (24)$$

$$\text{where } \Delta x_{DGS}^g = \begin{bmatrix} \Delta i_{sq}^g & \Delta i_{sd}^g & \Delta i_{kq1}^D & \Delta i_{fd}^D & \Delta i_{kd}^D & \Delta \omega_{Dr} & \Delta \delta_D \end{bmatrix}^T, \Delta u_{DGS} = \begin{bmatrix} \Delta e_{fd}^D & \Delta T_{mS} \end{bmatrix}^T, \Delta V_{DGS}^g = \begin{bmatrix} v_{sq}^g & v_{sd}^g \end{bmatrix}^T.$$

### 3) Dynamic model of SCIG WT

The dynamic model of SCIG WT consists of: (i) the electrical system of the induction generator, (ii) the wind energy capturing mechanism, and (iii) the rotating shaft. The mathematical model of the induction generator in the local synchronously rotating reference frame  $d_I q_I$  can be expressed by

$$W \frac{d}{dt} (i^I) = Y i^I + v^I \quad (25)$$

where

$$i^I = \begin{bmatrix} i_{Wqs}^I & i_{Wds}^I & i_{Wqr}^I & i_{Wdr}^I \end{bmatrix}^T, v^I = \begin{bmatrix} v_{Wqs}^I & v_{Wds}^I & v_{Wqr}^I & v_{Wdr}^I \end{bmatrix}^T$$

are the current and voltage vectors of the stator ( $Wqs, Wds$ ), and the rotor ( $Wqr, Wdr$ ), respectively. The matrices  $W$  and  $Y$  can be obtained from [48].

The electromagnetic torque of the SCIG can be written in terms of rotor and stator current as

$$T_{el} = X_{MA} (i_{Wqs}^I i_{Wdr}^I - i_{Wds}^I i_{Wqr}^I) \quad (26)$$

where  $X_{MA}$  is the magnetizing reactance.

The shaft system of a SCIG WT unit can be represented by the two-mass model as follows:

$$\frac{2H_I}{\omega_b} \frac{d\omega_{Ir}}{dt} = K_{ss} \theta_{ss} - D_I \omega_{Ir} - T_{el} \quad (27)$$

$$\frac{2H_{Tur}}{\omega_b} \frac{d\omega_W}{dt} = T_{mW} - K_{ss} \theta_{ss} - D_W \omega_W \quad (28)$$

$$\frac{d\theta_{ss}}{dt} = \omega_b (\omega_W - \omega_{Ir}) \quad (29)$$

where  $H_I$ ,  $H_{Tur}$ ,  $D_I$  and  $D_W$  are the inertia constant and damping factor of the induction generator rotor and wind turbine rotor, respectively.  $\omega_{Ir}$  and  $\omega_W$  are the mechanical angular velocity of the induction generator rotor and wind turbine rotor, respectively.  $K_{ss}$  is the shaft stiffness.  $T_{mW}$  is the input mechanical torque of the wind turbine.  $\theta_{ss}$  is the shaft twist angle. The capturing mechanism of wind energy can be described by (30)–(31):

$$T_{mW} = \frac{\rho_A \pi C_W(\lambda, \beta) R_W^2 V_W^3}{2\omega_W} \quad (30)$$

$$\lambda = \frac{\omega_w}{V_w} R_w \quad (31)$$

where  $\rho_A$  is the air density,  $R_w$  is the blade length of wind turbine,  $V_w$  is the wind speed,  $\lambda$  is the tip-speed ratio,  $C_w(\lambda, \beta)$  is the power coefficient, which is a function of  $\lambda$  and the pitch angle  $\beta$  [51].

Thus, using (25)–(31), the linearized state-space model of the SCIG WT in the global reference frame is derived as:

$$\Delta \mathbf{x}_{SCIG}^g = \mathbf{A}_{SCIG} \Delta \mathbf{x}_{SCIG}^g + \mathbf{B}_{SCIG}^u \Delta \mathbf{u}_{SCIG} + \mathbf{B}_{SCIG}^V \Delta \mathbf{V}_{SCIG}^g \quad (32)$$

where

$$\Delta \mathbf{x}_{SCIG}^g = \begin{bmatrix} \Delta i_{Wqs}^g & \Delta i_{Wds}^g & \Delta i_{Wqr}^I & \Delta i_{Wdr}^I & \Delta \omega_r & \Delta \omega_w & \Delta \theta_{ss} \end{bmatrix}^T, \Delta \mathbf{u}_{SCIG} = \begin{bmatrix} \Delta v_{Wqr}^I & \Delta v_{Wdr}^I & \Delta T_{mW} \end{bmatrix}^T, \Delta \mathbf{V}_{SCIG}^g = \begin{bmatrix} \Delta v_{Wqs}^g & \Delta v_{Wds}^g \end{bmatrix}^T.$$

#### 4) Dynamic model of network including loads

As presented in Fig. 7, the dynamic of the network can be modeled in the form of the relationships between current and voltage as

$$V_{DGS}^g - V_{PCC} = R_1 i_{L1} + L_1 i_{L1} \quad (33)$$

$$V_{PCC} - V_B^g = R_2 i_{L2} + L_2 i_{L2} \quad (34)$$

$$V_B^g - V_{SCIG}^g = R_3 i_{L3} + L_3 i_{L3} \quad (35)$$

$$C_c V_{PCC} = i_{L1} - i_{L2} \quad (36)$$

where  $R_n$  and  $L_n$  ( $n=1,2,3$ ) are equivalent impedance of the series  $RL$  branches.  $i_{Ln}$  are the corresponding current vectors.  $V_{PCC}$  is the instantaneous voltage of BUS-1.  $C_c$  is the shunt-capacitor for reactive power compensation. Based on (33)–(36), the dynamic model of the microgrid network can be incorporated as follows:

$$\Delta \mathbf{x}_{NET}^g = \mathbf{A}_{NET} \Delta \mathbf{x}_{NET}^g + \mathbf{B}_{NET}^{V1} \Delta V_{DGS}^g + \mathbf{B}_{NET}^{V2} \Delta V_B^g + \mathbf{B}_{NET}^{V3} \Delta V_{SCIG}^g \quad (37)$$

where  $\Delta \mathbf{x}_{NET}^g = \begin{bmatrix} \Delta i_{qd}^{L1} & \Delta i_{qd}^{L2} & \Delta i_{qd}^{L3} & \Delta V_{qd}^{PCC} \end{bmatrix}^T$ . In addition, the voltage vectors of BUS-3, BUS-2 and BUS-4 can be obtained by

$$V_{DGS}^g = R_5 (i_{DGS}^g - i_{L1}) + L_5 \frac{d(i_{DGS}^g - i_{L1})}{dt} \quad (38)$$

$$V_B^g = R_4 (i_{L2} - i_B^g - i_{L3}) + L_4 \frac{d(i_{L2} - i_B^g - i_{L3})}{dt} \quad (39)$$

$$V_{SCIG}^g = R_6 (i_{L3} - i_{SCIG}^g) + L_6 \frac{d(i_{L3} - i_{SCIG}^g)}{dt} \quad (40)$$

where  $R_n$  and  $L_n$  ( $n=4,5,6$ ) are equivalent impedance of the adjustable load banks. Thus, the linearized equations of the voltage vectors can be written as

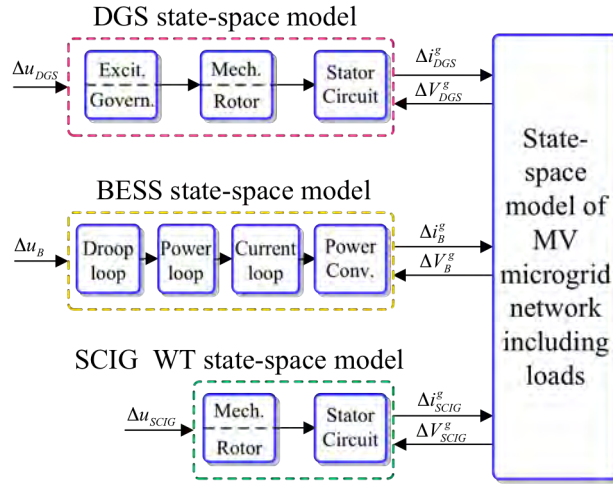


Fig. 8. Block diagram of the complete dynamic model of the MV microgrid.

$$\Delta V_{DGS}^g = D_{NET}^{11} \Delta x_{NET}^g + D_{NET}^{12} \Delta x_{NET}^g + E_{NET}^{11} \Delta x_{DGS}^g + E_{NET}^{12} \Delta x_{DGS}^g \quad (41)$$

$$\Delta V_B^g = D_{NET}^{21} \Delta x_{NET}^g + D_{NET}^{22} \Delta x_{NET}^g + E_{NET}^{21} \Delta x_{B,p}^g + E_{NET}^{22} \Delta x_{B,p}^g \quad (42)$$

$$\Delta V_{SCIG}^g = D_{NET}^{31} \Delta x_{NET}^g + D_{NET}^{32} \Delta x_{NET}^g + E_{NET}^{31} \Delta x_{SCIG}^g + E_{NET}^{32} \Delta x_{SCIG}^g \quad (43)$$

##### 5) Complete dynamic model of MV microgrid with negligible communication delay

Fig. 8 depicts the block representation for establishing the small-signal dynamic model of the MV microgrid with all of the subsystems integrated together. It is worth mentioning that the output current of the DG units  $\Delta i_{DGS}^g$ ,  $\Delta i_B^g$  and  $\Delta i_{SCIG}^g$ , are the input signals of the microgrid network model, while the bus voltages vectors  $\Delta V_{DGS}^g$ ,  $\Delta V_B^g$  and  $\Delta V_{SCIG}^g$ , which can be eliminated using (41)–(43), can be treated as the output of the network and inputs of the DG units. Now, the complete state-space model of the MV autonomous microgrid can be constructed based on (19), (20), (24), (32) and (37):

$$\Delta x_{MVMG} = A_{MVMG} \Delta x_{MVMG} + B_{MVMG} \Delta u_{MVMG} \quad (44)$$

where  $\Delta x_{MVMG} = [\Delta x_{DGS}^g \quad \Delta x_{B,p}^g \quad \Delta x_{B,c}^g \quad \Delta x_{SCIG}^g \quad \Delta x_{NET}^g]^T$ ,  $\Delta u_{MVMG} = [\Delta u_{DGS} \quad \Delta u_B \quad \Delta u_{SCIG}]^T$ .

##### 6) Microgrid dynamic model considering communication delay

In order to carry out the delay-dependent stability analysis of the proposed FPZPC scheme of Zone B in Subsection IV-B-3 and show its robustness in the presence of communication delay, the state-space model of (44) is extended to consider a communication delay time  $\tau_{cd}$  for the data transmission between MGCC and BESS, as depicted in Fig. 5. In this case, the equations of (8)–(9) should be modified as

$$P_{Bref} = P_{MEMS} + K_{fP} (f(t - \tau_{cd}) - f_n) - K_{scl} \cdot \frac{df(t - \tau_{cd})}{dt} \quad (45)$$

$$Q_{Bref} = Q_{MEMS} + K_{VQ} (V_{rms}(t - \tau_{cd}) - V_n) \quad (46)$$

Therefore, the state-space model of the microgrid system based on delay differential equations (DDEs) can be given by

$$\Delta x_{MVMG}(t) = A_{MVMG-NCD} \Delta x_{MVMG}(t) + A_{MVMG-CD} \Delta x_{MVMG}(t - \tau_{cd}) + B_{MVMG} \Delta u_{MVMG}(t) \quad (47)$$

Note that the matrices  $A_{MVMG-NCD}$  and  $A_{MVMG-CD}$  can be readily obtained based on the decomposed model in the previous subsections.

### B. Design and Stability Analysis of the MV Isolated Microgrid System

The complete linearized state-space model of (44) is then to be adopted for conducting sensitivity analysis of eigenvalues in order to have a better evaluation of the proposed supplementary control loop in Fig. 5, and to design the critical control parameters of the FPZPC in Zone B in a way that both system stability margin and dynamic performance constraints are met. The key parameters of the microgrid system are selected to be the same as in the simulation, as provided in Tables II and III. And the detailed parameters of the DGS and SCIG WT can be found in [52] and [53], respectively. It is to be noted that since the focus of this paper is on frequency stability control method in MV microgrid, the voltage-reactive power droop gain  $K_{rQ}$  in FPZPC is remained constant throughout this work.

#### 1) Sensitivity to control parameters

Sensitivity of the system eigenvalues to variations in the  $f/P$  droop gain  $K_{fp}$ , supplementary control loop gain  $K_{scl}$ , and the

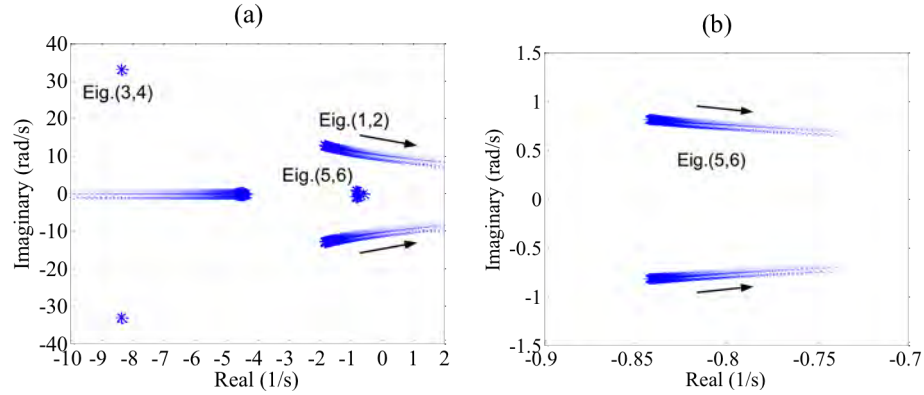


Fig. 9. (a) Trace of the dominant modes as a function of frequency droop gain ( $-0.2\text{kW/Hz} \leq K_{fp} \leq -900\text{kW/Hz}$ ) with the conventional frequency control scheme reported in [6] and [39]. (b) Magnified trace of eigenvalues (5, 6).

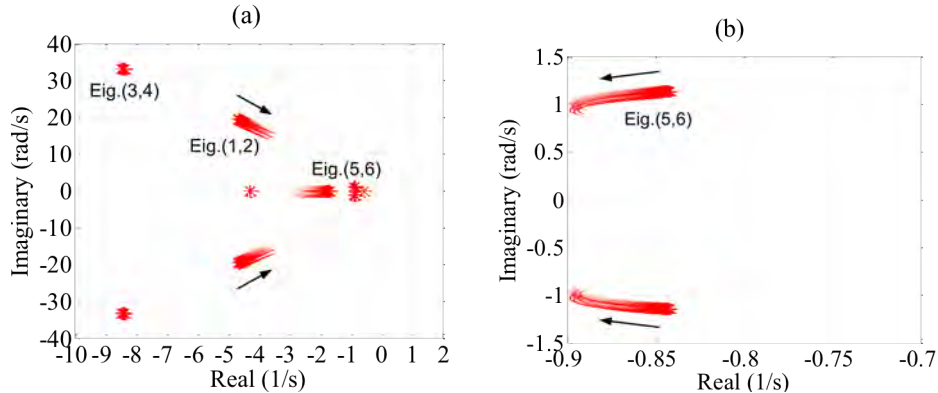


Fig. 10. (a) Trace of the dominant modes as a function of frequency droop gain ( $-0.2\text{kW/Hz} \leq K_{fp} \leq -900\text{kW/Hz}$ ) with the proposed supplementary control loop in FPZPC ( $K_{scl} = 0.3\text{kW} \cdot \text{s}^2$ ). (b) Magnified trace of eigenvalues (5, 6).

corresponding filter cutoff frequency  $\omega_c$ , of the FPZPC in Zone B are demonstrated. Fig. 9 shows the trace of the microgrid dominant modes for the frequency droop gain  $K_{fp}$  variations in the range of  $-0.2$  to  $-900$  kW/Hz when the conventional  $f/P$  frequency control scheme in [6] and [39] is adopted in FPZPC. Note that the low-frequency oscillatory modes are identified to be the dominant modes of the system, which is essential for the stability analysis. Moreover, it can be seen that the dynamic characteristics of the MV microgrid are noticeably affected by three pairs of eigenvalues, i.e., (1, 2), (3, 4) and (5, 6). It is observed that eigenvalues (1, 2) is identified to be the electromechanical mode of the microgrid system. As can be seen, the trace of the eigenvalues (1, 2) indicates that the  $f/P$  droop gain have remarkable impact on the electromechanical mode. It should be mentioned that high  $f/P$  droop gain can enhance the transient response of the microgrid. However, it can be seen from Fig. 9 that as the coefficient of  $f/P$  droop loop increases, the dominant mode (1, 2) shifts towards to the unstable region, which leads to more oscillatory or even instability of the microgrid.

Fig. 10 compares the system dominant eigenvalues spectrum when the supplementary control loop is introduced in the  $f/P$  conventional frequency control loop in FPZPC. It is shown that the dominant oscillatory modes of the system shift to the left-hand plane (LHP), which yields less oscillatory behavior. Moreover, the electromechanical mode shows less sensitive to the  $f/P$  droop gain compared with the conventional droop approach. This indicates that the microgrid system remains stable for a wider range of  $f/P$  droop gain variations. It is worth mentioning that using a high droop gain with larger stability margin is favorable during the operation of the MV microgrid.

Fig. 11 illustrates the loci of the dominant modes for the supplementary control loop gain  $K_{scf}$  variations in the range of 0 to 20 kW.s<sup>2</sup>. Fig. 11 shows that as  $K_{scf}$  increases, the damping of the electromechanical mode represented by the eigenvalues (1, 2) goes up significantly. However, the loci of the eigenvalues (3, 4) and (5, 6) indicates the damping of the corresponding oscillatory modes first increase and then decrease. It can be revealed that the damping ratio ( $\zeta$ ) of the eigenvalues (3, 4) reduces to 0.058 when  $K_{scf}$  increases to 20 kW.s<sup>2</sup>, which might well become underlying factor leading instability of the microgrid. Therefore,  $K_{scf}$  should be

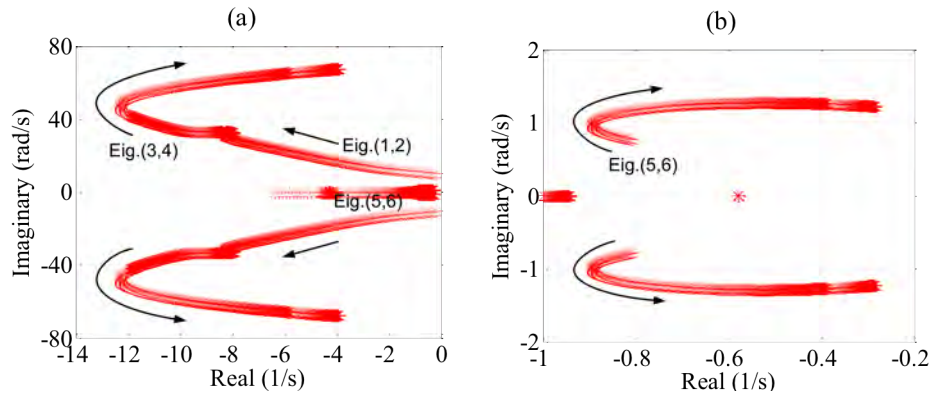


Fig. 11. (a) Trace of the dominant modes when  $K_{scf}$  is increased from 0 to 20 kW.s<sup>2</sup> ( $K_{fp} = -400$  kW/Hz). (b) Magnified trace of eigenvalues (5, 6).

limited according to the locations of the eigenvalues (3, 4) and (5, 6). As can be seen from Figs. 10 and 11, system stability margin is met even with high  $K_{fp}$  or  $K_{scf}$ . Hence, final values will be discussed and selected thoroughly in Section V-A considering charging/discharging limits of the BESS.

Fig. 12 shows the effect of the filter bandwidth on the dominant modes. It shows that as  $\omega_c$  decreases from  $50\pi$  to  $\pi$  rad/s, the damping of eigenvalues (5, 6) increases first, then decreases, whereas the damping of eigenvalues (1, 2) decreases significantly. Obviously, by selecting a high cutoff frequency of the frequency filter, the system stability margin can be increased. However, the attenuation property of the high frequency components is reduced, thus the noise will be amplified by the supplementary control loop and leads to output power oscillations of the BESS. On the contrary, a low cutoff frequency will impose a certain delay that can degrade the performance of the supplementary control loop and worsen the system stability. In this instance, the final value of  $\omega_c = 20\pi$  rad/s was chosen to obtain the desirable transient response specifications, considering the tradeoff between high frequency noise attenuation and the response speed of the supplementary control loop.

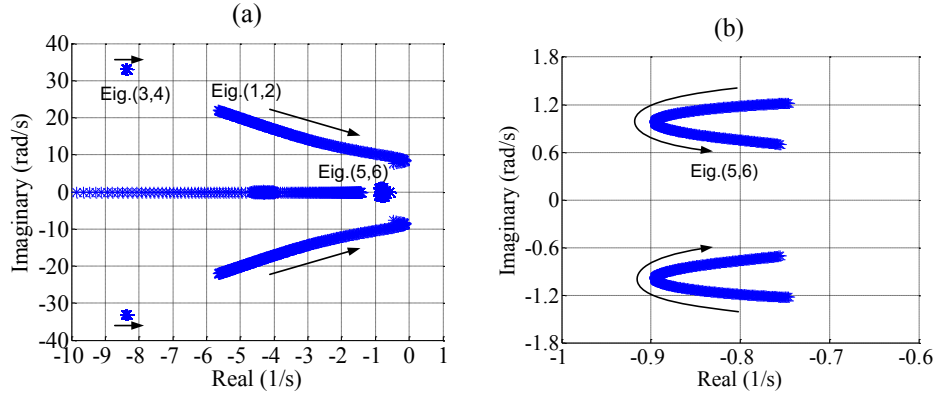


Fig. 12. (a) Trace of the dominant modes when  $\omega_c$  is decreased from  $50\pi$  to  $\pi$  rad/s ( $K_{fp} = -400\text{kW/Hz}$ ,  $K_{scf} = 0.3\text{kW}\cdot\text{s}^2$ ). (b) Magnified trace of eigenvalues (5, 6).

## 2) Sensitivity to operating points

Figs. 13 and 14 show the trajectory of the dominant oscillatory modes as the total load (TL) power increases from 800 kW to 1200 kW, corresponding to conventional frequency control scheme and proposed supplementary control scheme in FPZPC, respectively. As Figs. 13 and 14 show, with the total load in the microgrid grows, the damping of the electromechanical mode increases, while the mode represented by eigenvalues (5, 6) is attracted to the unstable region. Comparing Fig. 14 to Fig. 13, obviously eigenvalues (1, 2) and (5, 6) shift to the LHP when adopting the supplementary control loop. This behavior clearly reveals that the proposed supplementary control loop is effective for stability margin enhancement in different load power conditions.

## 3) Impact of communication delay

One of the major challenges facing the proposed FPZPC in Zone B is the effect of communication delay. To evaluate the impact

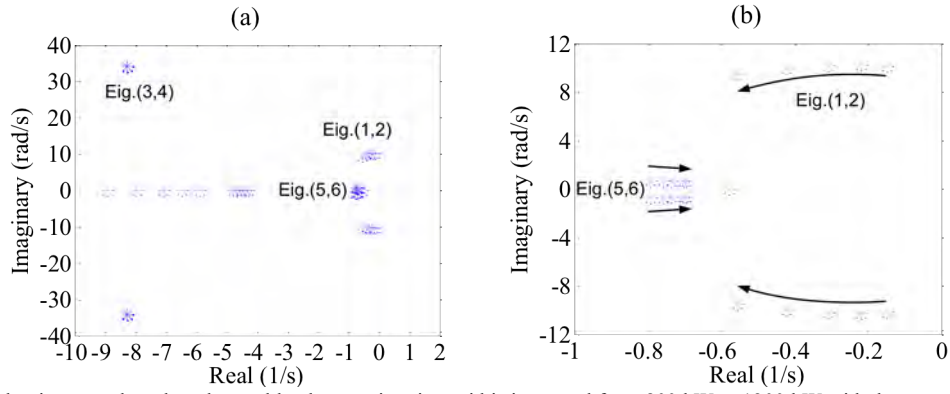


Fig. 13. (a) Trace of the dominant modes when the total load power in microgrid is increased from 800 kW to 1200 kW with the conventional frequency control scheme ( $K_{fp} = -400 \text{ kW/Hz}$ ) reported in [6] and [39]. (b) Magnified trace of eigenvalues (1, 2) and (5, 6).

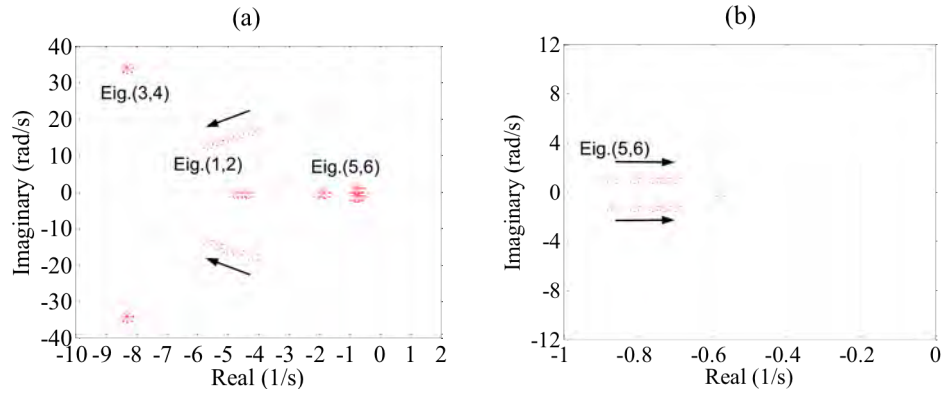


Fig. 14. (a) Trace of the dominant modes when the total load power in microgrid is increased from 800 kW to 1200 kW with the proposed FPZPC scheme ( $K_{fp} = -400 \text{ kW/Hz}$ ,  $K_{scf} = 0.3 \text{ kW} \cdot \text{s}^2$ ). (b) Magnified trace of eigenvalues (5, 6).

of the communication delay on the microgrid stability, Chebyshev's discretization based method proposed in [54] is adopted to calculate the eigenvalues of the system with DDEs represented by (47). Fig. 15 demonstrates the system eigenvalues spectrum as the communication delays ranges from 0 to 500 ms. Note that  $M = 3$  is chosen for the numbers of nodes formatting the Chebyshev's discretization scheme. As can be seen, the dominant eigenvalues of the microgrid system keep in the LHP, which indicates that the introduced frequency control strategy remains stable even though the communication delay is assumed to be as large as 500 ms. Therefore, system stability will not be compromised with the proposed centralized control structure for BESS management.

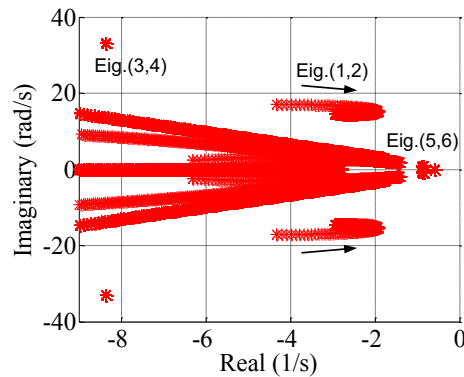


Fig. 15. System eigenvalues spectrum as the communication delays ranges from 0 to 500 ms.

## V. VERIFICATION RESULTS AND DISCUSSION

In order to verify the proposed multiple-time-scales hierarchical frequency stability control strategy, comprehensive simulations analysis under MATLAB/Simulink environment and experimental study in Dongao Island microgrid have been conducted. The main parameters of the microgrid system are selected to be the same in both simulation and experiments, as listed in Tables II and III.

### A. Evaluation of FPZPC in MGCC

Comprehensive simulated results have been obtained to examine the performance of the introduced control scheme of FPZPC in Zone B.

TABLE II  
SYSTEM PARAMETERS

| Elements                          | Types                  | Value                     |
|-----------------------------------|------------------------|---------------------------|
| BESS                              | Power converter        | 500 kW                    |
| DGS                               | Synchronous generator  | 1000 kW                   |
| SCIG WT                           | Asynchronous generator | 750 kW                    |
| Line 1                            | Series $RL$ branch     | $0.180 + j0.147 (\Omega)$ |
| Line 2                            | Series $RL$ branch     | $1.422 + j1.163 (\Omega)$ |
| Line 3                            | Series $RL$ branch     | $0.351 + j0.287(\Omega)$  |
| Load 1<br>(Adjustable load banks) | Series $RL$ load       | 2000 kW / 1000 kVar       |
| Load 2                            | Series $RL$ load       | 100 kW / 50 kVAr          |
| Load 3                            | Series $RL$ load       | 50 kW / 50 kVAr           |
| Capacitor $C_c$                   | Fix-capacitor bank     | 250 kVAr                  |

TABLE III  
MAIN BESS PARAMETERS

| Parameter               | Symbol             | Value                      |
|-------------------------|--------------------|----------------------------|
| DC link voltage         | $V_{dc}$           | 500 V-835 V                |
| PWM switching frequency | $f_s$              | 4 kHz                      |
| Equivalent impedance    | $L_{Bf}; R_{Bf}$   | L:1.15mH; R:0.002 $\Omega$ |
| Power controller        | Proportional gains | $K_{pp}; K_{pq}$           |
|                         | Integral gains     | $K_{ip}; K_{iq}$           |
| Current controller      | Proportional gains | $K_{p1}; K_{p2}$           |
|                         | Integral gains     | $K_{i1}; K_{i2}$           |
| PLL                     | Proportional gains | $K_{Bp}$                   |
|                         | Integral gains     | $K_{Bi}$                   |

Fig. 16 shows the dynamic responses of the system under a step change of frequency droop gain  $K_{fp}$  from  $-80$  to  $-720$  kW/Hz at  $t = 10.2$  s with the conventional  $f/P$  frequency control scheme reported in [6] and [39]. It can be seen that the introduction of droop controller in a MV multi-source microgrid would introduce oscillations in system frequency and active power of the microsources, which reveals the intrinsic nature of the conventional droop control approach. Moreover, Fig. 16 suggests that as  $K_{fp}$

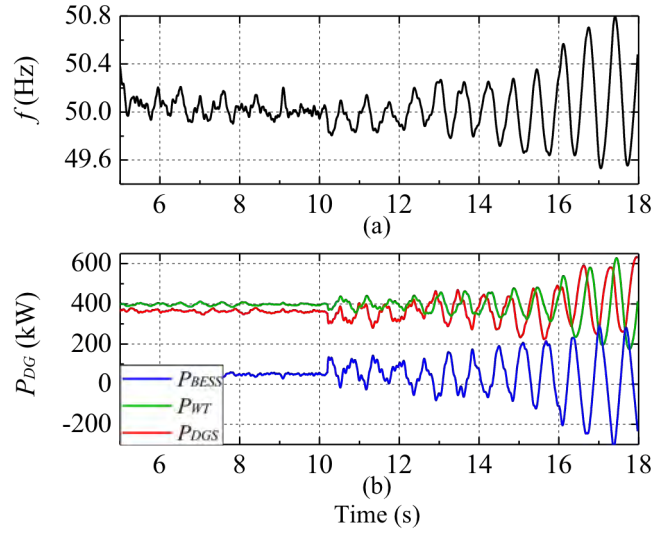


Fig. 16. Responses of the MV microgrid as  $K_{fp}$  is increased from  $-80$  to  $-720$  kW/Hz with the conventional  $f/P$  frequency control scheme reported in [6] and [39]. (a) Frequency. (b) Active power: BESS ( $P_{BESS}$ ), SCIG WT ( $P_{WT}$ ), and DGS ( $P_{DGS}$ ).

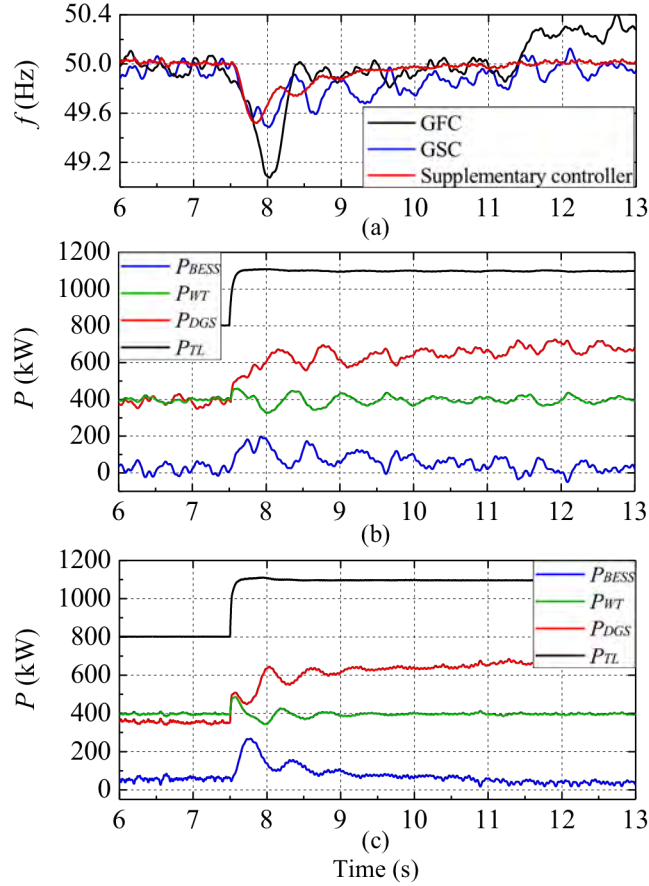


Fig. 17. Responses of the MV microgrid under step load increase of 300kW with different control schemes. (a) Comparison of frequency responses with GFC reported in [38], conventional GSC reported in [6] and [39] ( $K_{fp} = -400$  kW/Hz), and the proposed control scheme in FPZPC ( $K_{scf} = 0.3$  kW.s<sup>2</sup>). (b) Active power response with conventional GSC: BESS ( $P_{BESS}$ ), SCIG WT ( $P_{WT}$ ), DGS ( $P_{DGS}$ ) and the total load in microgrid ( $P_{TL}$ ). (c) Active power response with the proposed control scheme.

is increased, the system appears much more oscillatory performance, and eventually instability can be yielded. Note that this agrees with the findings from the sensitivity analysis presented in Section IV-B.

Fig. 17 shows the performance of the microgrid under different control schemes when a step load increase of 300 kW occurs at

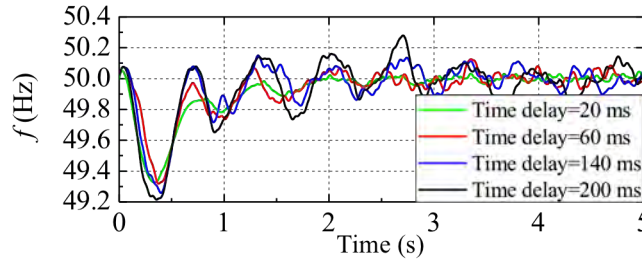


Fig. 18. Frequency response at different time delays.

$t = 7.5$  s. Compared with the responses of GFC reported in [38], as can be seen from Fig. 17(a), frequency drop and fluctuations subsequent to a step load increase can be mitigated and stabilized significantly when adopting the droop control approach. Additionally, comparing the responses of the proposed control scheme, as shown in Fig. 17(a) and (c), to the conventional GSC (see Fig. 17(a) and (b)) clearly verifies the effectiveness of the introduced supplementary control loop in FPZPC. The injected supplementary stabilization signal is able to damp the system frequency so that to yield damped active power responses of all DG units. This is also consistent with the trend of dominant modes based on sensitivity analysis. Therefore, the proposed control scheme synthesizes the advantages of the conventional droop and supplementary control loop, providing fast response stabilization under disturbances.

Fig. 18 illustrates the impact of the communication delay on the frequency dynamic response to a step load increase of 300 kW. Fig. 18 suggests that the system frequency remains stable in the presence of large communication delay (200 ms) with the proposed frequency stability control scheme in FPZPC. Note that this is in line with the eigenvalue analysis shown in Fig. 15.

As previously described, the parameters of the proposed control scheme in FPZPC should be selected from the constraints of stability and the charging/discharging limits of the BESS. It can be seen from Fig. 17(c) that the active power of BESS increases to the peak of 280 kW during load disturbance, which exceeds the discharging limit  $P_{Bdmax}$ . Considering the maximum frequency deviation of the microgrid in steady state to be  $\pm 0.3$  Hz (Zone A),  $f/P$  droop gain  $K_{fp}$  was selected a relatively smaller value ( $-250$  kW/Hz). In regards to the selection of  $K_{scf}$ , although the sensitivity analysis in Fig. 11 suggests that  $K_{scf}$  can be higher to achieve better damping effect, the design of the supplementary control loop ( $K_{scf} = 0.1$  kW.s<sup>2</sup>) is properly conservative. One of the main reason is that the charging/discharging limits of the BESS might be easily exceeded as the derivative term has a strong magnifying effect.

In addition to the parameters mentioned above, another main factor in the parameter selection of the proposed control strategy is the border of Zone B ( $f_{BL}, f_{BH}$ ). As transient control measures, OFGT and UFLS of FEZPC have noticeable impact on the generators and prime movers in the microgrid because of the sudden change of the electrical and mechanical stress. Besides, frequency fluctuations are yielded even during normal OFGT or UFLS due to the low inertia characteristic of the microgrid, as shown in Fig. 21 of experimental test. In a practical microgrid design, in order to avoid the frequency falling into Zone C and

triggering FEZPC, it is desirable to expand the frequency range of Zone B. However, on the one hand,  $K_{fp}$  and  $K_{scf}$  are fixed by the designer to ensure desired transient response considering the charging/discharging limits of the BESS, thus the proposed control scheme in Zone B might limit to power saturation and become ineffective if the border is too large. On the other hand, the local frequency protection setting of all DG units and loads (e.g., the allowable frequency range of the SCIG WT is 47.5–52 Hz) must be within the frequency range of Zone C; otherwise, uncontrollable generator tripping and load shedding might lead to microgrid collapse. In this situation, the range of Zone B is chosen as a synthetic tradeoff taking into account the transient performance, power limit of BESS and the protection coordination of the microgrid.

### B. MGCC and MEMS Test Under Actual Conditions

Multiple-time-scales hierarchical frequency stability control strategy is tested and verified in the Dongao Island MV microgrid under various actual conditions. Fig. 19 shows the main primary equipment and secondary equipment in the microgrid. The setting parameters of MGCC and MEMS are selected as presented in Tables IV and V respectively.

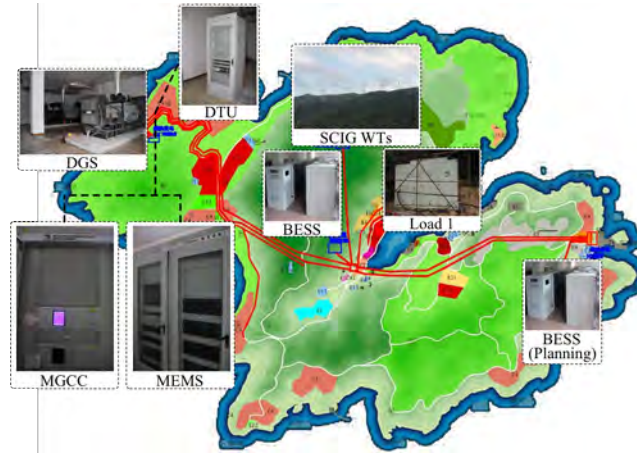


Fig. 19. Main primary equipment and secondary equipment in Dongao Island microgrid.

TABLE IV  
MGCC PARAMETERS SETTING

| Parameter                                     | Symbol          | Setting | Unit              |
|-----------------------------------------------|-----------------|---------|-------------------|
| SoC Upper threshold                           | $SoC_{MGCCmax}$ | 99      | %                 |
| SoC Low-threshold                             | $SoC_{MGCCmin}$ | 20      | %                 |
| Zone A                                        | $f_{AL}$        | 49.7    | Hz                |
|                                               | $f_{AH}$        | 50.3    | Hz                |
| Zone B-                                       | $f_{BL}$        | 49.0    | Hz                |
| Zone B+                                       | $f_{BH}$        | 51.0    | Hz                |
| Zone C-                                       | $f_{CLs}$       | 45.0    | Hz                |
| Zone C+                                       | $f_{CH2}$       | 55.0    | Hz                |
| Droop coefficient of $f/P$ loop               | $K_{fp}$        | -250    | kW/Hz             |
| Droop coefficient of $V/Q$ loop               | $K_{VQ}$        | -100    | kVar/kV           |
| Coefficient of the supplementary control loop | $K_{scf}$       | 0.1     | kW.s <sup>2</sup> |
| Filter cutoff frequency                       | $\omega_c$      | $20\pi$ | rad/s             |

TABLE V  
MEMS PARAMETERS SETTING

| Parameter                                      | Symbol             | Setting                       | Unit |
|------------------------------------------------|--------------------|-------------------------------|------|
| SoC Upper threshold                            | $SoC_{MEMSmax}$    | 95                            | %    |
| SoC Low-threshold                              | $SoC_{MEMSmin}$    | 40                            | %    |
| $\eta$ Upper limit                             | $\eta_H$           | 70 ( $N=1$ );<br>60 ( $N>1$ ) | %    |
| $\eta$ Low limit                               | $\eta_L$           | 30                            | %    |
| Discharging power limit                        | $P_{Bdmax}$        | 210                           | kW   |
| Charging power limit                           | $P_{Bcmax}$        | -210                          | kW   |
| Oscillation coefficient                        | $K_{osc}$          | 10                            | %    |
| Regulating coefficient                         | $K_{reg}$          | 5                             | %    |
| Sensitivity coefficient                        | $K_{sen}$          | 3                             | kW   |
| Impact coefficient of WT start-up              | $k_{WT}$           | 27                            | %    |
| Penetration rate limit of start-up/shutdown WT | $S_{pr1}, S_{pr2}$ | 45, 30                        | %    |

Fig. 20 shows the experimental test results of the MV microgrid performances during the process of continuous load variations when MGCC and MEMS are both enabled. The real scenarios of operation mode optimization in MEMS and rapid compensation control in MGCC are summarized as follows:

- Scenario  $S_1$ : The total load in the microgrid  $P_{TL}$  is rising from 188 kW to 752 kW gradually, and  $\eta$  exceeds the load rate upper limit  $\eta_H$  at  $t = 202$  s, as shown in Fig. 20(b). Meanwhile, BESS increases the discharging power by  $\Delta P_{MEMS1}$  as the spare capacity of the DGS  $\Delta P_{sc}$  is not met to start up the WT. Then the command of WT start-up is issued by FSZPC scheme in MEMS as *Criterion 1* is satisfied. Afterwards, the SCIG WT connects to the microgrid smoothly at  $t = 485$  s.
- Scenario  $S_2$ : The DGS is operating in normal range of load rate between  $\eta_L$  and  $\eta_H$ . Following continuous step load change, the power of the BESS is regulated by the FPZPC scheme in MGCC to stabilize the system frequency rapidly, as shown in Fig. 20(a).
- Scenario  $S_3$ : The charging power of the BESS is manually increased in remote control mode to speed up the charging process, as shown in Fig. 20(d). Thus, we can evaluate the system performance near the upper threshold of SoC of the BESS in scenario  $S_5$ .
- Scenario  $S_4$ : In order to be able to observe the power oscillation due to repetitively regulating the BESS nearby the load rate limit,  $K_{osc}$  is set to be zero in this case. As can be seen from Fig. 20(a) and (c), the system frequency and the output power of the DGS fluctuate up and down near  $\eta_L$  until  $K_{osc}$  is restored to nominal value.
- Scenario  $S_5$ : As  $\eta$  falls below  $\eta_L$  caused by a step load decrease of 200 kW, the charging power of the BESS grows gradually

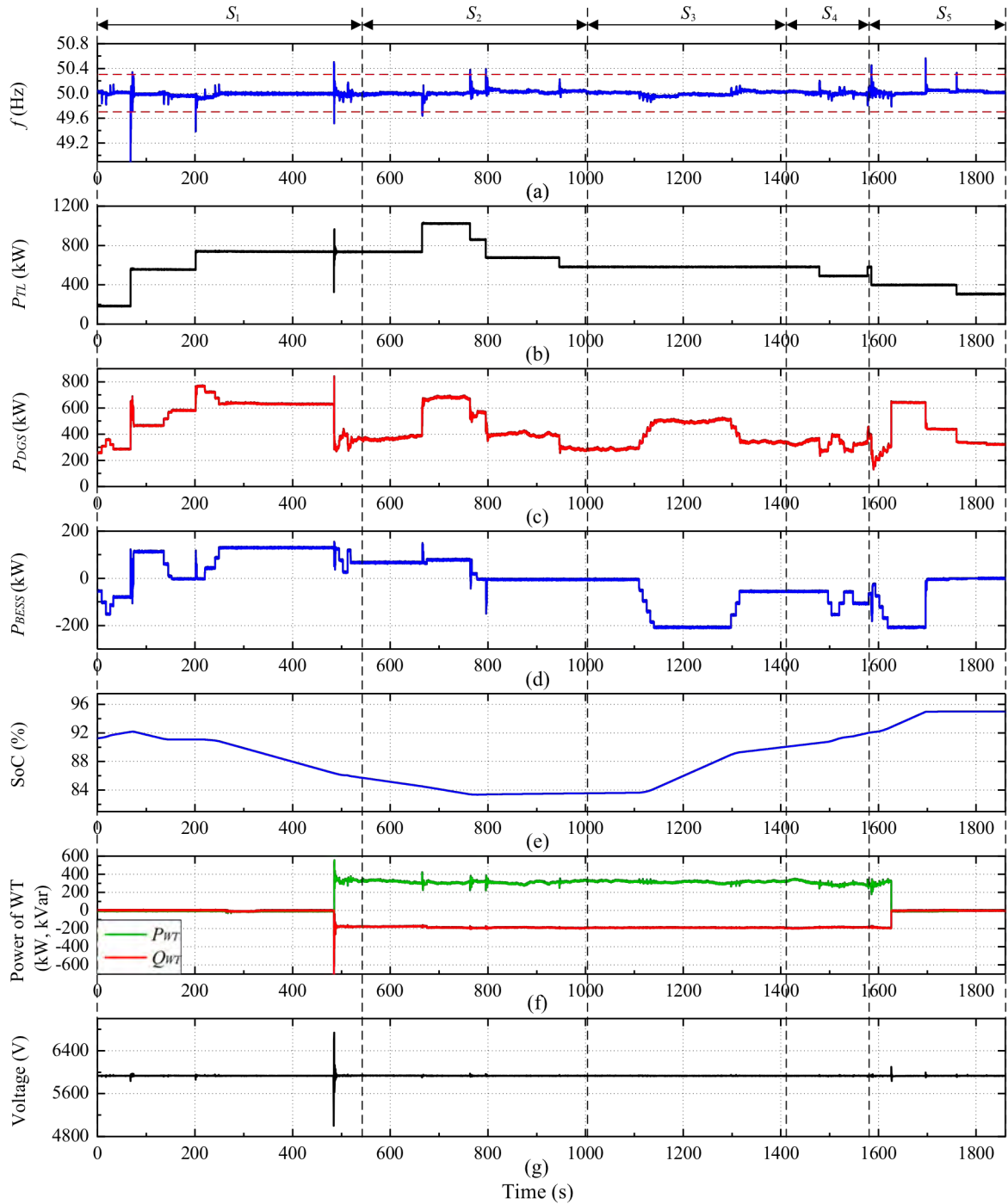


Fig. 20. System performances to continuous load variations with MGCC and MEMS. (a) Frequency. (b) Active power of the total load in microgrid. (c) Active power of DGS. (d) Active power of BESS. (e) SoC of BESS. (f) Active power ( $P_{WT}$ ) and reactive power ( $Q_{WT}$ ) of SCIG WT. (g) Voltage of BUS-2.

with  $\Delta P_{MEMS2}$  until reaches the charging power limit  $P_{Bcmax}$ . Nevertheless, as shown in Fig. 20(e), the SoC of the BESS increases to 93.5% which almost reach the upper threshold 95%. Hence, the MEMS checks *Criterion 2* to shut down the DGS or the WT in advance. Resulting from *Criterion 2* is met, the SCIG WT is shut down according to the command issued by MEMS at  $t = 1627$  s, as shown in Fig. 20(f).

Consequently, it can be observed that the MEMS is capable of dealing with frequency fluctuations in long-time scale through optimization of microgrid operating mode, which is similar to the tertiary frequency control in interconnected power systems.

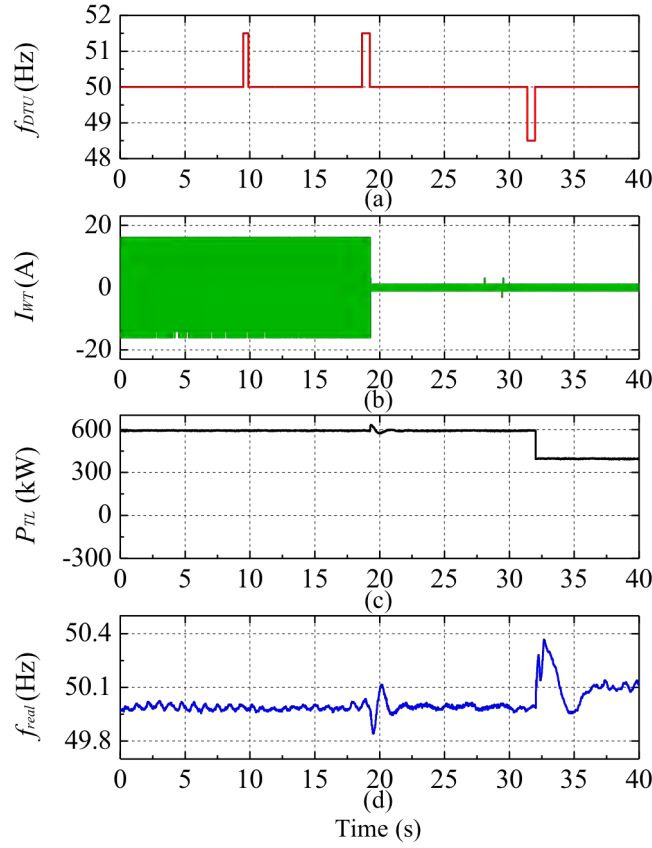


Fig. 21. Experimental test results of UFLS and OFGT functions in MGCC. (a) Simulated frequency signal fed in the DTU. (b) SCIG WT output current. (c) Active power of the total load. (d) Real frequency.

Furthermore, there are ten times in which the frequency exceeds Zone A. Note that the frequency deviations caused by short-term large load demand can be suppressed by the MGCC effectively.

### C. Function Test of FEZPC in MGCC

To test the validity of FEZPC scheme in MGCC under large disturbances (extreme conditions), simulated frequency signal generated using protection relay test system (PRTS) are fed in the DTU at BUS-1, which can be detected by the MGCC, as shown in Fig. 21(a). Fig. 21 shows the experimental test results of UFLS and OFGT functions in the MGCC. As can be seen from Fig. 21(b), there are three transient frequency pulses detected by the DTU, including 51.5 Hz last for 0.35 s at  $t = 9.5$  s, 51.5 Hz last for 0.6 s at  $t = 18.7$  s, and 48.5 Hz last for 0.6 s at  $t = 31.4$  s, respectively. However, only the second and the third frequency pulse variations are valid and trigger OFGT at  $t = 19.4$  s [see Fig. 21(b)] and UFLS at  $t = 32.1$  s [see Fig. 21(c)], respectively, since the pulse-width in the first time is less than the setting delay time. It is shown that preventive control within emergency zone can be performed rapidly and correctly under the simulated extreme conditions.

## VI. CONCLUSION

This paper introduces a hierarchical frequency control strategy to ensure power balance and frequency stability in multiple-time-scales for MV isolated microgrids. The proposed control strategy is realized with both dynamic and steady-state stability controllers

based on different time scales. Dynamic stability control composed of preventive control in frequency precautionary and emergency zone is implemented by MGCC within 65 ms through GOOSE high-speed network. On the other hand, steady-state stability control which refers to the preventive control in frequency stable zone is executed by MEMS every 5 s through MMS supervisory network. By using the developed small-signal model of the MV microgrid, sensitivity analysis is conducted to analyze the dynamic stability margin of the microgrid and to identify the proper range of the main control parameters. Comprehensive simulated and experimental results in Dongao Island MV microgrid are presented to verify the effectiveness of the proposed control strategy. It is shown that the coordination between dynamic stability control based on the millisecond level and steady-state stability control based on the second level is able to realize the stable and optimal operation of the MV microgrid in Dongao Island. This paper provides practical solution for the frequency control, with insight information about the configuration, modeling, analysis and operation of the MV isolated microgrid.

This study aims to solve the problem of the stable operation of the microgrid, especially concerning the frequency stability in the MV microgrid. The power quality improvement using distributed BESS in MV microgrid is subject to further research and will be considered in future studies of Dongao Island. Another important issue is that the application of proposed supplementary control scheme in other microgrids, e.g., microgrids with decentralized control architecture. In this application, the supplementary control scheme comprises the derivative terms of the local frequency and voltage. They can be included in the droop equations of (9) and (10) in [55] respectively, thus to improve the transient response of the microgrid. In order to evaluate the effectiveness of this extension further, modeling, analysis and testing of such microgrids are needed to conduct in future work.

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