Coordinated Frequency Regulation of BESS with Renewable Generation in Microgrid

4.1 INTRODUCTION

Figure e4.1 shows two types of microgrid operation: grid-connected mode under normal conditions and islanded mode in case of emergencies. These two typical operation modes can be switched in a reliable manner with seamless transition. The switching from grid-connected mode to islanded mode can be achieved through “urgent-grid disconnection control” in the event of severe disturbance at the Point of Common Coupling (PCC). If the system frequency or voltage cannot be maintained well within the acceptable range due to inadequate regulation capability of micro power sources or if any additional severe fault in the islanded microgrid cannot be cleared in time, the microgrid will instantly transfer from islanded mode to outage mode by “stop control.” In this way, the microgrid will automatically stop supplying power to load in order to avoid permanent damage from the unsettled fault or poor power quality on the sensitive loads and relevant electrical equipment within the islanded microgrid. Once this fault is eliminated, the microgrid in outage mode is either ready to restore to grid-connected mode through “restoration grid connection control” or return to islanded mode through “start control.” The choice depends on the specified command of distribution system dispatch center and current operation conditions of the microgrid. When a microgrid operates in the grid-connected mode, all the distributed generators (DGs) embedded in the microgrid should operate in active and reactive power (PQ) control mode in which active and reactive power references are specified by the dispatch center or central controller. Meanwhile, the power output of energy storage system (ESS) is set to zero under normal operational condition of main grid. If a short-term, minor voltage fault occurs in the main grid, the ESS is able to stabilize the voltage at the PCC by supplying a desired amount of reactive power through control of the ESS’s power electronic interface. If a severe fault occurs on the main grid or the power quality fails to meet requirements, the microgrid is instantly disconnected.
from the main grid through the circuit breakers and begins to operate in islanded mode. A seamless transfer of microgrid from grid-connected mode to islanded mode can be significantly enhanced by the BESS functioning as a transient power buffer. In the islanded mode, operation and control of the ESS depends on the overall microgrid control strategy and the ESS characteristics. According to different operation characteristics of DGs in the islanded microgrid, the main control modes of microgrid include master-slave control, peer-to-peer control and hierarchical control [1,2].

In this chapter, we will focus on the coordinated frequency regulation and control of BESS and wind power in islanded mode of a microgrid or a microgrid cluster. The objective of microgrid frequency regulation is to regulate the frequency of an islanded microgrid to the specified nominal value under the frequency disturbance, and meanwhile maintain the tie line power interchange among different microgrids within one islanded microgrid cluster or between two virtual areas within a single islanded microgrid at the scheduled value by coordinating the outputs of wind power generation and BESS through virtual inertial response, frequency droop control and load frequency control (LFC).

4.2 APPLICATION OF BESS IN THE FREQUENCY REGULATION OF ISLANDED MICROGRID

Compared with frequency regulation by wind generation system, BESS is a more desirable alternative to provide frequency regulation and inertial response in a faster, more accurate and flexible manner [3]. So, participation of a BESS in islanded microgrid frequency regulation can assist
DGs to operate at their maximum efficiency without excessive power deloading. Furthermore, the BESS can mitigate frequency variations with a faster response when the frequency disturbance occurs in the islanded microgrid. If the energy capacity of the BESS is limited, a wind turbine generator can gradually take over the mid-to-long-term frequency regulation tasks through emulated droop response and AGC control.

In this section, a comprehensive frequency regulation strategy for BESS is introduced with the aim of achieving virtual inertial response, primary frequency response as well as secondary AGC control.

4.2.1 Modeling of BESS
4.2.1.1 Battery Modeling
The dynamic model of BESS applied in microgrid is established based on the battery module in Matlab/Simulink [4]. An aggregate model is used to represent the general characteristics of the energy storage unit that consists of multiple lithium-ion batteries connected in parallel and in series. This serves the purpose of improving the simulation efficiency and accurately showing the dynamic characteristics of BESS participating in the system frequency regulation.

For the simulink module of the battery, a generic dynamic model is provided to perform the dynamic simulations by selecting the desired type of rechargeable battery. Compared with the real physical model, this model exhibits a maximum error of 5% in dynamic performance when the SOC (state of charge) varies from 10% to 100% with charge current between 0 and 2C and discharge current between 0 and 5C. Therefore, this model can satisfy the requirement on simulation accuracy. The equivalent circuit of a battery model is illustrated in Figure e4.2.

The mathematical equations representing charge and discharge modes for a lithium-ion battery model are expressed as follows [4]:

Discharge mode ($i^* > 0$)

$$f_1(it, i^*, i) = E_0 - K \cdot \frac{Q}{Q - it} \cdot i^* - K \cdot \frac{Q}{Q - it} \cdot it + A \cdot \exp (-B \cdot it) \quad (4.1)$$

Charge mode ($i^* < 0$)

$$f_2(it, i^*, i) = E_0 - \left[ K \cdot \frac{Q}{it + 0.1 \cdot Q} \right] \cdot i^* - \left[ K \cdot \frac{Q}{Q - it} \right] \cdot it + A \cdot \exp (-B \cdot it) \quad (4.2)$$
where, \( E_0 \), constant voltage (V), \( K \), polarization constant (Ah\(^{-1}\)) or polarization resistance (Ohms), \( i^* \), low-frequency filtered current dynamics (A), \( i \), battery current (A), \( it \), extracted capacity (Ah), \( Q \), maximum battery capacity (Ah), \( A \), exponential zone voltage amplitude (V), and \( B \), exponential zone battery capacity (Ah) – 1.

In this model, the terms for polarization voltage and polarization resistance are applied to emulate the Open Circuit Voltage (OCV) of the battery in more accurate manner. The term inside the first square bracket in Eq. (4.2) represents the polarization resistance and the second square bracket shows the polarization voltage.

Depending on the particular battery type, the typical discharge-characteristic curve can be as shown in Figure e4.3.
This figure shows three sections of the battery discharge process. The exponential area represents the exponential variation in voltage when the battery is fully charged. The size of the area changes with battery type. The second section indicates the total energy discharged from the battery until the voltage drops below the nominal voltage. Lastly, the third section shows that the voltage tends to decline rapidly when the battery is fully discharged.

4.2.1.2 Inverter Modeling and Control
With the power inverter interface, the DC output of the battery is converted into three-phase AC power and is connected to the micro-grid via the filter [5–7]. A phase locked loop (PLL) is used to synchronize the BESS with the microgrid. Due to the inverter’s four-quadrant operation, as depicted in Figure e4.4, the BESS is capable of controlling both real power and reactive power in magnitude and direction based on the system power demand. Inverter control is implemented in the d-q synchronous frame for the system voltage oriented control, in which the direct current component \( i_d \) aims to control the real power while the quadrature current component \( i_q \) is set to control the reactive power. In addition, the power flow direction can be determined by
setting the power reference sign: a positive value for injecting extra power into the microgrid and a negative value for absorbing the surplus power from the microgrid.

4.2.2 Virtual Inertial Control

If the system frequency is lower than 50 Hz (under frequency) or higher than 50 Hz (over frequency), BESS is capable of emulating the inertial response from conventional generators by releasing (absorbing) the active power to (from) microgrid. This portion of emulated kinetic energy is transformed into the electromagnetic power through the inverter to deliver real power into the power grid according to the frequency regulation requirement [5]. The equation for calculating the inertial response is expressed as follows:

$$\Delta P_{\text{inertial}} = K_{\text{inertial}} \times \left( \frac{df}{dt} \right)$$

(4.3)

The magnitude of the inertial response $\Delta P_{\text{inertial}}$ depends on the virtual inertial constant $K_{\text{inertial}}$ and the rate of change of frequency $df/dt$. Figure e4.5 shows the basic control structure of the BESS virtual inertial response. In Figure e4.5, a low-pass filter is applied to suppress the high-frequency noise resulting from the system frequency measurement. A deadband controller can avoid unnecessary activation of the inertial response so as to avoid frequent discharging and charging and thus prolong the lifetime of the battery accordingly. In addition, the maximum value and limits of the rate of change of inertial response are determined in accordance with the physical characteristics of the battery and specific microgrid requirement, so the impact of overshoot response of battery can be avoided in the charging and discharging process.

Using the virtual inertial response, the rate of change of frequency (ROCOF) during the initial period of disturbance (within 5–10 s) can be reduced and frequency nadir (the minimum frequency value) can be raised as well. According to the swing equations [8], Eq. (4.4), which has an additional term from Eq. (4.3), is transformed into Eq. (4.5).
This indicates that the equivalent inertial coefficient of microgrid is increased when $K_{\text{inertial}}$ is set to be a negative value. Thus, the ROCOF of the system can be effectively mitigated.

$$2 \frac{H}{\omega_{\text{syn}}} \omega_{\text{p.u.}}(t) \frac{d\omega(t)}{dt} = P_{\text{mp.u.}}(t) - P_{\text{ep.u.}}(t) - D \frac{d\delta(t)}{dt} + K_{\text{inertial}} \frac{d\omega(t)}{dt}$$

(4.4)

$$\left(2 \frac{H}{\omega_{\text{syn}}} \omega_{\text{p.u.}}(t) - K_{\text{inertial}} \right) \frac{d\omega(t)}{dt} = P_{\text{mp.u.}}(t) - P_{\text{ep.u.}}(t) - D \frac{d\delta(t)}{dt}$$

(4.5)

With respect to the typical inertial response of a conventional generator, the kinetic energy extracted from the rotating mass of both turbine and generator needs to be regained from the available mechanical power so as to restore the rotor speed to its pre-disturbance value. Moreover, the inertial response still works to restrain the ROCOF during the recovery process, which results in a relatively long restoration. In contrast, no such “inertia recovery process” is needed for BESS in order to accelerate the frequency recovery process. Therefore, an improved inertial response is presented in this book by ceasing the emulated inertial response of BESS when the frequency reaches the nadir point and the delay condition is met as well. In other words, after the frequency declines toward the nadir, the system synthetic inertial response and primary droop regulation of other selected DGs can take over the mid-to-long term frequency regulation of the islanded microgrid. Thus, the overall frequency recovery process after the frequency nadir can be further improved.

### 4.2.3 Variable Droop-Based Primary Frequency Control

The primary frequency response of the BESS is also known as the droop response or frequency response reserve [5]. It aims to emulate the governor control of a conventional synchronous generator by taking advantage of the available reserve for the primary frequency regulation. The active power output is controlled in accordance with the system frequency deviation and droop characteristics so that the BESS is able to share the load change with other DGs to ensure that the frequency is restored to the acceptable range within a specified period of time. It belongs to the frequency regulation based on error control. According to the typical governor equation (4.6):

$$\Delta P_{\text{droop}} = \frac{1}{R_{\text{droop}}} \cdot \Delta f = \frac{1}{R_{\text{droop}}} \cdot (50 - f_{\text{actual}})$$

(4.6)
Figure e4.6 shows the droop-frequency control curve in which the power reference for the primary frequency control can be calculated according to equation (4.7).

\[
\Delta P_{\text{droop}} = \begin{cases} 
\Delta P_{\text{max}} & \Delta f \leq f_{\text{min}} - 50 \\
- \frac{1}{R_{\text{droop1}}} \times \Delta f & f_{\text{min}} - 50 \leq \Delta f \leq 0 \\
\frac{1}{R_{\text{droop2}}} \times \Delta f & 0 \leq \Delta f \leq f_{\text{max}} - 50 \\
- \Delta P_{\text{max}} & \Delta f \geq f_{\text{max}} - 50 
\end{cases}
\] (4.7)

The positive value of \( \Delta P_{\text{droop}} \) represents the active power delivered into the microgrid in the under-frequency case while the negative value represents the active power absorbed from the microgrid in the over-frequency case. The performance of overall primary frequency regulation of the BESS depends on the droop coefficient \( R_{\text{droop}} \), dead zone, reserve margin for the primary frequency regulation, the droop characteristics of other DGs as well as the system load damping.

Figure e4.7 shows the control block diagram of primary droop response, where the high pass filter is utilized to eliminate the impact of low-frequency disturbance on the control system.

Here, a variable droop primary frequency regulation approach is presented to adjust the droop coefficient based on the real-time SOC value as shown in Figure e4.8. To be specific, the corresponding maximum droop coefficient \( R_{\text{max}} \) and minimum droop coefficient \( R_{\text{min}} \)
should be defined in accordance with the allowable minimum $\text{SOC}_{\text{min}}$ and maximum $\text{SOC}_{\text{max}}$ value. With the SOC measured, the actual droop coefficient $R_{\text{actual}}$ can be acquired using linear interpolation method in equation (4.8).

\[
R_{\text{actual}} = R_{\text{max}} - (R_{\text{max}} - R_{\text{min}}) \cdot \frac{\text{SOC}_{\text{actual}} - \text{SOC}_{\text{min}}}{\text{SOC}_{\text{max}} - \text{SOC}_{\text{min}}} \quad (4.8)
\]

Using this method, more additional active power can be injected or absorbed under the high SOC state in order to enhance the primary frequency regulation of the microgrid. On the contrary, less additional active power is exchanged between the BESS and the microgrid under the low SOC state. Therefore, more storage energy is reserved for the secondary frequency regulation while reducing the frequency deviation. In this way, the capability of the BESS participating in primary frequency regulation in the islanded microgrid can be optimized based on SOC so as to increase the transient frequency nadir and improve the frequency recovery process. This also helps to avoid the situation of the battery being over-discharged in case of under frequency.

**4.2.4 Secondary AGC Frequency Control**

The BESS is able to emulate the AGC frequency regulation or LFC of conventional generators by rescheduling its output based on the power
reserve for the secondary frequency regulation [7,9]. This control aims to restore the frequency of islanded microgrid to a nominal value, which is achieved by no-error control. Meanwhile, AGC control of the BESS can reduce the area control error (ACE) to maintain the tie-line interchange power at the scheduled value by adjusting its output.

\[
ACE = \Delta P_{\text{tie line}} + B \cdot \Delta f = \Delta P_{\text{tie line}} + \left( \frac{1}{R} + D \right) \cdot \Delta f
\]  

(4.9)

where \( R \) is composite droop coefficient and \( D \) is composite load damping constant. Figure e4.9 shows a basic control diagram for the BESS secondary frequency regulation in which AGC controller can adopt integrator to achieve this function.

### 4.2.5 Comprehensive Frequency Control Strategy for BESS

In Figures e4.10 and 4.11, the islanded microgrid operates in its under-frequency (\(<50\) Hz) and over-frequency condition (\(>50\) Hz), respectively, when the power imbalance between supply and demand occurs. Energy storage systems can participate in dynamic frequency regulation. This process comprises three stages: combined virtual inertial response and primary droop response in the first stage, only primary droop response in the second stage as well as secondary AGC frequency regulation in the third stage. The SOC value is monitored in real time by the battery energy management system (BEMS) of the BESS. As long as the SOC is in the range of 20—80\%, the energy storage system is able to participate in each stage of the frequency regulation of islanded microgrid, otherwise BESS is forced to exit the frequency regulation status.

The first stage: when ROCOF \( \frac{df}{dt} \) is smaller than the lower limit \( a = -0.8 \) Hz/s (or larger than upper limit \( b = 0.8 \) Hz/s) and the delay time is longer than \( T_a \) (\( T_a = 100 \) Ms), the virtual inertial response is activated. The BESS tends to inject (or absorb) power \( \Delta P_{\text{inertia}} \) to (from) the microgrid. Meanwhile, as the absolute value of system frequency deviation \( |\Delta f| \) exceeds its limit \( \Delta f_{\text{limit}} \) (200 mHz) and the
Figure e4.10 The flow chart of comprehensive frequency regulation of a BESS in under-frequency condition.
Figure e4.11 The flow chart of comprehensive frequency regulation of a BESS in over-frequency condition.
delay time is over $T_b$ (100 ms), the primary droop response will inject (or absorb) power $\Delta P_{\text{droop}}$ to (from) the microgrid.

The second stage: when the ROCOF $df/dt$ is larger than 0 (or smaller than 0) and the delay time is over $T_c$ (100 ms), the virtual inertial response quits with $\Delta P_{\text{inertia}} = 0$. At this moment, the frequency reaches the lowest point (or the highest point) and starts to restore toward the nominal value. The droop coefficient $R$ can be adjusted by the primary droop response on the basis of real-time SOC value so that the injected (or absorbed power) $\Delta P_{\text{droop}}$ through the primary frequency regulation can be optimized.

The third stage: when the absolute value of frequency deviation $|\Delta f|$ is smaller than the limit $\Delta f_{\text{limit}}$ (200 mHz) and the delay time is over $T_d$ (100 ms), the primary droop response quits with $\Delta P_{\text{droop}} = 0$. The secondary AGC frequency regulation starts to inject (or absorb) power $\Delta P_{\text{AGC}}$ to (from) the microgrid. Once the absolute value of frequency deviation $|\Delta f|$ is smaller than 20 mHz and delay time is over $T_e$ (100 ms), the BESS quits the AGC frequency regulation starts to be charged (or discharged) to the nominal state with SOC = 50%.

It should be noted that the various delay time $Ts$ can be tuned in accordance with dynamic characteristics of the system in question. $T_a$ is used to avoid the frequent activation of the inertial response; $T_b$ is used to avoid the frequent activation of the primary droop response; $T_c$ is used to ensure that the frequency regulation of BESS can smoothly switch from the first stage to the second stage and the frequency reaches the lowest point (or the highest point); $T_d$ guarantees the smooth transition of frequency regulation of BESS from the second stage to the third stage so that the system frequency can be maintained within the desired range ($\pm 49.8 \text{ Hz}$); $T_e$ is used to constrain the frequency deviation within the small range of $\pm 20 \text{ mHz}$.

4.2.6 Case Study
To demonstrate the effectiveness of the coordinated frequency regulation strategy of a BESS, a line-to-line voltage 380 V/50 Hz microgrid in Figure e4.12 is built in Matlab/Simulink, consisting of two small-scale synchronous generators at 150 kW and 200 kW respectively, one 2 kWh BESS with a rated charging/discharging power of 20 kW and one constant power load. Assume that a sudden disconnect of the microgrid from the main grid occurs at 15 s due to a voltage fault at the PCC.
The frequency will dramatically decline in the islanded mode since a certain amount of active power is supplied from the main grid to the microgrid. Prior to this grid fault, the BESS exchanged no power with the microgrid. Here, typical inertial control of BESS refers to its capability of delivering inertia power and restoring the kinetic energy from the microgrid until its SOC returns to the pre-disturbance value, with an inertial response equivalent to that of a conventional synchronous generator. In contrast, improved inertial control of BESS is proposed based on the typical inertial response to provide its inertial response and improve the frequency recovery process by disabling the inertial response of BESS at the moment of frequency nadir. In the following two case studies, one is used to compare the improved inertial response and typical inertial response for transient frequency regulation. The other aims to compare and analyze the system frequency response by taking into account the
BESS without frequency control, BESS with only improved inertial response, BESS with only variable droop control and BESS with combined variable droop response and improved inertial response.

Case 1. Comparison of improved inertial response and typical inertial response of BESS
In Figures e4.13 and 4.14, the same inertial coefficient K is considered for improved and typical virtual inertial response. The results show that the improved virtual inertial controller can enable BESS to release additional active power to the islanded microgrid during the initial transient process. As the frequency reaches the frequency nadir and the delay time meets 0.1 s, the inertial response will cease. However, typical inertia response still remain active after frequency reaches nadir. Meanwhile, the microgrid starts to restore the frequency through the primary droop regulations provided by other two synchronous generators. So, BESS with typical inertia response will restore the inertial energy from the islanded microgrid so as to return to the original SOC state, which slows down the frequency recovery process to a certain extent. In addition, the improved and traditional inertial controllers are more effective to mitigate ROCOF during the early stage of frequency transient process than the case without inertial response.

Case 2. Comparisons among the BESS without frequency control and with different frequency controls
Due to an independent control structure between active power output and system frequency through the interfacing inverter, the change in

Figure e4.13 Comparison of the frequency response with a BESS using improved and typical inertia control.
frequency does not generate any corresponding adjustment in the active power output of BESS. As shown in Figures e4.15—4.17, if additional frequency control of BESS is not activated, the difference between power supply and demand under the low-frequency condition is the largest, the rate of decline of frequency is the highest and the frequency nadir is the lowest. The frequency falls to 49.3 Hz at the frequency nadir, which exceeds the security limit of 49.5 Hz so that the
under-frequency load shedding protection will be triggered. The improved inertial response of the BESS is based on the ROCOF to inject the emulated inertial power into the islanded microgrid through the inverter. This is equivalent to the practice that increases the system
damping inertia of the microgrid, which can decrease the ROCOF and increase the frequency nadir as well. However, the steady-state frequency error cannot be reduced. Compared with improved inertial response, the primary variable droop frequency regulation is based on the system frequency deviation to adjust the power output of BESS. So, it is not used to reduce the ROCOF, but it can increase the frequency nadir and mitigate the steady-state frequency error as well.

From Table e4.1, it is obvious that the comprehensive frequency regulation combining variable droop control and improved inertial response inherits both advantages of these two types of control so as to achieve the optimal frequency performance. It not only can reduce the ROCOF and increase the frequency nadir, but can also best mitigate the steady-state frequency deviation and takes less time to reach the steady-state condition. Meanwhile, the SOC remains a relatively high level of 41.6% after the primary droop regulation is completed, thus a sufficient amount of storage energy is available to proceed to the secondary frequency regulation. Note that there is a deadband range of ±0.02 Hz and a time delay of 0.1 s for starting the primary droop response in blue and red curves. Once these conditions are met, variable droop response is triggered by injecting the BESS power to the grid. It causes a transient frequency disturbance with a 0.08% in magnitude, which is small enough to be ignored in this study.

### 4.2.7 Conclusions

In this section, a novel coordinated control strategy suitable for BESS to perform frequency regulation is presented to enhance both transient and dynamic frequency stability of microgrid operating in the islanded
mode. From the simulation results, it can be concluded that the presented comprehensive frequency regulation approach not only can reduce the ROCOF value at the initial stage of frequency event, but can also boost the frequency nadir and diminish the frequency deviation at the steady state. Moreover, the duration for frequency to restore to the steady-state condition can be significantly reduced.

Referencing conventional frequency regulation methods and taking into account the battery physical properties such as SOC and rapid charging and discharging ability, the proposed BESS control strategy can ensure BESS to provide adequate frequency regulation capacity for islanded microgrid.

4.3 APPLICATION OF WIND GENERATION SYSTEM IN THE FREQUENCY REGULATION OF ISLANDED MICROGRID

To achieve a reliable, secure and economic operation, especially when operating in islanded mode, a microgrid is required to maintain the system frequency around a specified value within predetermined boundaries. As wind turbine generators (WTGs) are increasingly integrated into microgrid, wind plants are expected to provide frequency regulation and inertial response through a fast and flexible active power control.

A WTG possesses a certain amount of kinetic energy stored in the rotating mass which can be utilized to provide a short-term frequency support in the event of load/generation unbalance. In general, wind turbine can be divided into two main groups: fixed-speed WTs (FSWT) and variable-speed WTs (VSWT). Each group has its own advantages and drawbacks in terms of their contributions to the system frequency support. The FSWT can inherently provide a certain inertial response to minimize the ROCOF since the generator stator is directly connected to the grid [8]. In contrast, VSWTs can supply hardly any inertial energy stored in rotating mass into the power grid due to partial or full decoupling between generator rotor speed and system frequency due to power converters. However, modern VSWTs are able to fulfill the emulated inertial response and primary frequency regulation by adding supplementary control loops into the power converter and pitch angle controls. Although the frequency regulation principles and concepts of a doubly-fed induction generator wind turbine generation system (DFIG-WTG) are similar to a type 4 direct drive permanent magnet synchronous generator with variable speed
and full converter system (PMSG-WTG), PMSG-WTG can provide much greater frequency regulation capabilities due to its full power converter. It can also make full use of more available kinetic energy for a stronger inertial response due to the wider rotor speed range of the PMSG. In addition, PMSG-WTG with full power back to back converters is another type of promising and popular wind turbine technology owing to its many inherent advantages, such as a simplified drive train, elimination of DC excitation system, high power density, flexible controllability and enhanced grid support during grid disturbances. The efficiency and reliability of a PMSG-WTG are perceived to be more desirable due to the elimination of the gearbox [8,10–12].

In this section, we will focus on the potential frequency regulation capabilities of PMSG-WTG in an islanded microgrid. A novel coordinated frequency regulation method is proposed to enable PMSG-WTG to effectively participate in the system frequency regulation by combining rotor speed control and modified pitch angle control [13]. Based on the simulation results under three wind speed scenarios, it is proved that the proposed coordinated frequency control strategy can enhance the frequency regulation capability of PMSGs over a wide range of wind speeds.

4.3.1 Modeling of PMSG-WTG

Here, a comprehensive and detailed 150 kW variable speed wind turbine system (VSWT) equipped with a permanent magnet synchronous generator (PMSG) and a full-scale IGBT voltage source converter (VSC) is developed for Power Systems Computer Aided Design (PSCAD) / Electromagnetic Transients including DC (EMTDC) simulation study on the dynamic characteristics of PMSG-WTG. The control scheme comprises both maximum efficiency operation and active/reactive power independent control functions: the generator side converter can control the generator rotor speed to achieve the maximum power operating point while the grid-side converter can maintain the DC-link capacitor voltage constant as well as the reactive power exchanged with grid at the set value. Meanwhile, a DC-link over-voltage protection scheme is designed and implemented in this model.

In addition, this WT model is also coupled with dynamic pitch control to regulate the output power according to the curve in Figure e4.18 so that it is capable of maintaining optimal power operation over a wide range of wind speed conditions. A two-mass drive
The operation modes are divided into four different operating zones in accordance with the magnitude of wind speed as follows [13]:

**Zone I:** $P = 0$. The wind turbine does not rotate and no power is generated when wind speed $V_{\text{wind}} < V_{\text{cut-in}}$.

**Zone II:** $P < P_{\text{rated}}$, $P = f(V_{\text{wind}})$ with pitch angle $\beta = 0$. The wind turbine operates with the maximum efficiency by maintaining the optimal $C_p$ when $V_{\text{cut-in}} < V_{\text{wind}} < V_{\text{rated}}$.

**Zone III:** $P = P_{\text{rated}}$ with $\beta > 0$. Output power is maintained at $P_{\text{rated}}$ through the dynamic pitch control when $V_{\text{rated}} < V_{\text{wind}} < V_{\text{cut-off}}$.

**Zone IV:** $P = 0$. The turbine is suspended by using mechanical brakes when $V_{\text{wind}} > V_{\text{cut-out}}$. 

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**Figure e4.18** Operation modes of PMSG-WTG system under different wind speed conditions.
Note that the above curve is only suitable for the ideal PMSG-WTG system. For a practical system, the stator winding power loss of generator and mechanical power losses of turbine should be taken into account, so the actual output power of PMSG at the rated wind speed is a little smaller than the 150 kW rated capacity. However, the operational objective of the proposed PMSG-WTG model is to utilize the wind power with the optimal power conversion efficiency. Meanwhile, the pitch control aims to regulate the generator power output within the rated power due to mechanical constraints and the converter current rating limit, especially when the actual output exceeds the rated value under a high wind speed condition as shown in Zone III.

4.3.1.1 Variable Speed Wind Turbine with Maximum Efficiency Operation

The mechanical power extracted from the kinetic wind energy is typically expressed by the following equation:

\[ P_w = \frac{1}{2} \pi R^2 \rho V_w^3 C_p(\lambda, \beta) \]  \hspace{1cm} (4.10)

where, \( P_w \) is the extracted wind power, \( \rho \) is the air density (= 1.225 kg/m\(^3\)), \( R \) is the rotor radius, \( V_w \) is the wind speed in m/s, \( \lambda \) is the tip speed ratio, \( \beta \) is the blade pitch angle in deg, \( C_p \) is the power efficiency coefficient (\( C_{p,\text{max}} = 0.438 \) at \( \beta = 0 \)) as a function of \( \lambda \) and \( \beta \).

The tip speed ratio is defined by:

\[ \lambda = \frac{\omega_t R}{V_w} \]  \hspace{1cm} (4.11)

where \( \omega_t \) is the mechanical rotational speed of the turbine in rad/s. For modern PMSG-WTG systems, the wind turbine and generator rotate on the same shaft without a gearbox. So, the generator rotor speed \( \omega_{\text{gen}} \) is equal to WT rotor speed \( \omega_t \). The aerodynamic efficiency of the wind turbine is approximately modeled as a non-linear function of pitch angle \( \beta \) and tip speed ratio \( \lambda \) as follows [8,13]:

\[ C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda_i} - 0.4 \beta - 5 \right) e^{\frac{12.5}{\lambda_i}} \]  \hspace{1cm} (4.12)

\[ \lambda_i = \frac{1}{\left( \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{\beta^3 + 1} \right)} \]  \hspace{1cm} (4.13)
The maximum output power of PMSG-WTG is achieved by tracking the rotor speed to the optimal point $\lambda_{opt}$. The corresponding optimal wind turbine rotor speed $\omega_{turb, opt}$ can be obtained by rewriting Eq. (4.14) as follows:

$$\omega_{turb, opt} = \frac{\lambda_{opt} V_{wind}}{R} \quad (4.14)$$

In the case of variable-speed PMSG-WTG, the rotational speed of the wind turbine is adjusted according to different wind speeds to ensure that the tip speed ratio $\lambda$ is maintained at the optimal value $\lambda_{opt}$. In this way, the power efficiency coefficient $C_p$ can reach its maximum value and consequently the maximum mechanical power can be extracted from wind energy. Furthermore, the maximum power $P_{max}$ can be expressed as:

$$P_{max} = \frac{1}{2} \rho \pi R^2 C_{p, opt} \left( \frac{\omega_{turb, opt} R}{\lambda_{opt}} \right)^3 \quad (4.15)$$

where $C_{p, opt}$ and $\lambda_{opt}$ are the optimal power coefficient and the optimal tip speed ratio, respectively. From this equation, it is obvious that the maximum power extracted from the wind is proportional to the cube of turbine rotational speed when the blade pitch angle $\beta$ is set to $0^\circ$. Thus, the optimal power operation of PMSG-WTG system can be achieved by regulating the generator rotor speed [8].

### 4.3.1.2 Two-Mass Drive Train Model

To fully assess the dynamic characteristics of multiple rotating masses connected to one single rotating shaft, an equivalent two-mass drive train model consisting of a turbine and a generator is established by applying a built-in multi-mass torsional shaft module. It can be directly interfaced with the PMSG module in PSCAD by using the rotor speed signal. The shaft dynamics with two rotating masses are shown in Figure e4.19. The larger rotor mass represents the wind turbine inertia while the other smaller rotor mass corresponds to the PMSG inertia. The specific mathematical model of this shaft system is expressed in the following:

$$J_W \frac{d^2 \theta_w}{dt^2} = T_w - D \left( \frac{d\theta_w}{dt} - \frac{d\theta_g}{dt} \right) - K(\theta_w - \theta_g) - D_W \frac{d\theta_w}{dt} \quad (4.16)$$

$$J_g \frac{d^2 \theta_g}{dt^2} = D \left( \frac{d\theta_w}{dt} - \frac{d\theta_g}{dt} \right) + K(\theta_w - \theta_g) - T_g - D_g \frac{d\theta_g}{dt} \quad (4.17)$$

with:
\[ J_w \text{ and } J_g \text{ are equivalent wind turbine inertia and PMSG inertia constant in kg}^2, \text{ respectively.} \]

\[ T_w \text{ and } T_g \text{ represent the mechanical torque and generator electrical torque in N} \cdot \text{m, respectively.} \]

\[ \theta_w \text{ and } \theta_g \text{ are the wind turbine’s angle and generator rotor’s angle in rad/s, respectively.} \]

\[ D \text{ is shaft mutual damping coefficient between two masses in N} \cdot \text{m/rad} \]

\[ D_w \text{ and } D_g \text{ is self-damping coefficient to represent friction and windage for wind turbine and generator mass.} \]

\[ K \text{ is the shaft stiffness factor in kg m}^2/\text{s}^2 \]

4.3.1.3 Pitch Control Model

One built-in model of a wind turbine pitch controller in PSCAD [11] is used to carry out the dynamic pitch angle regulation in the operation zone 3 in Figure e4.18. The basic control block diagram of this pitch servo is shown in Figure e4.20.
Here, a model of a three-blade wind turbine is defined by selecting MOD2 to conduct the power regulation. Moreover, dynamic pitch control is applied to maintain the actual output power of the generator below the rated power of 150 kW by increasing the pitch angle when the wind speed exceeds the rated wind speed. Therefore, the mechanical and electrical components of PMSG-WTG can be protected effectively under the high-wind speed condition.

4.3.1.4 Permanent Magnet Synchronous Generator
In this study, a built-in PMSG module in PSCAD is applied to build overall PMSG-WTG model. The rotor excitation of PMSG is provided by permanent magnets as a constant value, so the model of PMSG in the synchronous reference frame is given as:

\[
\begin{align*}
\frac{di_d}{dt} &= -\frac{R}{L_d} i_d + \frac{L_q}{L_d} i_q \omega_e + \frac{1}{L_d} u_d \\
\frac{di_q}{dt} &= -\frac{R}{L_q} i_q - \left(\frac{L_q}{L_d} i_d + \frac{1}{L_q} \psi_f\right) \omega_e + \frac{1}{L_q} u_q
\end{align*}
\] (4.18) (4.19)

The electromagnetic torque is expressed as follows:

\[
T_e = 1.5n_p ((L_d - L_q)i_d i_q + i_q \psi_f)
\] (4.20)

where subscripts “d” and “q” represent the physical quantities in the d- and q-axis respectively with the transformation of the synchronously rotating reference frame; \(R\) is the stator resistance; \(L_d\) and \(L_q\) are the d- and q-axis components of generator inductances, respectively; \(u_d\) and \(u_q\) are the d- and q-axis components of the stator voltage, respectively; \(i_d\) and \(i_q\) are the d- and q-axis components of the stator current, respectively; \(\omega_e\) is the electrical rotating speed; \(n_p\) is number of pole pairs; \(\psi_f\) is the permanent magnetic flux; \(T_e\) is the electromagnetic torque [10].

4.3.1.5 Power Converter System
4.3.1.5.1 Rotor-Side Converter
In Figure e4.21, a coordinated control strategy of back-to-back double pulse width modulation (PWM) converter is used in accordance with the dynamic characteristics of the PMSG system. The rotor magnetic flux oriented control technique is implemented for a decoupling control of d- and q-axis stator current components of the PMSG. For this purpose, the controller of the rotor-side converter has a cascade structure: a faster inner current loop for the q-axis current control is combined...
Figure 4.21 The control and protection scheme of proposed PMSG-WTG system.
with a slower outer loop for the optimal rotor speed regulation. By this means, the reference speed of the generator is dynamically modified in accordance with the variable wind speed so as to enable the wind turbine to operate at its maximum power tracking point.

The other control loop is used to regulate the $d$-axis current component for controlling the excitation flux of generator. As the $i_d$ is usually set to 0, the stator current is completely utilized for generating the maximum electromagnetic torque. Furthermore, the $d$- and $q$-axis voltage control signals of the machine-side converter are obtained by comparing the $d$-axis and $q$-axis current references with the actual generator stator $d$-axis and $q$-axis current values. With this control design, the current-regulated voltage-source PWM converter fulfills the optimal operation of PMST-WT system.

4.3.1.5.2 Grid-Side Converter
For the grid-side converter, a control method with a reference frame aligned along the inverter ac voltage is adopted, so the active power and reactive power delivered from PMSG-WT to the grid can be independently controlled. The grid-side converter takes advantage of two outer Proportional-integral (PI) control loops that define reference values $i_{d}^{	ext{ref}}$ and $i_{q}^{	ext{ref}}$ for two inner current control loops that control the $d$- and $q$-axis decoupling current components. Meanwhile, the inner current control loops determine the PWM modulation indices for the inverter control.

In this way, a grid-side converter is able to maintain the DC-link voltage constant and control the reactive power at the desired value. In addition, once the reference value of reactive power is set as 0, the inverter can operate in unity power factor mode to produce the maximum active power output.

4.3.1.6 DC-Link Over-Voltage Protection Scheme
An effective DC-link over-voltage protection controller is designed and integrated into this PMSG-WTG model. It is used to detect and limit the voltage magnitude across the DC-link within an acceptable level by applying a crowbar circuit at the stator side of the PMSG [13].

If a short-circuit fault occurs in the grid, the PMSG will continue to maintain the maximum power operation although the active power injected into the grid is reduced. As a result, the DC-link voltage will surge due to the power imbalance between the generator-side converter and the grid-side converter. Once the DC-link voltage exceeds
the protection limit (e.g., 1.07 p.u. as defined in this study), the crowbar will be activated through a power electronic circuit to consume excessive power from the PMSG. In this way, LVRT capability of the PMSG-WTG system is enhanced especially under the three-phase grid fault condition. As shown in Figure e4.21, a 150 kW PMSG-WTG system with the proposed control and protection scheme is connected to a 380 kV distribution network.

4.3.2 Coordinated Frequency Controller Design for PMSG-WTG System

Figure e4.22 presents the general control structure of a PMSG equipped with the proposed coordinated frequency regulation [14]. The constant inertial control and droop control are added into the rotor-speed controller to provide the rotor speed reference for the generator-side controller. Under normal grid operation, the rotor-speed controller regulates the rotor speed to make PMSG-WTG operate in de-loaded mode regardless of wind speed conditions. At this moment, both Switch 1 and Switch 2 stay in 0 mode.

According to the actual wind speed and measured system frequency at point of interconnection (POI), the coordinated frequency controller can identify specific frequency control strategy corresponding to the current wind speed and meanwhile coordinate the sub-controllers to provide a combined inertial response and primary frequency regulation during any frequency events. If a large frequency drop is detected through the coordinated frequency controller, sub-controller I changes the Switch 2 mode from 0 to 1. Through the action of the constant inertial controller, a constant amount of kinetic energy is quickly injected into the grid, sustaining for the predefined several seconds throughout the frequency event. Once the inertial response is completed, the mode of sub-controller I returns to 0 and at the same time the mode of sub-controller II changes Switch 1 from 0 to 1. From now on, the droop-speed controller and de-loaded controller function together to generate the rotor speed reference value for primary frequency regulation. For medium and high wind speed conditions, sub-controller III is activated to coordinate with the rotor speed controller for the inertial response and primary frequency regulation. If wind speeds are low, it acts to keep the pitch angle at zero. By this means, the system frequency is coupled with the rotational speed to facilitates frequency regulation of PMSG-WTG.
Figure 4.22 Schematic of overall control configuration of PMSG-WTG system with coordinated frequency regulation.
4.3.2.1 Rotor Speed Control
4.3.2.1.1 Constant Inertial Control
Using an inertial controller, a part of rotor kinetic energy is quickly delivered to the microgrid through the power converter, which can enhance the overall inertial response by mitigating the ROCOF and arresting any frequency nadir during the initial few seconds of the frequency event. Moreover, the inertial response can be controlled by changing the magnitude and duration of inertial power injection [15]. From literature review, there are three major types of inertial control methods including natural inertial control, constant inertial control and virtual inertial control [15–18]. For this study, the constant inertial control is adopted to change the rotor speed of PMSG to release the kinetic energy in a controllable manner.

As for constant inertial control, the inertial power refers to a constant amount of active power extracted from the WT kinetic energy of rotating mass, which is used to support the system frequency for a specified duration [18–20]. The equation for constant inertial power is derived from

\[ P_{\text{in}} = \frac{1}{2} J \omega^2_{r0} - \frac{1}{2} J \omega^2_{rt} \]  \hspace{1cm} (4.21)

where \( t \) is the duration of time for constant inertial power injection, \( \omega_{r0} \) is the initial rotor rotational speed and \( \omega_{rt} \) is the rotor rotational speed at the moment \( t \). Accordingly, the reference value for rotor rotational speed is as follows:

\[ \omega_{\text{ref}} = \omega_{rt} = \sqrt{\frac{\omega^2_{r0} - 2 \frac{P_{\text{in}}}{t}}{J}} \]  \hspace{1cm} (4.22)

By defining \( \omega_{\text{pu}} = \left( \omega / \omega_{\text{base}} \right) \) as the per-unit rotor speed and \( P_{\text{in\_pu}} = \left( P_{\text{in}} / S \right) \) as the per-unit inertial power output, the inertial constant \( J = \left( 2HS / \omega^2_{\text{base}} \right) \) is substituted into (4.23) so that the per-unit rotor speed reference is expressed as:

\[ \omega_{\text{rt\_pu}} = \sqrt{\frac{\omega^2_{\text{ro\_pu}} - \frac{P_{\text{in\_pu}}}{H}}{t}} \]  \hspace{1cm} (4.23)

The constant inertial response aims to reduce the system ROCOF by providing a continuous and steady amount of extra active power for a required period of time. The block diagram of constant inertial control is shown in Figure e4.23. Based on Eq. (4.24), the rotor speed
reference $\omega_{\text{ref}}$ is calculated and compared with measured rotor speed $\omega_{\text{r,meas}}$ through PI controller to obtain the $d$-axis current reference value that controls the active power output.

4.3.2.1.2 Droop Control
Based on the active power-frequency droop characteristic of a conventional synchronous generator, the droop controller is incorporated into the rotor speed control to regulate the active power output in proportion to the frequency deviation, so the PMSG-WTG shares the large increase in load with existing synchronous machine governors in a coordinated way. Compared with inertial control, droop control cannot effectively mitigate the initial ROCOF but can boost the frequency nadir and improve the frequency recovery process [20,21]. In case of a large frequency deviation, the extra active power generated by PMSG-WTG is derived from:

$$\Delta P = P_1 - P_0 = -\frac{f_{\text{sys}} - f_{\text{nom}}}{R}$$  \hspace{1cm} (4.24)

where, $f_{\text{sys}}$ is the per-unit system frequency and $f_{\text{nom}}$ is the per-unit nominal frequency, slope $R$ corresponds to the rotor speed adjustment rate. $P_1$ is the active power corresponding to $f_{\text{sys}}$ and $P_0$ is the initial active power output corresponding to $f_{\text{nom}}$. The value of $R$ usually lies within 3% to 5% for conventional generators. As shown in Figure e4.24, a high pass filter is applied to ensure that a permanent
frequency deviation has no effect on the overall control system. Meanwhile, a deadband controller is included for the droop function to be effective under large frequency disturbance.

4.3.2.1.3 De-loaded Control

In order for a PMSG-WTG to participate in primary frequency regulation, a certain level of primary reserve margin needs to be maintained so that an amount of regulation power can be provided to enhance the system frequency response following a frequency disturbance.

According to the requested power reserve from system operator, the primary reserve can be carried out through either “balance” or “delta” control [22]. In this chapter, delta control is adopted based on the maximum power point tracking (MPPT) strategy to ensure PMSG-WTGs de-loaded operation with a constant and steady reserve margin in accordance with different wind speeds. In principle, there exist three types of PMSG-WTG operation modes corresponding to low wind speed, medium wind speed and high wind speed. Regardless of wind speed conditions, the rotor speed reference for PMSG-WTG’s de-loaded operation can be obtained through the sub-optimal operation curve, which is established using the de-loaded algorithm and saved in a look-up table.

To equip the PMSG-WTG with de-loaded operation capability, the sub-optimal active power reference can be attained from the optimal power calculation for a given wind speed condition. By reading a look-up table with respect to the mechanical power and rotor speed characteristics, the reference rotor speed can be acquired through the sub-optimal extraction power curve at a certain wind speed which corresponds to a specified percentage of de-loaded power. By this means, the wind turbine is able to operate in the de-loaded mode with a predefined amount of power reserve margin.

In Figure e4.25, the left and right de-loaded power reference curves for PMSG-WTG under various wind speeds are depicted according to high, medium and low wind speed regions. The wind turbine is supposed to operate at the right sub-optimal curve in order to maintain a stable operation for providing power reserves over a full scope of wind speeds as well as storing more extra inertial energy in the wind turbine when operating at the higher tip speed ratio than optimal value. The left sub-optimal operation point is unstable and more likely to cause the wind turbine to stall when the grid frequency drops to a certain point [16,23].
Using rotor speed control, the wind turbine initially works at point A with the power output of $P_0$. Assuming a sudden increase in load when WT runs under medium wind speed, a resulting $\Delta P$ increase in the electromagnetic power will cause the wind turbine rotor speed to decelerate from operating point A on the right de-loaded curve toward point E due to power imbalance. Once the rotor speed eventually arrives at the point E, PMSG-WTG will maintain stable operation at a new equilibrium state with a mechanical power output of $\Delta P + P_0$.

4.3.2.2 Modified Pitch Angle Control

In order to ensure dynamic power balance, a modified pitch angle controller is designed corresponding to high, medium and low wind speed conditions. The mechanical power of wind turbine is dynamically regulated through pitch angle controller for the primary frequency regulation.

Using this modified pitch angle control, the power balance between the mechanical power input and electrical power output of PMSG-WTG is achieved during the primary frequency regulation in the medium and high wind speed modes. As shown in Figure e4.26, the variable pitch servo system is modeled by first-order delay module. In this way, the coordinated frequency regulation is fulfilled using the PMSG mechanical component over a full range of wind speeds.
4.3.3 Coordinated Frequency Control Scheme
From the perspective of response time, the coordinated frequency control strategies are specifically implemented in the following two stages when system frequency drops due to a heavy load ramp-up or large generator trip. (1) In the initial state, constant inertial control plays a significant part in reducing the ROCOF in the short term. As the inertial energy is quickly released into the microgrid over several seconds, primary frequency regulation will take over after inertial response is completed. (2) For an extended period of time, both rotor speed controller and pitch angle controller are coordinated to support the system primary frequency control in the long term by using the reserved power [14,24].

From the perspective of operational flexibility and security, the coordinated frequency regulation of PMSG-WTG needs to be accommodated for different wind speeds as shown in Figure e4.27. The value of $\omega$ required for the de-loaded operation between medium and high wind speeds is often greater than maximum allowable rotor speed $\omega_{\text{max}}$. To enable WT to operate in the delta de-loaded mode for coordinated frequency regulation, three types of wind speed modes have to be identified: low wind speed mode where the de-loaded operation and frequency regulation is realized only by rotor speed control; medium wind speed mode where a coordinated frequency regulation is achieved by both pitch angle control and rotor speed control; high wind speed mode where the modified pitch angle control is adopted for the de-loaded operation and frequency regulation. Note that a delta reserve corresponding to 90% de-loaded operation is achieved by the PMSG-WTG system in order to
Figure 4.27 Schematic of coordinated frequency regulation controller at the generator side converter.
maintain a 10% power reserve for system frequency regulation. This 10% load margin is available over a full range of wind speeds. Therefore, the 90% de-loaded rotor speed reference for PMSG-WTG steady-state operation can be obtained by tracking the purple solid line GCH in Figure e4.25.

1. Mode 1: in the low wind speed range from cut-in speed to 9.58 m/s, the over-speed operation of rotor is capable of achieving the 90% de-loaded operation without pitch angle control used. The active power output can be regulated only by a rotor speed controller. The rotor speed reference $\omega_{\text{ref}}$ is obtained from the de-loaded operation curve as depicted in line segment I-G-F-C in Figure e4.25. The pitch angle controller is deactivated by setting the pitch angle reference to zero. For instance, if the frequency drops below the lower limit, the rotor speed control will boost the active power output by decelerating the rotor speed, so that the operating point moves from the 90% right de-loaded curve toward the MPPT curve. If the rotor speed decreases toward the lower limit of 0.7 p.u., the rotor speed is settled by locking $\omega_{\text{ref}}$ as 0.7 p.u. Meanwhile, the pitch control is still inactive. During the very low wind speed profile, the WTG system cannot provide more additional active power for a longer duration due to the minimum rotor speed limit.

2. Mode 2: in the medium wind speed range from 9.58 to 11.98 m/s, the active power output should be regulated by means of both rotor speed and pitch angle controller since it is not possible for the rotor-speed controller alone to maintain the 90% sub-optimal operation owing to the rotor speed upper limit (1.0 p.u.) as indicated by the line C-A-H in Figure e4.25. A rotor speed control combined with a pitch angle control is presented in Figure e4.26. As an illustration, in Figure e4.25 assuming a wind speed of 10.78 m/s, then the rotor speed is controlled at point A with aid of pitch angle control. Here, it is assumed that a sudden increase in load occurs when PMSG-WTG runs in medium wind speed. The extra active power production, $\Delta P$, needed from pitch angle control is calculated according to the droop control Eq. (4.25). Lastly, the steady-state operating point will arrive at the point E according to the dashed straight line A–B in order to realize the droop control primary response. The rotor speed reference value $\omega_{\text{ref}}$ for the generator side controller will change from 1.0 p.u. to $\omega_E$, which
can be calculated simply through implementation of a linear interpolation method as follows [24].

\[
\frac{\omega_B - \omega_E}{\omega_B - \omega_A} = \frac{P_B - P_E}{P_B - P_A}
\]

(4.25)

where, \( \omega_B \) is the optimal rotor speed; \( P_B \) is the optimal active power; \( P_A \) is equal to 90% of optimal active power. So, if there is an increase \( \Delta P = \Delta P_{\text{droop}} \) in the active power output of PMSG-WTG, then the total power output at the operating point E will be \( P_E = P_A + \Delta P = 0.9P_{\text{MPPT}} + \Delta P \) with \( \omega_A = 1.0 \text{ p.u.} \). The rotor speed reference \( \omega_{\text{ref}} \) for generator side controller is obtained from

\[
\omega_{\text{ref}} = \omega_E = 1 + \frac{\Delta P}{0.1P_{\text{MPPT}}} (\omega_{\text{MPPT}} - 1)
\]

(4.26)

All the variables in above equation are measured in per-unit system. Using this method, combined rotor speed and pitch angle controller is capable of operating the wind turbine at the steady point E and it effectively participates in the primary frequency regulation under medium wind speeds.

3. Mode 3: in the high wind speed range from rated wind speed of 11.98 m/s to cut-out speed, the pitch angle control alone is responsible for maintaining the 90% de-loaded operation as well as regulating the extra active power output during the frequency event. The rotor speed controller cannot contribute to auxiliary frequency regulation since the rotor speed is kept at the upper limit of 1.0 p.u. Therefore, the active power needs to be kept at 0.9 p.u. for constant de-loaded operation merely through the pitch angle controller. For example, once a drop in system frequency occurs, extra active power is delivered only by reducing the pitch angle without the rotor speed control used.

4.3.4 Test System and PMSG-WTG Model
A microgrid model is established using the PSCAD/EMTDC software package. As depicted in Figure e4.28, the 50 Hz test system comprises a 150 kW PMSG-WTG, a 900 kVA small-scale synchronous generator, one constant active power load as well as a reactive power compensation capacitor connected to a 380 kV bus bar. The PMSG-WTG system is directly connected to the common bus through the PCC to supply the required active power and reactive power. Also, the governor of synchronous generator has a droop controller to assist in stabilizing the system frequency by sharing the load change with the PMSG-WTG.
In order to evaluate the effectiveness of the coordinated frequency regulation of a single PMSG-WTG in an islanded microgrid, an abrupt disconnection of the microgrid from the main grid is simulated at $t = 2$ s, which leads to a sudden drop in the system frequency. Once the system frequency drops below the minimum allowable value (49.95 Hz limit is assumed for this inertial control), the inertial response of 0.01 p.u. will be immediately provided by PMSG-WTG and then its primary frequency regulation will follow, as long as the inertial power injection is finished. As a consequence, the ROCOF, frequency nadir and the process of frequency recovery can be observed in a noticeable manner when the results of four cases consisting of no auxiliary control, constant inertial control, droop control and coordinated frequency control are compared together.
4.3.5 Simulation Cases

Case 1: Low wind speed \( (V_{\text{wind}} = 8.38 \text{ m/s}) \)

Case 2: Medium wind speed \( (V_{\text{wind}} = 10.2 \text{ m/s}) \)

Figure e4.29 Performance of PMSG-WTG under a low wind speed. (a) System frequency, (b) active power output of PMSG-WTG, (c) rotor speed of wind turbine, and (d) pitch angle (Blue curve: no auxiliary control, green curve: only constant inertia control, yellow curve: only droop control, red curve: coordinated frequency control).

Figure e4.30 Performance of PMSG-WTG under a medium wind speed. (a) System frequency, (b) active power output of PMSG-WTG, (c) rotor speed of wind turbine, and (d) pitch angle (Blue curve: no auxiliary control, green curve: only constant inertia control, yellow curve: only droop control, red curve: coordinated frequency control).
Case 3: High wind speed ($V_{\text{wind}} = 12.5 \text{ m/s}$)

![Graphs and figures illustrating system frequency, active power output, rotor speed, and pitch angle for different control strategies under high wind speed.]

Figure 4.31 Performance of PMSG-WTG under a high wind speed. (a) System frequency, (b) active power output of PMSG-WTG, (c) rotor speed of wind turbine, and (d) pitch angle (Blue curve: no auxiliary control, green curve: only constant inertia control, yellow curve: only droop control, red curve: coordinated frequency control).

From Figures 4.29 to 4.31, PMSG-WTG’s operation characteristics and system frequency regulation performances subjected to different controls are compared with the proposed coordinated frequency control under various wind speed modes. In case 1, the extra active power output is regulated from the rotor speed control while the pitch angle is set as $0^\circ$. In case 2, a combined pitch angle and rotor speed control are implemented together to generate the additional active power using the droop control. In case 3, the extra active power is controlled only by pitch angle control by taking into account both rotor speed upper limit and specified reserve margin constraint.

Without any auxiliary frequency control scheme, the output of PMSG-WTG remains constant so no additional active power is generated to improve the frequency of the islanded microgrid if a frequency disturbance occur. In contrast with the natural inertial response in Ref. [24], the implementation of constant inertial response will result in the controlled active power output with moderate ramping rate. It helps reduce the structural load induced on wind turbine and also prevent
the excessive load and permanent damage on power converter plus generator. Moreover, the rate of change of frequency can be substantially smoothed due to constant inertial response and frequency nadir can be obviously lifted as shown in Figures e4.29(a)–4.31(a). During the stage of kinetic energy release in Figures e4.29(b)–4.31(b), the kinetic energy stored in the rotating mass is quickly extracted and released in conjunction with a portion of the 10% reserve power. Thus, this combined power injected into the microgrid can serve as additional active power support through the power electronic converter when the rotor speed of the wind turbine decelerates. During the stage of kinetic energy recovery, one portion of aerodynamic energy has to be utilized to contribute to both rotor speed recovery and kinetic energy restoration for the future supplementary frequency support. Due to the power imbalance between generation and demand in an islanded microgrid, it is more likely to result in a secondary frequency decline and even make frequency nadir lower. To avoid this unacceptable situation, a constant inertial response is required to sustain as long as possible (usually above 10 s or so) so that it could go through the initial frequency nadir and then last for several extra seconds.

Using only governor-droop control, PMSG-WTG is capable of cooperating with the conventional synchronous generator to share the large increase in load, so the rate of change of frequency can be slightly reduced and at the same time the frequency nadir can be significantly increased as shown from Figure e4.29(a) to 4.31(a). In this way, the amount of conventional spinning reserve used for the primary frequency regulation can be reduced accordingly. Moreover, the frequency can settle down to a new steady-state operation point after undergoing transient oscillations. In contrast, droop control takes much longer period to restore the microgrid frequency to steady state than only constant inertial response does. Compared with the pitch control applied in the high wind speed case, droop control has faster dynamics in response to a frequency event because of the fast and robust power conversion control under low and medium wind speed conditions. As a result, the frequency recovery process under low and medium wind speeds is much shorter than the case under high wind speeds.

4.3.6 Conclusions
Based on simulation results from case 1 to case 3 under different wind speed conditions, the coordinated frequency control scheme can optimally enhance the overall system frequency regulation of islanded
microgrid. During the initial few seconds, the inertial response can greatly mitigate the rate of change of frequency. By means of combined rotor speed and pitch angle control, a certain specified amount of reserved power is utilized to enhance the primary frequency regulation capability in order to boost the frequency nadir and stabilize the frequency oscillation.

Therefore, the system frequency stability of microgrid operating in the islanded mode can be greatly improved by enabling PMSG-WTG to provide the coordinated frequency regulation capability.

### 4.4 COORDINATED FREQUENCY REGULATION BETWEEN WIND POWER GENERATION AND ENERGY STORAGE SYSTEM IN THE ISLANDED MICROGRID

In this part, three-section coordinated frequency control strategy between wind power generation and BESS is proposed to realize the comprehensive frequency regulation consisting of inertial response, primary droop control and secondary AGC regulation. It aims to improve the overall frequency response of an islanded microgrid in the event of severe frequency disturbance. As shown in Figure e4.32, a complete frequency regulation of islanded microgrid or microgrid cluster comprises the inertial response, primary frequency control

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**Figure e4.32** Schematic diagram of multi-level frequency control following a large generation loss. (Figure based on image provided by Pouyan Pourbeik of EPRI).
(droop control), secondary frequency control (AGC) and tertiary frequency control (economic dispatch) in terms of time scale when a sudden loss of generator or sudden connection of a large load occurs.

4.4.1 Coordinated Inertial Response between Wind Power Generation and BESS

4.4.1.1 Coordinated Control of VSWT with BESS for Enhanced Inertial Response

Since VSWT can utilize the pitch angle controller to reduce the active power output during the over-frequency event, this book will mainly focus on the more complicated under-frequency case. In comparison with virtual inertial response of wind power generation, response of BESS is much faster with a response time of about 30 ms [3]. Unlike wind generation, there is no need for BESS to restore the inertial energy and thus potential secondary frequency drop and frequency oscillation can be avoided [23,25]. However, the inertial response from kinetic energy in the rotating mass of wind turbine and generator is of great help in reducing the ROCOF and increasing the frequency nadir in the under-frequency event of an islanded microgrid. In general, the faster the rotor speed of WT declines, the larger the transient active power injection is and consequently the less steep the ROCOF of islanded microgrid becomes, despite extra time being required for restoring the system to another steady state condition. So, a simple coordinated inertial response between wind power generation and BESS is applied here to leverage their own strengths for better performance in the inertial response.

In Figure e4.33, the real-time inertial power output from BESS is distributed as additional power reference among selected wind power generators based on Participation Factor (PF). In this way, those wind

$$
\Delta P_{\text{inertial, BESS}} = \frac{P_{F_{\text{WTG1}}}}{C_1 s + 1} \Delta P_{C_1} + \frac{P_{F_{\text{WTG2}}}}{C_2 s + 1} \Delta P_{C_2} + \ldots + \frac{P_{F_{\text{WTGn}}}}{C_n s + 1} \Delta P_{C_n}
$$

Figure e4.33 Block diagram of coordinated inertial control between BESS and WTG in the islanded microgrid [26].
power generators are able to follow the inertial response of the BESS as early as possible by adjusting their outputs based on the allocated additional power reference so that the descending inertial power output can be compensated during the later stage of the improved inertial response as seen in Figure e4.33. This coordinated control strategy is technically feasible because those selected WTGs are operated in the de-loaded mode. Note that the PF$^i$ of a certain wind turbine generator is determined by its ramp rate ($R^i_{WTG}$) that varies as wind speed changes. Assume that there are $n$ VSWTs operating in the islanded microgrid. The PF$^i$ of each VSWT is computed from the individual ramp rate $R^i_{WG}$ in Eq. (4.27). If the wind speed is higher, the rotor speed is faster and the ramp rate can be set higher accordingly since more kinetic energy is available for inertial power provision of VSWT and thus the resulting PF$^i$ is set at higher value. Hence, this method is effective in reducing the power imbalance caused by the decreased inertial response of BESS as the frequency approaches the nadir point, so the overall inertial response of islanded microgrid can be further improved.

\[
\begin{align*}
PF_{WTG1} &= \frac{R_{WTG1}}{R_{WTG1} + R_{WTG2} + R_{WTG3}} \\
PF_{WTG2} &= \frac{R_{WTG2}}{R_{WTG1} + R_{WTG2} + R_{WTG3}} \\
PF_{WTG3} &= \frac{R_{WTG3}}{R_{WTG1} + R_{WTG2} + R_{WTG3}} \\
\sum_{i=1}^{n} PF_{WTGi} &= 1
\end{align*}
\]

(4.27)

4.4.1.2 Coordinated Control of BESS for Assisting VSWT in Inertial Recovery

On the other hand, a BESS can assist VSWTs in the rotor speed restoration during their inertia recovery process. In general, once the wind turbine is totally released up at the moment of frequency nadir, the energy extracted from rotating mass needs to be recovered from the available wind power in order to restore the rotor speed and kinetic energy to the pre-disturbance value. However, a short-term dip occurs in the active power output of the VSWT and thus this temporary power imbalance in islanded microgrid leads to a secondary frequency drop. To avoid this situation, BESS is controlled to provide a certain amount of active power that allows VSWT to regain the rotor speed without compromising their electrical power outputs during the recovery stage.
As shown in Figure e4.34, the rotor speed of VSWT should be restored in a controlled manner with reference to Eqs (4.28) and (4.29), so that it gradually returns to the de-loaded value that corresponds to present wind speed using the rotor speed recovery buffer function [23,25]. In Eq. (4.29), \( t_{re} \) is the rotor speed recovery duration. In this way, the frequency oscillations of an islanded microgrid is mitigated during the VSWT rotor speed restoration.

\[
\omega_{ref} = (\omega_{deloaded} - \omega_t) * f(t) + \omega_t \quad (4.28)
\]

\[
f(t) = \begin{cases} 
\ln 2 \cdot t \over t_{re} & , \quad 1, t < t_{re} \\
2^t - 1 & , \quad 1, t \geq t_{re} 
\end{cases} \quad (4.29)
\]

In Figure e4.35, the BESS will discharge the maximum power \( P_{max} \) at \( t_1 \) when the VSWTs rotor speed is ready to be restored. The maximum output sustains until the microgrid frequency reaches the
steady-state value $f_{\text{ref}}$. From $t_2$ on, the active power released by the BESS descends to prevent the sudden rise of system frequency due to its excessive power injection. A supplementary control loop is added to generate the $P_{\text{Ef}}$ from the BESS. In Eq. (4.30), the total power reference of BESS is $P_{\text{Eref}}$ for coordinated inertial response with VSWT. This reference aims to maintain the steady-state frequency constant during the descending process of $P_{\text{E1}}$.

$$P_{\text{Eref}} = P_{\text{E1}} + P_{\text{Ef}}$$  \hspace{1cm} (4.30)

The coordinated control strategy suitable for BESS and VSWT is illustrated in Figure e4.36 to provide the comprehensive inertial response during event of under frequency. The main objective of this
control method is to take full advantage of both VSWT and BESS characteristics to enhance the overall inertial response of the islanded microgrid and minimize the impact of the VSWTs inertial recovery on the system frequency as well. The system inertial response in under-frequency case basically comprises four steps as follows [23,25]:

1. The monitoring system detects the ROCOF $\frac{df}{dt}$ value in a real-time manner. Once $\frac{df}{dt}$ is found to be smaller than the specified value $-a$ ($a$ is positive) and the time delay exceeds $T_a$, the inertial response of BESS is triggered to offer a faster power injection and allocated as the power reference $\Delta P_{\text{inert}}$ among other VSWTs for timely tracking of the inertia power output of the BESS when the SOC is above the minimum limit (SOC$_{\text{min}}$).

2. Based on the above condition, if the rotor speed $\omega_r$ of VSWT goes beyond the allowable limit $\omega_{r\text{, max}}$ and power output of VSWT $P$ retains below the maximum value $P_{\text{max}}$, VSWT will start to provide the inertial response by reducing the rotor speed.

3. When $\frac{df}{dt}$ is larger than zero and the delay time is over $T_b$, the frequency of the islanded microgrid will be restored. If the SOC is higher than SOC$_{\text{min}}$, $\omega_r$ is restored with the support of the BESS. Otherwise, $\omega_r$ is restored only by the VSWT in a controlled manner as shown in Figure e4.36 so as to reduce the negative effect of inertial recovery on the frequency.

4. When the $\frac{df}{dt}$ value is kept within a small limit and sustains for a certain period of time that exceeds $T_c$, it implies that system frequency has reached another steady-state condition and rotor speed restoration of VSWT is completed. At that moment, SOC restoration will get started by charging the BESS. The entire process of coordinated frequency regulation ends up with the SOC getting restored to its normal level.

### 4.4.2 Coordinated Frequency Droop Control Strategy with Wind Power Prediction and Energy Storage System Participation

To overcome the limitations of the classical feedback frequency droop control method, which is only activated after the frequency deviation happens, a novel coordinated droop control strategy for ESS based on wind power prediction is presented. The proposed frequency control strategy includes two stages: in the first stage, the ESS regulates its power output based on the wind power prediction; in the second stage,
frequency feedback is used to regulate the ESS power output to further reduce the steady-state frequency deviation. Since the ESS power output can be regulated before the frequency deviation happens, the dynamic response speed of ESS’s frequency regulation can be significantly improved. Besides, frequency deviation can be decreased thanks to the step command in the first stage.

Based on the wind power prediction technology, active power regulation requirement for ESS can be predicted. Hence, the upper limit can be calculated so that the required active power regulation capacity for ESS can be guaranteed. Simulations of a microgrid wind power system are performed in Real Time Digital Simulator (RTDS). The results show the effectiveness of the presented frequency regulation methods.

**4.4.2.1 Frequency Regulation by BESS**

**4.4.2.1.1 Effect of BESS on Frequency Regulation**

Due to the variability and difficulty in the forecast of wind power, wind power can be treated as negative load and added with the grid loads. In this way, the equivalent grid load is obtained after wind power integration. According to different regulation modes of shifting daily load peaks and valleys, wind power’s peak shaving function can be divided into positive peak shaving mode and negative peak shaving mode. Positive peak shaving effect refers to the scenario in which wind power output curve is positively correlated with load curve. In contrast, negative peak shaving effect refers to the scenario in which wind power output curve is negatively correlated with the load curve.

The effect of a BESS on frequency regulation is discussed in detail in Ref. [27]. Due to its fast active power compensation ability, BESS is very effective in reducing system frequency deviations. For example, frequency deviations with and without BESS are compared for a month in Ref. [27], as shown in Figure e4.37. The frequency deviation without BESS reaches a maximum peak of 490 mHz on the 24th of the month, while the value is only 130 mHz during the same time period with a BESS. Hence, a significant improvement in dynamic frequency performance is obtained with the application of a BESS. The deadband here is set from 49.95 to 50.05 Hz. Within this deadband range, primary frequency regulation is not activated. Beyond this deadband, primary frequency control is activated according to the power-frequency (p-f) droop characteristic. Since renewable generators
are connected to the microgrid through an inverter interface, there is very limited system inertia. That is to say, compared to the interconnected grids, the inertia of the microgrid is much smaller. Thus, even relatively small power disturbances may result in great frequency deviations in the microgrid. Once the measured frequency reaches the deadband threshold value, primary controllers activate the primary frequency regulation to compensate for the power mismatch between power generation and load.

BESS is able to alternatively supply and absorb power to and from the microgrid quickly. At and beyond the deadband threshold value, the BESS supplies to or absorbs from the microgrid. For example, if frequency exceeds the deadband threshold value (50.05 Hz), the BESS absorbs power, and conversely it delivers power to the grid during under-frequency period. On the other hand, if the frequency deviation is within the range of 49.95–50.05 Hz, the power supplied or absorbed by BESS is zero.

4.4.2.1.2 Classical Frequency Feedback Control for BESS
The classical droop control scheme regulates the BESS power output based on the frequency deviation. The classical frequency droop control for a BESS is shown in Figure 4.38. For example, when the frequency drops, the reference of BESS power output will increase to
support the system frequency. The amount of change in the BESSs power output can be computed as:

\[ \Delta P = -K \times \Delta f \]  

(4.31)

where \( K \) is the droop coefficient of the BESS frequency response.

4.4.2.2 Novel Frequency Control Scheme for BESS Based on Wind Power Prediction

Here, a two-stage control scheme for BESS is proposed to participate in frequency regulation. In the first stage, a step command is issued to the BESS controller based on the wind power prediction information. The required frequency regulation capacity from the BESS can be calculated as a step command based on the wind power prediction. Because of the inaccuracy of wind power prediction, classical frequency droop control is used to regulate the BESS power output according to the actual requirement of frequency regulation capacity for the BESS.

A flowchart of the proposed control scheme for frequency regulation with BESS participation is shown in Figure e4.39. This new control scheme can improve the response speed of the BESS and decrease the frequency deviation when power disturbance happens in the microgrid system. The details of control scheme are described as follows.

4.4.2.2.1 First Stage Control Based on Wind Power Prediction

The wind power prediction system can predict wind power output at every time step. For example, if the time step is 10 s, prediction system can send the predicted value for wind power output of next time step. Hence, power disturbance \( P_w \) resulting from wind fluctuation at every time step can be obtained.

Frequent charging and discharging will shorten the life of the battery. Hence, the participation of the BESS in the frequency regulation should be activated only when frequency regulation capacity of the conventional units such as gas turbines are not sufficient to counteract the wind power disturbance.
According to the primary frequency regulation formula of a conventional generator, its maximum primary frequency regulation capacity $P_{\text{max}}^G$ can be expressed as follows:

$$P_{\text{max}}^G = \sum_{i=1}^{n} K_i \cdot \Delta f_{\text{max}}$$

(4.32)

where, $K_i$ is the coefficient of frequency response of unit $i$; and $\Delta f_{\text{max}}$ is the maximum permissible frequency deviation value. The spinning reserve of the conventional power units $P_{\text{reserve}}$ can be expressed by:

$$P_{\text{reserve}} = P_{\text{MAX}} - P_G$$

(4.33)

where $P_{\text{MAX}}$ and $P_G$ are the installed capacity and the measured power output of the conventional power units, respectively. $P_G$ can be monitored by a Remote Terminal Unit (RTU) or a Phasor Measurement Unit (PMU).
Hence, the regulation capacity of the conventional power units $P_{\text{regu}}$ can be calculated by:

$$P_{\text{regu}} = \min(P_G^{\text{max}}, P_{\text{reserve}})$$

(4.34)

The regulation capacity of the conventional power units $P_{\text{regu}}$ is the smaller value of maximum primary frequency regulation capacity $P_G^{\text{max}}$ and spinning reserve of the conventional power units $P_{\text{reserve}}$. When $P_{\text{regu}} < P_W$, frequency regulation of BESS is activated because frequency regulation capacity of the conventional units is not enough. The controller computes the frequency regulation capacity shortage as the step command value to regulate the power output of BESS. The step command for BESS can be computed as:

$$P_{\text{command}} = P_W - P_{\text{regu}}$$

(4.35)

Since the step command is sent to the BESS before any frequency deviation occurs, the dynamic response of frequency control can be greatly improved. Besides, the frequency deviation can be decreased thanks to this feed-forward step command.

### 4.4.2.2.2 Second-stage Control Based on Frequency Droop Control

Note that the wind power prediction inaccuracy may result in control error of the BESS’s frequency regulation. Hence, the frequency droop control is also used to regulate power output of BESS based on the real-time measurement information. Thanks to this, even if significant prediction error occurs, the proposed control scheme is still effective.

When power disturbance ($P_{\text{step}}$) occurs in the power system, we have the following frequency deviation:

$$\Delta f = \frac{P_{\text{step}}}{n K_{\text{ESS}} + \sum_{i=1}^{n} K_i}$$

(4.36)

where $K_{\text{ESS}}$ is the equivalent frequency droop coefficient of the BESS. With the proposed two-stage control droop coefficient applied, the steady-state frequency deviation can be computed as:

$$\Delta f = \frac{P_{\text{step}} - P_{\text{command}}}{n K_{\text{ESS}} + \sum_{i=1}^{n} K_i}$$

(4.37)

Since $P_{\text{command}}$ is independent of the frequency deviation, frequency deviation can be decreased.
4.4.2.3 Case Study – Simulation Results
This section presents RTDS simulation results to demonstrate the effectiveness of the proposed control scheme. The installed capacity of the test system is 120 kW, including two 35 kW thermal power units, one 30 kW wind turbine generator and one 20 kW BESS. The total load of this system is 80 kW and 36 kVar. The structure of the system is shown in Figure e4.40. Note that the test system’s nominal frequency is 50 Hz.

In the simulation case, wind power output decreases from 30 kW to 15 kW, as shown in Figure e4.41(b). Before this power disturbance, the total power output of two thermal power units is 50 kW. $\Delta f_{\text{max}}$ is set to 0.5% (0.25 Hz) and $P_{G}^{\text{max}}$ is set to 10% of the rated active power capacity. Calculated by (4.32) and (4.34), $P_{\text{regu}}$ is equal to 7 kW.

Without the frequency regulation participation of BESS, thermal power units are burdened with all the required regulation capacity, that is, 15 kW, as shown in Figure e4.41(a). Figure e4.41(c) shows the power output of the BESS. Due to the poor frequency regulation capacity of the overall system, the frequency drops below 49.5 Hz in transient process and stabilizes at 49.52 Hz in steady state, as shown in Figure e4.41(d). This frequency deviation exceeds $\Delta f_{\text{max}}$, which might result in the activation of under-frequency protection.
With the classical frequency feedback control applied, BESS shares the burdens of the frequency regulation capacity together with the thermal power units when frequency deviation occurs. As shown in Figure e4.42 (c), power output of BESS increases by 8 kW when frequency drops. Thanks to this, frequency is maintained at 49.77 Hz in steady state, as shown in Figure e4.42(d). The wind power and thermal power output is shown in Figure e4.42(a) and (b), respectively.

Better control effect can be obtained if the proposed two-stage control scheme as shown in Figure e4.39 is applied. In this case, the wind power prediction error (under-prediction) is considered as 10% of the installed capacity of the wind turbine, that is, 3 kW. Based on the control scheme shown in Figure e4.39, the step command in first stage is computed as 5 kW when $P_{\text{regu}}$ is equal to 7 kW and $P_W$ is equal to 12 kW. Besides, frequency droop control is also applied to mitigate the effects due to inaccuracy of wind power prediction.

Figure e4.41 Simulation result without BESS participation in frequency regulation: (a) thermal power units output; (b) wind power output; (c) BESS power output; and (d) grid frequency.
As it is shown in Figure e4.42(c), the output power of the BESS increases by 10.2 kW when wind power decreases rapidly. The frequency deviation in steady state is 0.15 Hz, which is 0.08 Hz smaller than the case with only classical frequency feedback control scheme, as shown in Figure e4.43(d).

4.4.2.4 Conclusion and Discussions

The stochasticity and intermittency of wind power bring operational challenges to security of microgrid systems with high penetration of renewable energy sources. This chapter presents a two-stage frequency regulation strategy with BESS participation. Since the BESS can regulate its active power output based on the wind power prediction information, the frequency regulation response speed can be improved. Besides, frequency deviation can also be decreased when a power disturbance occurs. RTDS simulation results show the effectiveness of the proposed control strategy. With this method, the dynamic response
speed of frequency regulation of BESS can be significantly improved. Besides, since the step command for the BESS output control system is independent of frequency deviation, the frequency regulation error can be decreased compared with the classical frequency droop control scheme. The proposed control strategy provides a solution to the frequency regulation issue of renewable energy based microgrids.

Additionally, according to the droop characteristics of VSWTs as well as reserve capacity demand for primary frequency regulation of the islanded microgrid, the regulation coefficients \( K_{\text{BESS}} \) and deadband of BESS should be reasonably set in order to share a sudden change in load with other VSWT equipped with droop control. The coordinated primary droop control strategy aims to ensure that the system frequency can quickly and steadily restore to the acceptable range after disturbance, with little or no power oscillation occurring during

\[ \text{Figure e4.43 Simulation result with proposed two-stage control scheme for BESS participation in frequency regulation: (a) thermal power units output; (b) wind power output; (b) BESS power output; and (d) grid frequency.} \]
this recovery process. Meanwhile, a sufficient amount of reserve capacity for secondary frequency regulation/AGC of BESS should be maintained as well.

4.4.3 Coordinated Secondary AGC Control Strategy Between Wind Power Generation and BESS

For microgrids containing BESS and VSWTs, the primary objective of the AGC is to maintain the islanded microgrid’s frequency deviation at zero and regulate the power interchange between the grid-connected microgrid and main grid at the scheduled value over time by coordinating the output of BESS and VSWTs on the basis of the principle of optimal allocation. This function is also referred to as load frequency control [28]. The secondary objective is to allocate the desired change in generation among BESS and VSWTs so as to minimize the total operation cost in the microgrid. Here, we are mainly centered on the LFC aiming to restore the system frequency to the specified nominal value and maintain the interchange power at the scheduled value. As for interchange power through tie line, there are different definitions in terms of a single islanded microgrid and an islanded microgrid cluster.

4.4.3.1 LFC Applied for a Single Islanded Microgrid

In the single islanded microgrid, tie line power can be envisaged by dividing the microgrid into two areas systems as depicted in Figure e4.44. During this division process, at least one power
A generation system or BESS with its adjustable output and one load are incorporated into each area and these two areas are connected through a virtual “tie line” that allows for the bidirectional power flow exchange. In this case, each area is responsible for achieving its own LFC objective of eliminating the frequency deviation and tie-line power error by adjusting the output power of designated generation units. In other words, if there is a sudden change in the load of area 1, AGC control merely acts to restore the balance between load and generation in area 1 rather than area 2. In Ref. [29], a novel metric named virtual area control error (VACE) is proposed by taking into account the SOC of the BESS in order to enhance the LFC performance of two areas within a single microgrid. In Ref. [30], a type of power demand estimation method is presented to maintain the tie-line power flow deviation.

In Figure 4.45 and Eq. (4.32), area control error (ACE) of a single islanded microgrid is computed based on the frequency deviation $\Delta f_i$ and virtual tie line power flow deviation $\Delta P_{tie,i}$, and then passed through filter and PI controller to generate area regulation command (ARC) with the unit in kW. Note that parameters of PI controller applied in LFC model can be optimally tuned by using several optimization algorithms, such as genetic algorithm (GA), in accordance with a certain objective function [31].

$$VACE_i = (P_{tie,i} - P_{sched,i}) + B_i(f_i - f_{norm}) = \Delta P_{tie,i} + B_i\Delta f_i \quad (4.38)$$

$B_i$ is bias factor of separated area in kW/0.1 Hz, and proper value for an area is its frequency-response characteristics $\beta_i$ calculated using the following equation:

$$B_i = \beta_i = \frac{1}{R_i} + D_i \quad (4.39)$$

The change in reference power setting ARC of BESS or VSWT within each area under LFC is proportional to the integral of ACE multiplied by constant $K_i$ as follows:

$$ARC_i = -K_i \int ACE_idt \quad (4.40)$$
\(ARC_i\) represents the power imbalance between total generation and load demand within one area. In other words, \(ARC_i\) corresponds to total adjustment in outputs of BESS and selected VSWTs, where \(R_i\) is the equivalent droop coefficient of all generators participating in the droop response and \(D_i\) is the equivalent load damping coefficient. A first-order low pass filter is applied to eliminate the high-frequency component that appears in the load random variation. So, \(SACE_i\) is the smoothed \(ACE_i\) value. It is noted that the selection of \(B_i\) and \(K_i\) will influence the transient response to load changes. The \(B_i\) can be set high enough so that each microgrid sufficiently contribute to their own frequency regulation. The \(K_i\) should not be too large, otherwise it is more likely to cause instability. The time interval between successive dispatched LFC signals (\(ARC_i\)) should be long enough to account for the response time or avoid unnecessary control action. If the power imbalance between generation and load is too large, LFC is bypassed and emergency controls kicks in to ensure the stability of the islanded microgrid [32].

### 4.4.3.2 LFC Applied for Islanded Microgrid Cluster

In an islanded microgrid cluster, two fundamental LFC objectives should be met as follows [32]:

1. Assuming a load change occurs in a certain microgrid, that microgrid should be responsible for restoring its frequency to the nominal value by adjusting the reference power settings of WTG and BESS. Meanwhile, other microgrids manage to maintain its own frequency at the scheduled value.
2. Each microgrid should keep the tie-line power flow exchanged with other microgrids at its predetermined value.

Equation (4.35) is for calculation of \(ACE\) for each microgrid, assuming that there are \(n\) microgrids to form a microgrid cluster in which each microgrid is connected through tie-lines. Real-time tie line power flow among different microgrids and each islanded microgrid’s system frequency \(f_i\) is monitored through its own microgrid central controller (MGCC). The relevant variables, such as \(R_i\) and \(D_i\), should be identified based on the operational characteristics of microgrid. \(\sum_{j=1,j\neq i}^{n-1} \Delta P_{\text{tie-}ij}\) represents the deviation of power interchange of \(i\)th microgrid with other neighboring \(j\)th microgrid if one tie line exists between \(i\)th microgrid and \(j\)th microgrid; otherwise, \(\Delta P_{\text{tie-}ij}\) is zero. \(\Delta f_i\) is the frequency deviation in \(i\)th microgrid. Note that \(B_i\) and \(ARC_i\) can be calculated using the same equations in (4.39) and (4.40). Here, \(B_i\) is bias factor of \(i\)th microgrid in...
kW/0.1 Hz and proper value for the \( i \)th microgrid is its frequency-response characteristics \( \beta_i \). The change in reference power setting \( \text{ARC}_i \) of BESS\(_i\) and VSWT\(_i\) within \( i \)th microgrid under corresponding LFC\(_i\) is proportional to the integral of \( \text{ACE}_i \) multiplied by constant \( K_i \).

\[
\text{ACE}_i = \sum_{j=1, j \neq i}^{n-1} (P_{\text{tie}_{ij}} - P_{\text{sched}_{ij}}) + B_i(f_i - f_{\text{norm}}) = \sum_{j=1, j \neq i}^{n-1} \Delta P_{\text{tie}_{ij}} + B_i \Delta f_i
\]  

(4.41)

Figure e4.46 illustrates a LFCs block diagram of a microgrid cluster consisting of two microgrids connected through a tie line [33]. There is one WTG and one BESS in each microgrid. The dynamics of the WTG and the BESS are represented by a simplified first order lag transfer function in the LFC system model in which \( K \) is gain constant and \( T \) is the time constant. \( P_s \) is the synchronizing power coefficient that is used for calculating the tie-line power deviation \( \Delta P_{\text{tie}} \) based on the phase angle difference \( \Delta \delta_1 - \Delta \delta_2 \) between microgrid 1 and microgrid 2. In addition, this LFC model takes into account the droop response of both the BESS and the WTG as well as the ACE separate-zone control strategy that will be discussed next.

### 4.4.3.3 ACE Separate-zone Control

In a practical AGC system, the control zone is basically divided into four sub-zones in accordance with the absolute value of \( \text{ACE}_i \) (or \( \text{ARC}_i \)). It consists of deadband zone, normal regulation zone, sub-emergent regulation zone and emergent regulation zone as shown in Figure e4.47 [34]. According to preset control logic in different sub-zones, power reference signals are transmitted via the telemetering channels from the microgrid AGC central station to the BESS and other VSWGs.

Here, a type of proportional control is introduced to optimize the coordinated AGC regulation among battery energy storage system (BESS) and VSWTs in the standalone microgrid cluster (namely a microgrid group consisting of multiple microgrids) or divided areas within one single standalone microgrid by taking into account the real-time SOC variation and its limit as well as diverse Area Regulation Command (ARC) control zones. Using this strategy, BESS is capable of fully performing the AGC frequency regulation of islanded microgrid in a fast and flexible manner while reducing frequent activation of frequency regulation in deadband zone. This allows a sufficient margin for the BESS to
Figure 4.46 LFC block diagram of two microgrid clusters.
provide other ancillary services, such as peak load shaving, balancing the oscillation, spinning reserve and voltage support [3,33], so the comprehensive economics of BESS utilization is enhanced to a certain extent. Based on ACE separate-zone control strategy as shown in Figure e4.47, the BESS can help with implementation of the AGC control strategy corresponding to a certain AGC zone and achieve the seamless transfer among different AGC control strategies as well.

1. As ACE lies in the emergent zone ($ACE \geq ACE_E$), the regulation amount allocated for the BESS and the VSWT by the AGC are given as follows:

$$P_{BE} = \begin{cases} -P_{C_{\max}}, & ARC < 0 \\ P_{D_{\max}}, & ARC > 0 \end{cases}$$

$$\Delta P_{WEi} = \frac{R_{WEi} \times (ARC - P_{BE})}{\sum_{i=1}^{n} R_{WEi}}$$

where $P_{BE}$ is regulation amount (kW) allocated to the BESS by the AGC; $P_{C_{\max}}$ and $P_{D_{\max}}$ are the maximum charging and discharging powers (kW), respectively. Modern BESS technology can attain the maximum charging or discharging power of 1.5 times rated power with maximum sustained operation duration of 90 s. $R_{WEi}$ represents the ramp rate of VSWT (kW/min); $n$ is the number of VSWTs participating in the microgrid AGC control; $\Delta P_{WEi}$ is the allocation amount (kW) distributed to $i$th VSWT by AGC. In the ACE emergent zone, the BESS takes a priority to perform the fast regulation capability with maximum power output $P_{\max}$ (e.g., 1.5 times rated value) and duration $T_{\max}$ (e.g., 60 s) while remaining amount is undertaken by other VSWTs according to individual ramp rate $R$. If the operation period of maximum power exceeds the scheduled time (60 s), BESS output will automatically decrease to rated power output for the sake of security of converter and battery operation. The objective of this control zone is to mitigate the ACE deviation as fast as possible and reduce ACE toward the sub-emergent zone during the initial stage as well.
2. As ACE lies in sub-emergent zone \((\text{ACE}_{\text{SE}} \leq \text{ACE} < \text{ACE}_{\text{E}})\), the regulation amount allocated for the BESS and VSWT\(_i\) by the AGC are given as follows:

\[
P_{\text{BE}} = \begin{cases} 
  -P_{\text{rate}}^C, & \text{ARC} < 0 \\
  P_{\text{rate}}^D, & \text{ARC} > 0 
\end{cases} \quad (4.44)
\]

\[
\Delta P_{\text{WE}i} = \frac{R_{\text{WE}i} \times (\text{ARC} - P_{\text{BE}})}{\sum_{j=1}^{n} R_{\text{WE}j}} \quad (4.45)
\]

Similarly, \(P_{\text{BE}}\) is regulation amount (kW) allocated to BESS by AGC; \(P_{\text{rate}}^C\) and \(P_{\text{rate}}^D\) is the rated charging and discharging power (kW), respectively. \(R_{\text{WE}i}\) represents the ramp rate of VSWT (kW/min), \(n\) is the number of VSWTs participating in the microgrid AGC control; \(\Delta P_{\text{WE}i}\) is allocation amount (kW) distributed to \(i\)th VSWT by AGC. In ACE sub-emergent zone, BESS continues to take a priority to perform the fast regulation capability with rated power output \(P_{\text{rated}}\) while remaining amount is undertaken by other VSWTs in accordance with individual ramp rate \(R\). The larger the \(R\) is, the more AGC regulation the VSWT undertakes. In this way, ACE is reduced toward the normal zone (security zone) as fast as possible.

3. As ACE lies in normal zone \((\text{ACE}_{\text{D}} \leq \text{ACE} < \text{ACE}_{\text{SE}})\), the regulation amount allocated for the BESS and the VSWT\(_i\) by the AGC are given as follows:

\[
P_{\text{BE}} = \begin{cases} 
  -\frac{|\text{ACE}_x| - \text{ACE}_{\text{D}}}{\text{ACE}_{\text{SE}} - \text{ACE}_{\text{D}}} \times P_{\text{rated}}, & \text{ARC} < 0 \\
  \frac{|\text{ACE}_x| - \text{ACE}_{\text{D}}}{\text{ACE}_{\text{SE}} - \text{ACE}_{\text{D}}} \times P_{\text{rated}}, & \text{ARC} > 0 
\end{cases} \quad (4.46)
\]

\[
\Delta P_{\text{CE}i} = \frac{P_{\text{WE} \_R} \times (\text{ARC} - P_{\text{BE}})}{\sum_{j=1}^{n} P_{\text{WE}j \_R} + P_{\text{BE} \_R}} \quad (4.47)
\]

In the normal zone, \(P_{\text{BE}}\) is the regulation amount (kW) allocated to the BESS by the AGC, \(\text{ACE}_{\text{D}}\) and \(\text{ACE}_{\text{SE}}\) represents threshold values (kW) for ACE deadband and normal range, respectively. \(n\) is the number of VSWTs participating in the microgrid AGC control; \(\Delta P_{\text{WE}i}\) is allocation amount (kW) distributed to \(i\)th VSWT by
AGC. As shown in Figure e4.48, power reference value (kW) of BESS is calculated in linear proportional manner if ACE enters normal zone. Meanwhile, other VSWTs will take over and share the remaining regulation amount among themselves in accordance with current AGC reserve capacity. The larger the AGC reserve capacity is, the more regulation amount the VSWT will need to undertake. The control objective in normal zone is to reduce the demand on BESS as much as possible and also fully perform the potential regulation capabilities of VSWTs in order to collectively achieve the coordinated AGC control.

4. As ACE lies in deadband zone \((ACE < ACE_D)\), the BESS does not need to participate in AGC regulation. The total regulation amount is allocated among VSWTs in proportion to their AGC reserve capacities. So, regulation amount allocated for the BESS and VSWT\(_i\) by the AGC are given as follows:

\[
P_{BE} = 0
\]

\[
\Delta P_{WEi} = \frac{P_{WE_{-R}} \times ARC}{\sum_{i=1}^{n} P_{WE_{i-R}}}
\]

Note that the SOC of the BESS will be restored back to standby mode (e.g., SOC = 50\%) through a charging or discharging process, so sufficient reserve margin is maintained to enable the BESS to be prepared to participate in the subsequent frequency regulation of islanded microgrid. With respect to threshold \(ACE_D\), \(ACES_E\) and
ACE_E, their specific values should be determined in terms of the total AGC reserve capacity of all the VSWTs; the ramp rate of individual VSWT along with the rated power, maximum power and energy capacity of BESS while meeting the AGC dispatch demand of islanded microgrid.

Additionally, during the participation of BESS in ACE separate-zone regulation as shown in Figure e4.47, BESS will immediately suspend its power exchange with the islanded microgrid if SOC reaches the upper limit (80%) or lower limit (20%). As a result, system frequency is subject to a certain disturbance due to the temporary power shortage and an increased ACE may result. To avoid such an impact, a type of power reference adjustment is presented based on dynamic SOC value. As shown in Figure e4.49, when the BESS keeps releasing the power until its SOC reaches 30%, if it continues to discharge and SOC declines accordingly, the current discharged power is recorded as reference value \( P_1 \) through the real-time SOC detection system. As the SOC value \( X\% \) lies in between 30% and 20%, the corresponding power reference value of the BESS can be calculated through the following interpolation method:

\[
P_{BE} = \frac{P_1(X - 20)}{10} \tag{4.50}
\]

Similarly, when BESS keeps being charged until SOC = 70%, if it continues to be charged and SOC rises accordingly, the current charged power is recorded as reference value \( P_2 \) by the real-time SOC detection system. As the SOC value \( X\% \) lies between 70% and 80%,
the corresponding power reference value of the BESS can be calculated by using the following interpolation method:

$$P_{BE} = \frac{P(80 - X)}{10} \quad (4.51)$$

When SOC lies in the range from 30% to 70%, the power reference value of BESS is decided by the proposed ACE separate-zone regulation. In this method, a power smoothing buffer zone is added before the SOC hits the limits. So, the power variation is smoothed during the process of SOC’s approaching the bounds; and the stability of ACE regulation can be enhanced to a certain extent. When the ACE lies in deadband zone and at the same time the SOC is smaller than 20%, the power reference of BESS depends on specific charging mode, such as constant current or constant power charge. Similarly, when ACE lies in deadband zone and the SOC is larger than 80%, the power reference of BESS depends on specific discharging mode, such as constant power discharging.

REFERENCES


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