Hybrid energy storage systems for power system frequency control

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**HYBRID ENERGY STORAGE SYSTEMs FOR
POWER SYSTEM FREQUENCY CONTROL**

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HYBRID ENERGY STORAGE SYSTEMs FOR POWER SYSTEM FREQUENCY CONTROL

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Summary

In order to overcome the ever-challenging environmental issues caused by greenhouse gas emission, conventional energy sources are gradually being replaced by renewable energy sources. However, the increasing penetration of renewable energy sources leads to the decrease of power system inertia, since renewable sources barely contribute to the inertial response. To tackle this problem, a hybrid energy storage system (HESS), which is composed of the battery and the supercapacitor, is proposed in this project to enhance the system frequency control performance.

Besides, a sizing method for the HESS under system contingencies is also presented with the consideration of system cost and operation standards.

Furthermore, the battery used for improving secondary frequency control performance in normal operation scenarios with the consideration of SoC regulation is also investigated

The effectiveness of the proposed HESS control method is verified through simulations for both contingencies and normal operation scenarios.

Acronyms

LFC	Load Frequency Control
RES	Renewable Energy Source
PV	Photovoltaic
ESS	Energy Storage System
BESS	Battery Energy Storage System
HESS	Hybrid Energy Storage System
RMS	Root Mean Square
AGC	Automation Generation Control
VSS	Variable Structure Controller
PFR	Primary Frequency Response
IR	Inertial Response
SC	Supercapacitor
RoCoF	Rate of Change of Frequency
SoC	State of Charge
ACE	Area Control Area
ISE	Integral Squared Error
VSGs	Virtual Synchronous Generators
DR	Demand Response
VESS	Virtual Energy Storage System
LMI	Linear Matric Inequality
ANN	Artificial Neural Network
GA	Genetic Algorithm

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CHAPTER 1 INTRODUCTION

In this chapter, the background information as well as the literature summary for this research are discussed. Some limitations in the previous research works are listed in the motivation part. Then it is followed by the objectives and major contributions of this thesis. Lastly, the structure of this thesis is introduced in the organization part.

1.1 Research Background

The penetration level of renewable energy sources (RESs) keeps increasing in the modern power system. Traditionally, fossil energy from fuel and coal is utilized for electric power generation. However, fossil fuels may cause environmental pollutions by emitting greenhouse gases. Besides, such sources are non-renewable and with a fast consumption rate. Such severe issues emphasize the importance of replacing the fossil energy with renewable energy sources (RESs), since RESs, such as wind energy, hydrogen energy and solar energy are sustainable and have minimal impacts on the environment. Solar energy is one of the most widely-used RESs in Singapore, which is a tropical country with sufficient sunlight intensity. Over the past years, the installed capacity of solar Photovoltaic (PV) has been increased dramatically while the cost of installation decreases [1]. The capacity and cost of solar PV from 2009 to 2016 are shown in Fig 1. 1. Furthermore, the penetration of RESs has been increased, as shown in Fig 1. 2 [2]. According to a plan published in 2014, the penetration of solar PV in Singapore will be increased to 5 percent in electricity peak demand by 2020 [3].

Nevertheless, the increasing penetration of RESs may introduce other problems for power system operation. Above all, RESs have no contribution to system inertia. Inertia is defined as the resistance of any physical object to any change in its position and state of motion. Power system inertia can be regarded as its capability for maintaining the original operation state when facing power variations.

For a power system with insufficient inertia, severe frequency deviations may occur as a result of the imbalance between power generation and load demand. To maintain the normal operation of a power system, the frequency deviation needs to be controlled within a range, normally set as ± 0.2 Hz [4]. Replacing traditional synchronous generators with RESs will cause a decrease of the equivalent system inertia constant [5], and hence degrade the system frequency response. Besides, the intermittency nature of RESs can also introduce unpredictable power fluctuations. As a result, the power system frequency response becomes even worse.

Fig 1. 1 Growth in solar capacity led by falling price [1]

1.1.1 Literature Review

To properly regulate system frequency, especially to mitigate the aggravated frequency variations with increased RESs penetration, several methods have been proposed. The most commonly adopted method is called the load frequency control (LFC), which can ensure power system frequency stability after load disturbances

The LFC issues have been studied by many researchers. The basic concepts of frequency bias tie-line control are illustrated in [6]-[10], including the structure of the model, controller design and system performance regarding to parameters variation.

The increasing complexity of modern power system requires higher reliability and stability. Several controllers using the advanced control methodologies such as optimal control, adaptive control, self-tuning control, variable structure control and robust control are proposed for LFC improvement. An example of using variable structure control in a multi-area power system is shown in Fig 1. 3.

(a) Block diagram of area i

(b) Block diagram of variable structure controller

Fig 1. 3 Block diagram of variable structure approach for LFC [25]

The optimal control approach has provided a new method for solving the multi-variable control problems by considering the state variable of the model as well as the objective function to be minimized [11], [12]. On the other hand, as the change of system operating point may influence the control performances, adaptive controls [13], [14] and self-tuning controls [15], [16] are proposed to properly adjust the control parameters for different system operating points.

In addition, in the traditional LFC method with PI controller, optimizing the integrator gain through the conventional approach may cause relatively large frequency overshoots and transient frequency deviations. A significant advantage of the variable structure controller is the ability for changing the system structure based on some law of structure change [17]-[19]. Such characteristic makes the controller insensitive to system parameters changes.

Besides, the increasing scale of modern multi-area interconnected power systems has brought robustness issues since the conventional simply-tuned controllers are incapable of providing good dynamic performance over a wide range of regions and the constantly changing load. A novel controller which can ensure the stability of the overall systems is needed. In [20], the robust controller based on Riccati-equation approach is proposed. Furthermore, μ -synthesis approach, H_∞ control and linear matrix inequality (LMI) technique have also been reported in [21]-[24].

Additionally, the power system structure has become more complex due to the integration of RESs, and the reshaping of the plant may be required in the robust control schemes. Soft computing techniques, such as artificial neural network (ANN), fuzzy logic and genetic algorithm (GA) have been utilized, since they are more suitable for dealing with nonlinear conditions and uncertainty issues. Among them, the ANN is a black box, which represents the non-linear relationship between the input and output without the consideration of system structure. In [26], the neural networks which can act as the control intelligence in conjunction with a standard adaptive LFC scheme are studied. The application of ANN in automatic generation control (AGC) is discussed in [27], [28]. Apart from this, the robustness of fuzzy logic has also enriched its applications in multi-variable conditions [29]-[31]. Alternatively, the GA is an innovative optimization technique based on the natural selection and genetics with a randomly structured information exchange. The exploration of the GA used in the field of LFC is also discussed in [32]-[34].

One disadvantage of the aforementioned methods is that the original system structure may be changed with the implementation of different control schemes or soft computing techniques. Besides, system parameters are required for the controller design.

1.1.2 Energy Storage System

Recently, there has been a growing need for the application of energy storage system (ESS). In general, ESS can be regarded as an energy buffer, which is able to store the redundant energy when the power generation exceeds the load demand and release the stored energy when needed. Furthermore, compared with traditional devices, ESS can respond to fast power fluctuations since the time constant of ESS is relatively small, and hence can be adopted for different control objectives. For instance, ESSs can provide active power compensation to support peak-shaving and frequency regulation.

Besides, ESSs can be implemented in power systems without changing the original main system structure.

Therefore, the application of ESSs is another practical option for LFC performance improvement. Typical types of ESSs are listed in Table 1. 1 [35]. Since the characteristics of different types of ESSs vary from each other [36], the selection of ESS type depends on its application.

Table 1. 1 Typical types of ESSs [35]

Energy storage systems		
Electrochemical	Batteries	Lead Acid, NiCd, NiMh, NaS, NaNiCl, Li-Ion...
	Flow Batteries	Vanadium, ZnBr, PSBr
	Hydrogen	Electrolyser + Fuel Cells
Electromagnetic	Electric	Capacitors (Supercaps)
	Magnetic	SMES
Thermodynamic	Pressure	CAES
	Pressure + Heat	Adiabatic-CAES
	Heat	Thermo-Electric
Mechanical	Gravity	Pumped-Hydro
	Kinetic	Flywheels

The battery is one of the most commonly used storage technologies in the industry. The energy is stored in the form of electrochemical energy. A set of multiple cells can be connected in parallel or in series to get the desired voltage and capacity. As it can be seen in Fig 1. 4, each cell consists of two electrodes and one electrolyte. The electrolyte can provide the exchange channel for the ions between these two electrodes and the electrons flow through the external circuit.

Fig 1. 4 Operation principle of battery energy storage system [37]

In [38], [39], the effectiveness of using a battery energy storage system (BESS) to improve LFC dynamics is proved. [40] reveals that the BESS is effective in reducing the peak deviations of frequency and tie-power, since it can compensate the sudden load changes. The steady-state values of time error and inadvertent interchange can also be reduced. The effects of BESS considering governor dead band and generation rate constraints are discussed in [41]. Through using area control error (ACE) as the feedback signals, the BESS can provide greater improvement for LFC. In [42], the qualitative and quantitative comparison of the conventional controllers with the BESS and a typical two area interconnected power system highlights the improvement of system dynamic performance provided by the BESS.

Supercapacitors are also known as ultracapacitors or double-layer capacitors. Supercapacitors are based on electrochemical cells. As shown in Fig 1. 5, each cell consists of two electrodes, the electrolyte and a porous membrane. The reaction of electrostatically store charge occurs on the interface between two electrodes and the surface of the electrolyte. This structure can be regarded as two capacitors since there are two interfaces (positive electrode - electrolyte and electrolyte - negative electrode). Besides, the energy stored in the supercapacitor is in electrochemical type and the energy is proportional to its capacitor and the square of the voltage

between the terminals of the electrochemical cell. The cell voltage is low and the desired voltage and capacity of the supercapacitor are achieved through the series and parallel connection of several cells. The energy density of supercapacitors is around 100 times higher than conventional capacitors [43].

Fig 1. 5 Operation principle of supercapacitor energy storage system [37]

In [46], the implementation of a fuzzy logic controlled supercapacitor bank for LFC improvement in an interconnected power system is proposed. The simulation results prove the effectiveness of this method. The supercapacitor combined with GA tuned algorithm is proposed in [45] and a significant decrease in the frequency deviation and the tie-line power deviation is observed.

In summary, the battery and supercapacitor energy storage system can be quite effective for the system dynamic performance improvement. Normally, the charging and discharging time of a supercapacitor is significantly small (less than 1 millisecond) as compared with the battery [6], and its power density is approximately 10 times higher than the battery [43]. But the supercapacitor has relatively small energy density. Such features indicate that the supercapacitor is suitable for high-density energy charging or discharging situations which last for a short period of time. The most commonly used battery is the Li-ion battery, which is characterized by a high energy density, about 170–300 Wh/l [46]. Considering such characteristic,

the battery is often used for the situations where the power exchange will be needed for a long-time scale and the intensity is not quite high.

1.2 Motivations

Based on the deployment of frequency reserve figure in [4], inertial response (IR) is the initial reaction to control frequency drop after a load disturbance. This is then followed by primary frequency response (PFR), which will regulate system frequency to a steady-state value. After that, secondary control and tertiary control will respond to eliminate the steady-state frequency error and achieve economic dispatch, respectively.

Many impressive research works have been done to improve system dynamic performance of LFC. One of them is to use the energy storage system (ESS), since ESS can provide active power compensation for supporting frequency regulation. As one of the most commonly used energy storage technologies, battery is often used in frequency regulation area. However, compared with other energy storage devices, battery has a relatively low power density. For the inertial response stage of frequency regulation, relatively high power output will be needed in a short time. Besides, for the primary frequency response and secondary frequency control stage, a relatively high energy density will be needed. The single type of ESS may not be able to meet the power system operation requirements due to the diverse characteristics of different control stages.

Besides, the optimal sizing of ESS is crucial considering its high cost. Most sizing strategies focus on the financial profits. The sizing method considering system dynamic performance under contingencies also needs to be studied.

There have been some research works relating to the control schemes of the battery [47], [48]. Since the battery has a relatively high energy density, the implementation of

the battery in secondary frequency control can also be investigated.

In the traditional automatic generation control (AGC) method, the generator takes the responsibility for the frequency regulation. The battery, which can respond to fast fluctuating signals, can be used to further improve the secondary control performance. Apart from this, the former control schemes mainly consist of classical droop controller or PID controllers. The State of Charge (SoC) of the battery cannot be regulated. Therefore, additional control blocks need to be proposed based on the operation limitations of the battery.

1.3 Objectives

This project aims at improving power system dynamic performance for both normal and contingency scenarios through employing ESS. As ESS has the potential to mitigate frequency deviations by compensating the power imbalance, the scope of this thesis is mainly focusing on controlling ESS according to different types of input signals, including short-term load contingencies and long-term PV plus load variations profile.

The main objectives of this thesis are listed below:

Firstly, as the modern power system is normally characterized by interconnecting different subareas through tie lines, a multi-area frequency control model is more practical and generalized as compared to the single-area model. Driven by such need, a multi-area interconnected power system model is established in order to study the enhancement of the LFC performance.

Based on the established model, the hybrid energy storage system (HESS) is designed in this thesis to enhance the LFC performance by combining the advantages of the battery and the supercapacitor. The supercapacitor with high power density is utilized

to improve the inertial response [39], while the battery energy storage system with high energy density is sized and controlled to fulfill the requirement of the primary frequency response. Furthermore, secondary frequency control is conventionally taken charge by synchronous generators. The frequency performance can be significantly improved by the ESS as compared with the generator considering the relatively small time-delay. Therefore, the secondary frequency control based on the battery is also studied in this thesis.

Additionally, under system contingencies, only the improvement of inertial response and primary frequency control stage needs to be considered. An effective control scheme for the HESS can be proposed. Besides, the sizing method of the HESS based on power system operation standards also needs to be taken account.

Lastly, for the long-term simulations for normal operation scenarios, the contribution of the HESS in secondary control improvement needs to be studied. Apart from a practical control strategy of the HESS, the battery operation needs to be regulated considering the limitations of battery SoC. The influence of several parameters on the system dynamic performance can also be investigated.

1.4 Major Contribution of the Thesis

Main contributions of this thesis are listed as follows:

- 1) Instead of using a single type energy storage, a HESS with complementary energy storage devices is employed. The HESS can combine the advantages of different energy storage devices. The supercapacitor, which has high energy density, is used to achieve inertial response improvement. The battery, which has enough power density, is verified to be able to cover the improvement in primary frequency response and secondary frequency control.

- 2) The HESS is employed in a multi-area interconnected model. The research works based on the multi-area model are more practical and meaningful than using a single area model.
- 3) Under short-term system contingencies: A practical control scheme is proposed for the HESS. The effectiveness of HESS for inertial response and primary frequency control performance improvement is verified through both mathematical methods and simulation results. Besides, the determination of HESS size considering the need for power system operation standards is also introduced.
- 4) For the long-term power variations: Apart from the control methods mentioned earlier, the battery is further used to improve the secondary frequency control performance through a filtered ACE method. The battery operation regulation considering SoC limitations is also achieved. Besides, relatively long-term simulations are conducted to investigate the influence of different parameters on system dynamics, including battery size and capacity, the cut-off frequency of the high-pass filter and PI controller settings.

1.5 Organization

The thesis is organized as follows: chapter 1 introduces the background knowledge, the state-of-art LFC improvement methods, and the hybrid energy storage system. Besides, the motivations, objectives and main contributions of the thesis are presented. Chapter 2 is the fundamental principle and mathematical description of the basic LFC method. Chapter 3 focuses on the situation where the input signals are system contingencies. It begins with the introduction of the simulation model as well as the concepts of some grid frequency characteristics, followed by the modeling, analysis, and sizing method of the HESS. The effectiveness is verified through several case studies in simulation. Chapter 4 focuses on normal operation scenarios. The HESS is further used for the performance improvement of secondary

control. The control scheme of the battery including the operation regulations is introduced. The influence of different parameters on system dynamics, including the battery size and capacity, the cut-off frequency of the filter and the PI controller parameters tunings is also studied through simulations. Chapter 5 concludes the thesis and provides some possible research recommendations for future work.

CHAPTER 2 FUNDAMENTAL PRINCIPLE AND MATHEMATICAL DESCRIPTION

In this chapter, the basic knowledge about frequency control, including the relationship between active power and frequency control, different control stages and the establishment of frequency control model is presented. The fundamental principle of primary frequency control and automatic generation control in an isolated power system is introduced. Then the application of traditional LFC method in an interconnected power system model has been discussed.

2.1 Active Power and Frequency Control

Fig 2. 1 Equivalent diagram of the power system

An equivalent diagram of two different power system areas interconnected by a transmission line is illustrated in Fig 2. 1. The impedance Z is predominately inductive, so it is considered as purely inductive here. Thus, the complex power $\tilde{S}_R$ received at the receiving point can be calculated as:

$$\tilde{S}_R = P_R + jQ_R = \tilde{E}_R \tilde{I}^* = E_R \left[\frac{E_S \cos \delta + jE_S \sin \delta - E_R}{jX} \right]^* \quad (2.1)$$

Thus, the following equations can be derived:

$$P_R = \frac{E_S E_R \sin \delta}{X} \quad (2.2)$$

$$Q_R = \frac{E_S E_R \cos \delta - E_R^2}{X} \quad (2.3)$$

where E_S and E_R are the root-mean-square (RMS) voltage values at the sending point and receiving point, respectively, while δ is the voltage angle difference between the sending point and the receiving point. The transmitted active and reactive power can be calculated as:

$$P_S = \frac{E_S E_R \sin \delta}{X} \quad (2.4)$$

$$Q_S = \frac{E_S^2 - E_S E_R \cos \delta}{X} \quad (2.5)$$

From equations (2.2)-(2.5), the transferred active power can be controlled by adjusting the angle difference δ , while the reactive power is determined by the voltage magnitude difference.

$$\Delta \delta = 2\pi \int \Delta f dt \quad (2.6)$$

Additionally, as the angle difference $\Delta \delta$ is the integration of frequency Δf , the active power can be controlled by adjusting the frequency.

Since the active power and reactive power will influence the frequency and voltage respectively, the control problem of them can be considered separately. This project focuses on the improvement of the frequency performance, thus only the active power is considered in the regulation model.

2.2 Different Frequency Control Stages

Fig 2. 2 Frequency control stages in UCTE [8]

The frequency control stages after a system disturbance is shown in Fig 2. 2. The first stage is the inertial response (IR), during which the kinetic energy stored in the turbines will be released to resist the frequency change. The index that can describe such effect is known as inertia constant H . The second stage is the primary frequency response (PFR), during which the frequency deviation is settled down to a steady-state value with the assistance of the generating unit speed governors. The frequency deviation is determined by the corresponding disturbance and system characteristics. Then, the function of secondary control is to eliminate the frequency deviation to 0, and tertiary control will re-schedule all the generations.

2.3 Frequency Control in an Isolated Power System

2.3.1 Main Parts of Frequency Regulation Model

A. Dynamic system model

It is assumed that the interconnections between all the control parts and the power system are so strong that they can be analyzed together using only one frequency.

Under this assumption, the instantaneous power disturbance can be expressed as the difference of the power generation ΔP_G and the load variation ΔP_L .

As discussed in [49], such power imbalance will be mitigated through the following ways:

- 1) By transferring the surplus power to kinetic energy E_k , which are stored in the rotating mass of the system:

$$\frac{d}{dt} E_k = \frac{d}{dt} [E_k^* (\frac{f}{f^*})^2] \cong \frac{d}{dt} [E_k^* (1 + 2 \frac{\Delta f}{f^*})] \cong 2 \frac{E_k^*}{f^*} \frac{d}{dt} (\Delta f) \quad (2.7)$$

- 2) By the frequency-dependent load consumptions:

All the load speed or frequency will get an increase $D \triangleq \partial P_D / \partial f$ MW/Hz, where D is the load-damping constant.

- 3) By transferring the surplus power to an interconnected neighbouring system, and ΔP_{tie} represents the total power transferred out from this area.

From 1)-3), the following equation can be got:

$$\Delta P_G - \Delta P_L = 2 \frac{E_k^*}{f^*} \frac{d}{dt} (\Delta f) + D \Delta f + \Delta P_{tie} \quad (2.8)$$

Then, (2.8) can be normalized with each side of the equation divided by the nominal power S_b :

$$\Delta P_G - \Delta P_L = 2 \frac{H}{f^*} \frac{d}{dt} (\Delta f) + D \Delta f + \Delta P_{tie} \quad (2.9)$$

where the inertia constant H is defined as $H = E_k^* / S_b$.

Through Laplace transforms, equation (2.9) becomes:

$$[\Delta P_G(s) - \Delta P_L(s) - \Delta P_{tie}(s)] \frac{1}{2Hs + D} = \Delta F(s) \quad (2.10)$$

Since $M = 2H$, (2.10) can be expressed as:

$$[\Delta P_G(s) - \Delta P_L(s) - \Delta P_{tie}(s)] \frac{1}{Ms + D} = \Delta F(s) \quad (2.11)$$

So, the transfer function of the system can be defined by:

$$G(s) = \frac{1}{Ms + D} \quad (2.12)$$

In this project, the main focus is on the frequency regulation issue, and contributions of all generators are aggregated. To avoid unnecessary complications, the inter-machine effects and the transmission line influences are not considered in this project.

In (2.12), D represents the damping ratio of the whole power system. In addition, the whole power system inertia H_{sys} is calculated as the weighted average value of each generator's inertia, i.e.:

$$H_{sys} = \frac{\sum_{i=1}^n H_i S_i}{\sum_{i=1}^n S_i} \quad (2.13)$$

where H_i is the inertia constant of the generator i , and S_i is the corresponding rated power.

B. Reheat steam turbine model

Excessive moisture can erode the blades. The most important objective of using the reheat turbine is to avoid excessive humidity in the steam at the end of expansion process, thus protecting the turbine. In reheat turbines, after partial expansion, the steam with higher pressure will be transported to the boiler to reheat at constant pressure, and then it is fed back to the low pressure turbine for further use. The humidity of the steam can be reduced through this approach. The efficiency can also be improved.

In this project, the reheat steam turbine is represented using the following transfer function:

$$G_T(s) = \frac{1 + sF_{HP}T_{RH}}{(1 + sT_{CH})(1 + sF_{HP})} \quad (2.14)$$

where T_{RH} is the time constant of reheater. T_{CH} is the time constant of main inlet

volumes and steam chest. F_{HP} represents the proportion of the power generated by the *HP* section (the first section steams meet after entering through the control valve and the inlet piping) in the total power generated by the entire turbine.

C. Speed governor with droop control model

The synchronous generator normally consists of the valve/gate, the turbine, and the controller. When there is a difference between the reference speed and the real speed, an error signal will be generated and transported proportionally to the valve/gate. Then, through adjusting the valve/gate position, the output power of the turbine will be changed, until such error signal is eliminated. The system frequency can be adjusted back to the setpoint. But the governors cannot be used when two or more generators are connected. If the reference speeds of different generators are not set as the same value, speed control conflicts will arise among all the generators. To deal with this issue, the well-known droop control has been widely applied to adjust the rotation speed according to the delivered power, and the control diagram is shown in Fig 2. 3 [50].

(a) Governor with steady-state feedback control

(b) The simplicity of block structure

Fig 2. 3 Block structure with steady-state control loop [50]

Fig 2. 4 Simplicity of block structure for generation control

As mentioned in the previous part, the relationship between the generator speed and the load can be changed by adjusting the output power of the generator. This can be achieved through the method shown in Fig 2. 4, in which a load reference is given.

In practice, when there are two or more generators supplying power to the system cooperatively, the output power change value of each generator is decided by the speed droop coefficient, which is influenced by the load reference.

2.3.2 Primary Frequency Control

Fig 2. 5 Basic diagram of droop control

The basic model of primary frequency control, which is also known as droop control, is shown in Fig 2. 5. The overall model consists of the dynamic system model, the reheat steam turbine model and the speed governor with droop control.

Fig 2. 6 Typical Frequency response of droop control

A typical frequency response of an isolated power system with only droop control is shown in Fig 2. 6. Suppose that there is a disturbance due to the imbalanced power, the system frequency will drop since a portion of rotating energy has been utilized to compensate such power imbalance. Assuming that the system remains stable after such disturbance, the rate of change of frequency (RoCoF, $d(\Delta f)/dt$) at t_0 can be expressed as the following [51]:

$$\frac{d(\Delta f)}{dt}(t_0) = f_0 \frac{P_G(t_0) - P_L(t_0)}{2E_{keq}} = f_0 \frac{\Delta P^{pu}(t)}{2H_{eq}} = f_0 \frac{\Delta P^{pu}(t)}{M_{eq}} \quad (2.15)$$

where $P_G(t_0)$ is the power generation and $P_L(t_0)$ is the load demand. E_{keq} is the kinetic energy stored in the rotating mass of the generator at the frequency setpoint f_0 .

The second stage of frequency regulation is the primary frequency control. All the generators within one area will work cooperatively by adjusting the speed governor. Such process can be described with the following equation:

$$\frac{\Delta P}{S_b} = -\frac{1}{R} \frac{\Delta f(t)}{f_0} \quad (2.16)$$

where ΔP is the power change in this area. R is the permanent droop.

The frequency will drop to the nadir f_{min} after a certain amount of time. According to [6], the frequency nadir can be influenced by many factors, such as the power variation, system inertia, dynamic response characteristics of the generating units and loads, etc.

The system block used for frequency control analysis is shown in Fig 2. 7. ΔP_{mn} represents the n th generating unit.

Fig 2. 7 System block diagram for load frequency control analysis

Still, it is assumed that the system is stable after this disturbance, i.e., the primary frequency control can cover the requirements of frequency regulation. In the steady state, the frequency can be adjusted to a constant value f_∞ , which is determined by the power imbalance and system characteristics.

$$\Delta f_\infty = \frac{\Delta P}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}\right) + D} = \frac{\Delta P}{\frac{1}{R_{eq}} + D} \quad (2.17)$$

$$R_{eq} = \frac{1}{\left(\frac{1}{R_1} + \frac{1}{R_2} + \dots + \frac{1}{R_n}\right)} \quad (2.18)$$

where R_{eq} represents the combined influence of the droop constants in the generating units. D is the load-damping ratio, which can be regarded as the frequency characteristic of all the loads.

In the real power system, the automatic generation control (AGC) or secondary frequency control, which can eliminate the frequency deviation caused by PFR, is also included for further regulation.

2.3.3 Basic Automatic Generation Control

In AGC, a proportional integral (PI) controller is adopted to eliminate the frequency error. When there is a frequency error, the proportional controller can provide an output P_{out} in proportional with the original signal $e(t)$ so that the response speed can be improved. Such relationship is expressed using equation (2.19). It should be noted that the proportional gain needs to be appropriately tuned. A large proportional gain may lead to system instability, while a small proportional gain may degrade the dynamic performance.

$$P_{out} = K_p e(t) \quad (2.19)$$

As long as the error is not 0, the integral controller will continue to work until such error signal is eliminated. Equation (2.20) explains the input and output relationship of the integral controller.

$$I_{out} = K_i \int_0^t e(\tau) d\tau \quad (2.20)$$

Normally, AGC control includes two parts, the first part is the primary frequency control, which is provided by the speed governor of the turbine. The second part is the integral controller, which is used to improve the dynamic response of the system and eliminate the steady-state error. The simulation model of AGC control is shown in Fig 2. 8.

Fig 2. 8 Simulation model of AGC control

Fig 2. 9 Frequency response of AGC control

In this power system, only part of the generating units can simultaneously provide both droop control and secondary control, while the rests only have the function of droop control. This model is more practical than the commonly used one, in which all the generators can provide both droop control and supplementary control [52]. From the frequency response of AGC control, it can be seen that the steady-state error is eliminated, and it is vital for system stability and operation.

2.4 Traditional Load Frequency Control in the Multi-Area Interconnected Power System

For multi-area interconnected power systems, the most commonly used strategy for load frequency control is tie-line bias control method. The block diagram of this method is shown in Fig 2. 10 [5]. Tie-line bias control aims at limiting the frequency deviation within an acceptable range and keeping tie-line power within a pre-specified value. A well-designed LFC model can track power change or load disturbance in the system. This control method can not only improve the stability and dynamic response of the system but also improve the quality of electricity.

Fig 2. 10 block diagram of LFC in multi-area power system [5]

In this multi-area system, LFC is achieved through both droop control and bias control. Droop control is achieved through the speed governor of the generating units. Bias control is proposed for the following two objectives of interconnected power systems:

- 1) the frequency deviation should become 0 after this control process;
- 2) the power exchanged through the tie-line should be maintained as a constant value;

The control signal of bias control, which is known as area control error (ACE_i , $i=1, 2 \dots n$), is calculated by:

$$ACE_i = B_i \Delta f_i + \Delta P_{tie,i} \quad (2.21)$$

where B_i is the bias factor of the corresponding area. Δf_i is the frequency deviation and $\Delta P_{tie,i}$ is the power exchange through the tie-line.

Then the integral controller with a proportional gain K_i is used to eliminate this error signal. From equation (2.21), it can be concluded that only when both Δf_i and $\Delta P_{tie,i}$ are equal to 0, can ACE_i become 0. From which, the two control objectives mentioned earlier are achieved.

Apart from this, the selection of K_i can improve the system dynamic response. The choice of bias factor B_i can also influence system performance. It needs to serve the purpose of limiting the influence of disturbances in its own area. For example, assuming that a load disturbance occurs in area 1, if B_i is chosen inappropriately, this disturbance will arise control actions in area 2, but the controllers in area 2 will then react by trying to eliminate this change. These actions cause a degradation of system control scheme.

2.4.1 The Tie-line Model

For multi-area power systems, different areas are connected through tie-lines. The main difference between the one area model and the multi-area model is the existence of power exchange among different areas.

Fig 2. 11 Power exchange between two terminals

From Fig 2. 11, based on the analysis in [53], the power flow between the interconnected two areas is:

$$P_{12} = \frac{E_1 E_2}{X_T} \sin(\delta_1 - \delta_2) \quad (2.22)$$

where E_1 and E_2 are the terminal voltages. δ_1 and δ_2 are the voltage angles, and X_T is the reactance of the line.

When the load disturbance occurs, the balance between generation and demand cannot be maintained. As a result, a voltage phase angle difference $\Delta\delta_i (i=1, 2)$ will be imposed on the original value $\delta_{i0} (i=1, 2)$. The variation of the power exchange value ΔP_{12} can be calculated by:

$$\Delta P_{12} = \frac{E_1 E_2}{X_T} \cos(\delta_{10} - \delta_{20})(\Delta\delta_1 - \Delta\delta_2) \quad (2.23)$$

The relationship between $\Delta\delta_i (i=1, 2)$ and $\Delta f_i (i=1, 2)$ is:

$$\Delta\delta_i = 2\pi \int \Delta f_i dt \quad (2.24)$$

After combining equation (2.23) and (2.24), the following equation can be got:

$$\Delta P_{12} = 2\pi T_{12} (\int \Delta f_1 dt - \int \Delta f_2 dt) \quad (2.25)$$

in which,

$$T_{12} = \frac{E_1 E_2}{X_T} \cos(\delta_{10} - \delta_{20}) \quad (2.26)$$

T_{12} represents the electric relationship between these two areas, which can be decided by the power flow calculation. Power flow calculation is commonly used for power system plan and optimization, which is normally prior to the simulation procedures. However, the main objective of this project is to observe and improve the frequency response performance of an interconnected power system model. Thus, according to [7,54,55], an identical value $T_{12} = 0.086$ is used for simulation.

2.4.2 Frequency Bias Control Factor

When there is only droop control in this interconnected power system model, the frequency deviation Δf after a load disturbance ΔP_{L1} shall satisfy the following conditions [52]:

$$\Delta f \left(\frac{1}{R_1} + D_1 \right) = -\Delta P_{12} - \Delta P_{L1} \quad (2.27)$$

$$\Delta f \left(\frac{1}{R_2} + D_2 \right) = \Delta P_{12} \quad (2.28)$$

Thus, the steady-state frequency deviation can be calculated as:

$$\Delta f = \frac{-\Delta P_{L1}}{(\frac{1}{R_1} + D_1) + (\frac{1}{R_2} + D_2)} = \frac{-\Delta P_{L1}}{\beta_1 + \beta_2} \quad (2.29)$$

where β_1 and β_2 are also known as the composite frequency response characteristics.

The power exchange between these two areas is given by:

$$\Delta P_{12} = \frac{-\Delta P_{L1}(\frac{1}{R_2} + D_2)}{(\frac{1}{R_1} + D_1) + (\frac{1}{R_2} + D_2)} = \frac{-\Delta P_{L1}\beta_2}{\beta_1 + \beta_2} \quad (2.30)$$

To eliminate the frequency deviation, tie-line bias control is employed. The control signal is known as area control error (ACE). When a load disturbance occurs in area 1, the error signal of area 1 is:

$$ACE_1 = \Delta P_{12} + B_1 \Delta f \quad (2.31)$$

Similarly, for area 2,

$$ACE_2 = -\Delta P_{12} + B_2 \Delta f \quad (2.32)$$

where B_1 and B_2 are the bias factors.

The value of ACE is quite important for the performance of secondary control. From equations (2.29) and (2.30), the best value of the bias factor is the corresponding frequency response characteristic β .

From [8], [9], [56]-[58], it can be concluded that the steady-state does not have much impact on the selection of the bias factor, since the ACE signal can be adjusted to 0 with the integral controller in supplementary control. From the following equation:

$$ACE_1 = A_1 \Delta P_{12} + B_1 \Delta f = 0 \quad (2.33)$$

With any $A_1 \neq 0$ and $B_1 \neq 0$, ΔP_{12} and Δf must be 0 to make this equation established.

Suppose that a load disturbance occurs in area 1, a frequency deviation will occur and mitigated by the droop control. After this, the secondary control which is activated slower than the primary control begins to work to eliminate this deviation. The dynamic performance of this stage is influenced by the values of the bias factors. Several sets of the values for B_1 and B_2 are used to illustrate this problem.

It is assumed that all the other parameters and conditions are the same for these two areas.

- 1) If the parameters are set as $B_1 = \beta_1$ and $B_2 = \beta_2$, the following equations can be got:

$$ACE_1 = \Delta P_{12} + B_1 \Delta f_R = \frac{-\Delta P_{L1} \beta_2}{\beta_1 + \beta_2} + \frac{-\Delta P_{L1} \beta_1}{\beta_1 + \beta_2} = -\Delta P_{L1} \quad (2.35)$$

and

$$ACE_2 = -\Delta P_{12} + \beta_2 \Delta f_R = \frac{\Delta P_{L1} \beta_2}{\beta_1 + \beta_2} + \frac{-\Delta P_{L1} \beta_2}{\beta_1 + \beta_2} = 0 \quad (2.36)$$

It is indicated that only the supplementary control in area 1 will respond to this change, and this disturbance is unobservable for the corresponding control in area 2.

- 2) If the parameters are chosen $B_1 = 2\beta_1$, and $B_2 = \beta_2$, ACE_1 and ACE_2 become:

$$ACE_1 = \Delta P_{12} + B_1 \Delta f_R = \frac{-\Delta P_{L1}}{\beta_1 + \beta_2} (\beta_1 + 2\beta_2) = -\Delta P_{L1} (1 - \frac{1}{\beta_2}) \quad (2.37)$$

Similarly, for area 2:

$$ACE_2 = -\Delta P_{12} + B_2 \Delta f_R = \frac{-\Delta P_{L1}}{\beta_2} \quad (2.38)$$

From these equations, it can be observed that the supplementary control in these two areas will respond and adjust the frequency difference twice as fast as the adjusting speed in condition 1). However, the power undertaken by area 2 will arise an error signal ACE_2 and then the supplementary control will try to eliminate this change, which means to eliminating this power output change. Involving such redundant procedures in the control process is not reasonable.

3) If B_1, B_2 are set smaller than β_1 and β_2 , firstly, the response speed will be slower. Besides, the primary control and supplementary control in area 2 will be activated. Since the response speed is slower than the former conditions, the recovery time taken by this procedure will be longer. In fact, such action is a degradation of the frequency control process.

In addition to the previously explored conditions, if the values of the bias factors are too large, the excessive control actions may even influence system stability. In [5], an approach in which $B = 0.5\beta$ is chosen has not been accepted yet. In [58], it is illustrated that setting $B = 0.5\beta$ is reasonable and logical.

CHAPTER 3 INERTIAL RESPONSE AND PRIMARY FREQUENCY CONTROL BY USING A HYBRID ENERGY STORAGE SYSTEM

In this chapter, the utilization of hybrid energy storage system (HESS) for inertial response (IR) and primary frequency response (PFR) improvement under system contingencies is studied. First of all, the structure of the two-area interconnected power system model used in this project is introduced. After that, some frequency characteristics used for system dynamic performance description are presented. Then, a practical control scheme is proposed for the HESS. Besides, the determination of HESS sizes considering the requirement for power system operation standards is introduced. The effectiveness of this control method and sizing method is verified through both mathematical methods and simulation results.

3.1 Interconnected Power System Model for Simulation

The multi-area model is commonly used in the industry, since this structure can adapt to various outside conditions. In such model, the location of each generating unit is decided considering the distance to the main load demand, the cost impact, etc. Different areas are connected through the tie-lines.

The simulation model of a two-area interconnected power system used in this project is shown in Fig 3. 1. The main objective of this chapter is to investigate the system frequency response after contingencies. Furthermore, implementing the same contingency in these two areas respectively can also help to analyze the factors which may influence the frequency performance. In this model, a step-up load disturbance is used as the system contingency.

Fig 3. 1 Simulation model of the interconnected power system

For the tie-line bias control, the output signal of the integral controller $u(t)$ can be calculated by:

$$u(t) = -K_i \int ACE_i(t) dt \quad (3.1)$$

where K_i ($i=1, 2$) is the proportional gain of the integral controller and $ACE_i = B_i \Delta f_i + \Delta P_{12}$ ($i=1, 2$) is the area control error. B_i is the bias factor.

It is obvious that the value of K_i will influence system dynamic performance. The values of K_i ($i=1, 2$) can be optimized through the integral squared error (ISE) method [59], which can be expressed by:

$$J = \int_0^\infty (ACE_1^2 + ACE_2^2) dt \quad (3.2)$$

Since Δf_1 , Δf_2 and ΔP_{12} are all included in J , minimizing J can be translated into a smaller frequency deviation and a more stable power exchange, thus optimizing the

system dynamic response. From Fig 3. 2, it can be seen that J has the lowest point, which corresponds to the optimal values of K_I and K_2 .

Fig 3. 2 Values of J during the change of ACE_1 and ACE_2

3.2 Grid Frequency Characteristics

The system frequency response can be described using the following two identical values: the frequency nadir (the lowest point of the frequency change) and rate of change of frequency (RoCoF, df/dt). Besides, several more parameters can be involved when discussing the frequency performance: the inertia constant H , the droop coefficient R_i , the power/frequency characteristic λ and the load damping ratio D .

Based on the analysis in [60], the inertia constant H of an isolated area is defined as [12]:

$$H = \frac{E_k}{S_B} = \frac{1}{2} \frac{J \omega^2}{S_b} \quad (3.3)$$

where E_k is the kinetic energy stored in the rotor. ω is the rotational speed, and S_b is the rated power of the whole system. Furthermore, for a power system with multi

areas, the equivalent system inertia constant H_{sys} can be calculated through using equation (2.13).

According to equation (2.15), the relationship between RoCoF and H_{sys} can be expressed by:

$$\frac{2H_{sys}}{f_0} \frac{df}{dt} = \frac{P_G - P_L}{S_b} = \frac{\Delta P_b}{S_b} \quad (3.4)$$

where ΔP_b is the power deficit caused by the imbalance of power generation P_G and load demand P_L .

As indicated by equation (3.4), the system dynamics is influenced by the inertia coefficient H . To visualize this impact, the frequency and RoCoF curves changing with different H values are shown in Fig 3. 3. It can be concluded from this figure that a larger H can improve the frequency performance since a smaller frequency deviation and RoCoF value are achieved.

Fig 3. 3 Frequency responses and RoCoF of a single-area droop control model under a 1% step-up load change ($H = 2, 3, 4$ and 5)

Apart from H , another important parameter which can also influence the system frequency performance is the load damping ratio D , since the steady-state frequency deviation Δf_{ss} can be calculated by: $\Delta f_{ss} = -\Delta P_L / (1/R_1 + D_1 + 1/R_2 + D_2)$. The frequency response curves with different D values are shown in Fig 3. 4. It is proved by this

figure that the increase of D leads to a decreased frequency deviation as well as a smaller Δf_{ss} .

Fig 3. 4 Frequency responses of a single-area droop control model under a 1% step-up load change ($D=1, 2, 3$ and 4)

In addition to the discussion of H and D , another parameter is the droop coefficient R_i ($i=1, 2$), which is defined as [61]:

$$R_i = \frac{\frac{\Delta f}{f_0}}{\frac{\Delta P_i}{S_i}} \quad (3.5)$$

Based on the definition of R , the system frequency characteristic λ_i ($i=1, 2$) is illustrated as [62]:

$$\lambda_i = -\frac{\Delta P}{\Delta f_{ss}} = \sum_{i=1}^n \frac{1}{R_i} \frac{S_i}{f_0} \quad (3.6)$$

where, ΔP is the change of load demand and S_i ($i=1, 2$) is the rated power.

3.3 The Hybrid Energy Storage System

Due to environment and energy shortage concerns, the penetration of renewable energy in modern power system is gradually increasing. From equation (2.13), the H_{sys} will be decreased since the renewable energy barely contributes to system

inertia. Such decrease will weaken the system dynamic performance, and even threaten the system stability when under extreme contingencies. Energy storage system (ESS), which can be regarded as an energy buffer, can be used to solve this problem. ESS is able to store the redundant energy when the power generation exceeds the load demand and release the stored energy when needed.

Hybrid energy storage systems (HESSs) are drawing increasing research attention recently since they can combine the advantages of different energy storage devices. A HESS is often composed of two different types of energy storage devices. One of them has high energy density while the other one has high power density [8]. As discussed in the first chapter, the battery is one of the most popular energy storage devices. But considering the requirement for fast response after load disturbances, the battery alone might not be the best choice for frequency regulation due to its low power density. Since the supercapacitor has high power density, it can be used to achieve IR. Through proper selection of the battery size, the frequency deviations which exceed the frequency limitations can be covered by PFR. Thus, in this project, a HESS consisting of the battery and the supercapacitor is employed for LFC to enhance system dynamics. After the implement of the HESS, the block diagram of the power system becomes:

Fig 3. 5 Power system structure

3.3.1 Control Blocks of the Supercapacitor for Inertial Response

The supercapacitor is a novel type of ESS, which has a considerably high power density. The charging and discharging time constants of the supercapacitor can be significantly small and the power density can be 10 times higher than batteries. Such characteristics indicate that the supercapacitor is suitable for high-density energy charging or discharging situations which last for a short period. The inertial response (IR) is one of these situations. Based on [63], the model of using the supercapacitor for IR is shown in Fig 3. 6.

Fig 3. 6 The supercapacitor used for IR

In IR, the maximum RoCoF cannot exceed 0.5 Hz/s. The main effective module in the control block is the derivative element [64] and a first-order low-pass filter is employed to remove noises caused by the derivative function. A small time-delay is also provided by such filter so that the frequency control can be assisted by other supporting units from a larger part of the power system [65]. Besides, a dead band from -0.001 to 0.001 is included to eliminate the effect of small perturbations. Since RoCoF should be within 0.5, K_b is chosen as 2 to guarantee a full-capacity power output of the supercapacitor when RoCoF equals 0.5.

To analyze the effect of this derivative part, the system structure shown in Fig 3. 5 is used, and after the IR module is connected in parallel with the original power system model, the transfer function of the power system $G(s) = 1/Ms+D$ becomes:

$$G(s) = \frac{1}{Ms+D} = \frac{1}{(M+K)s+D} \quad (3.7)$$

After implementing this module, the inertia constant M is changed. As discussed previously, the system dynamic performance can be improved by the increase of M .

3.3.2 Control Blocks of the Battery for Primary Frequency Response

The battery, which has a relatively high energy density, is one of the most popular energy storage devices. Considering such characteristic, the battery is often used in the situations where the power exchange will be needed for a long time-scale, but the instantaneous energy demand is not quite high. PFR is one of these applications. Based on the analysis in [66], the model of the battery used for PFR is shown in Fig 3. 7.

Fig 3. 7 BESS used for PFR

Fig 3. 8 Effective power droop characteristic of ESS

In this model, R is the battery droop coefficient. The value of R is decided based on the effective characteristic of the ESS droop (Fig 3. 8). It can be seen from this figure that the value of R is influenced by the maximum frequency limitations. In this project, the frequency deviation limits are chosen as ± 0.1 Hz for PFR [67], which means that when the frequency deviation equals 0.1 Hz, the whole capacity of the battery needs to participate in the frequency regulation. To achieve such purpose, it can be calculated through using equation (3.5) that $R = (0.1/50)/(1/1) = 0.002$.

The function of R can be illustrated through the mathematical method. After the PFR model is connected in parallel with the power system model, the original system transfer function $G(s) = 1/(Ms+D)$ becomes:

$$G(s) = \frac{1}{Ms+D} \cdot \frac{1}{1 + \frac{R}{Ms+D}} = \frac{1}{Ms + (D + \frac{1}{R})} \quad (3.8)$$

It can be observed that the value of the load damping ratio D is increased. From the aforementioned discussion, the system dynamics can be enhanced by the increase of D .

3.3.3 Sizing of the Hybrid Energy Storage System

To achieve the desired dynamic response under specific load disturbances, a sizing method of the HESS is proposed mainly based on identifying the necessarily required power scale for the battery and the supercapacitor.

From equation (3.4), the system inertia constant H_{arei} can be calculated by:

$$H_{arei} = \frac{\Delta P_L}{S_{sys}} \times \left(\frac{df}{dt} \right)^{-1} \times \frac{f_0}{2} \quad (3.9)$$

It should be noted that the df/dt here is equal to the maximum value of RoCoF during the whole dynamic process of the frequency change.

Similarly, the target value of the system inertia constant H_{target} can be calculated and the corresponding value of df/dt is 0.5 considering the objective of controlling the maximum RoCoF within 0.5 Hz/s. Furthermore, the inertial contribution of the supercapacitor H_{SC} can be defined as:

$$H_{SC} = p_{SC} \times \left(\frac{df}{dt} \right)^{-1} \times \frac{f_0}{2} \quad (3.10)$$

where p_{SC} is the output of the supercapacitor.

Thus, the estimated capacity of the supercapacitor P_{SC} can be obtained as [60]:

$$P_{SC} = S_{sys} \times \frac{H_{target} - H_{area}}{H_{SC} - H_{target}} \quad (3.11)$$

In addition, the size of the battery is decided based on the objective of PFR, which is to adjust the steady-state frequency to 49.9 Hz. According to equation (3.6), the target frequency characteristic λ_{target} can be calculated as:

$$\lambda_{target} = -\frac{\Delta P_L}{\Delta f'_{ss}} \quad (3.12)$$

where ΔP_L is the increase of load demand. $\Delta f'_{ss}$ is the target steady-state frequency deviation 0.1 Hz.

Similarly, the frequency characteristic λ_{areai} of the power system can be got by:

$$\lambda_{areai} = -\frac{\Delta P_L}{\Delta f_{ss}} \quad (3.13)$$

where Δf_{ss} is the actual steady-state frequency deviation.

Normally, λ_{target} is larger than λ_{areai} and the required capacity of the battery $P_{battery}$ can be obtained as [60]:

$$P_{battery} = (R_{Battery} \times f_0) \times (\lambda_{target} - \lambda_{areai}) \quad (3.14)$$

3.4 Simulation Results and Analysis

3.4.1 Power System Under Study

The proposed method can be utilized in the multi-area model shown in Fig 2. 10. In this section, a two-area interconnected power system model is employed to verify this strategy. The rated active power of the system is 1000 MW, and the total system rating is 1125 MVA, based on the data in [60]. The inertia constant of Area 2 is 4, while in Area 1, this value is only 3 due to the increased penetration of renewable energy. Thus, the HESS is installed in Area 1 to improve the system dynamic performance.

Assuming that at 5 seconds, a load demand increase of 65 MW occurs in Area 1, which is then followed by another increase of 35 MW at 20 seconds in the same area. Besides, to visualize the influence of the reduced inertia constant, the same disturbance is also implemented in Area 2 in Case 1.

3.4.2 Case Study

A. Case 1

In this case, the function of the supercapacitor for IR improvement is discussed. Three scenarios are compared: 1) Area 1 without supercapacitor; 2) Area 1 with supercapacitor; 3) Area 2 under the same disturbances.

As previously discussed, RoCoF should be controlled within 0.5 Hz/s. From

simulations, it is observed that the worst case of RoCoF occurs during the larger load increase 65 MW, and the corresponding maximum value is 0.543 Hz/s. Using the values of the load increase 65 MW, the nominal power 1125 MVA and equations (3.9)-(3.11), it can be got that H_{area1} is 2.66 s, H_{target} is 2.889 s, and H_{SC} is 21.2 s through the simulation. Thus, the capacity of the supercapacitor P_{SC} can be calculated by:

$$P_{SC} = 1125 \times \frac{2.889 - 2.66}{21.2 - 2.889} = 14.07 \text{ MW} \quad (3.15)$$

Fig 3. 9 Dynamic response of Area 1 without/with SC and Area 2

The dynamic performance of the system frequency and RoCoF are shown in Fig 3. 9. From Fig 3. 9 (a), the frequency nadir of Area 1 without HESS during the first load disturbance is about 49.52 Hz. After implementing the supercapacitor, this value is adjusted to 49.56 Hz. While in Area 2, this value is 49.66 Hz owing to a higher inertia constant. During the later disturbance, the lowest point of the frequency change in Area 1 without the HESS is about 49.63 Hz, and an

improvement of 0.02 Hz is provided by the supercapacitor, yet still lower than the corresponding value of Area 2 which is 49.71 Hz. Besides, the frequency deviations of Area 2 are the smallest during most time of the adjusting process, which can be considered as that Area 2 is less affected by the same disturbances.

From Fig 3. 9 (b), the maximum absolute value of RoCoF which is 0.543 Hz/s occurs when facing the former load increase of 65 MW, thus the required capacity of the supercapacitor is calculated based on this value. After employing the supercapacitor, the corresponding value can be adjusted to 0.5 Hz/s, while the maximum value of RoCoF in Area 2 is only 0.4 Hz/s. Furthermore, the absolute value of RoCoF in Area 2 is the smallest during the changing process, followed by the value of Area 1 with the supercapacitor, and the largest value occurs under the condition of Area 1 without the supercapacitor.

Therefore, the influence of the decreased inertia constant is visualized. In addition, it can be concluded that the supercapacitor can effectively enhance the dynamic performance of IR.

B. Case 2

In this case, the function of the battery for PFR improvement is discussed. Two scenarios are investigated: 1) Area 1 without the battery (with the supercapacitor only); 2) Area 1 with the HESS

The steady-state frequency deviation limit is set as ± 0.1 Hz in this project. From simulations, it can be noticed that the actual steady-state frequency is 49.86 Hz after the total load demand increase of 100 MW. After implementing these values in equations (3.12)-(3.14), it can be obtained that λ_{area1} is 714.28 MW/Hz, λ_{target} is 1000MW/Hz. Thus, the capacity of the battery $P_{Battery}$ can be calculated by:

$$P_{Battery} = 0.002 \times 50 \times (1000 - 714.28) = 28.58 \text{ MW} \quad (3.16)$$

Fig 3. 10 Frequency response of Area 1 with only the supercapacitor (SC) and Area 1 with the HESS

The frequency responses of Area 1 with only the SC and Area 1 with the HESS are shown in Fig 3. 10. It is observed that the steady-state frequency can be adjusted to the limit 49.9 Hz with the sized battery. Also, the dynamic performance during the adjusting process is improved. The frequency nadir during the first load demand increase is adjusted from 49.56 Hz to 49.72 Hz and another improvement of about 0.043 Hz can be noticed during the later load increase. Therefore, the performance of PFR is improved through using the battery.

C. Case 3

In this case, the dynamic response improvement contributed by the HESS for the system with secondary control is discussed. Two scenarios are compared: 1) Area 1 without the HESS; 2) Area 1 with the HESS. Through using the ISE method, it can be obtained that the optimal value for K_I is -0.66, and for K_2 is -0.01 in scenario 1. After the employment of the HESS, the optimal values become -2.51 and -0.01 respectively.

Fig 3. 11 Frequency response of tie-line bias control of Area 1 without/with HESS

The frequency responses of Area 1 with/without the HESS are shown in Fig 3. 11. After the implement of tie-line bias control method, the steady-state frequency is adjusted to 50 Hz. Besides, it can be observed from Fig 3. 11 (a) that the lowest two extreme values of frequency variations in Area 1 without the HESS are 49.55 Hz and 49.77 Hz. With the employment of the HESS, these two values are increased to 49.75 Hz and 49.88 Hz respectively. Furthermore, under scenario 1, about 48 seconds are taken to recover from the disturbances, while only 35 seconds are used under scenario 2. Moreover, a remarkable decrease can be noticed for the frequency deviations during the changing process. Additionally, from Fig 3. 11 (b), the maximum value of RoCoF is reduced to the limit 0.5 Hz/s, and the stability of this system is also enhanced. Therefore, the LFC for the system is significantly enhanced by the HESS.

CHAPTER 4 SECONDARY FREQUENCY CONTROL BY USING A HYBRID ENERGY STORAGE SYSTEM

In this chapter, the HESS used for secondary frequency control in normal operation scenarios is studied. This chapter starts with the introduction of the secondary frequency control scheme used in this project considering the battery SoC regulation method. Simulations under normal operation scenarios are then conducted to verify the feasibility of this strategy. In addition, several parameters which may influence the HESS performance are investigated and the corresponding impacts are visualized through simulation results.

4.1 Introduction of the Control Method

4.1.1 Filtered ACE Method

Fig 4. 1 The framework of filtered ACE method

In traditional frequency regulation methods, the responsibility of secondary control is taken by the generators. Compared with the generator, the battery energy storage system (BESS) can respond to fast fluctuating signals. Thus, in this project, the BESS is used for secondary control improvement and the corresponding control method is called the filtered ACE method [68]. The framework of this method is shown in Fig 4. 1. Based on the balancing operation method of PJM [69], the ACE signal can be divided into two parts and the high-frequency part can be extracted

through using a high-pass filter. Such signals are then sent to the BESS for further regulation, while the remaining part will be sent to the generator for traditional regulation.

4.1.2 The Control Blocks of the Battery

Fig 4. 2 The control block of BESS

The control block of the BESS for frequency regulation is shown in Fig 4. 2. In this method, the frequency deviation and the high-frequency part of the ACE signals are used as the input. The primary frequency control has already been discussed in the former chapter. The operation principle of the remained parts in this control block is as follows:

When there is a frequency error, the ACE signal will be generated. The high-frequency part of the ACE signal will then be extracted and sent into this control block. After a small time-delay, the PI controller starts to work to eliminate this input error signal. After that, the sum of the primary control power command, the secondary control power request as well as the SoC regulation power command will be sent to the battery operation regulation block as the input signal. Then, the saturation module is employed to limit the total power output within the BESS capacity. Afterwards, the power output of this control block $P_{Battery}$ will be combined with the generator output to compensate for the power imbalance, thus to eliminate the frequency error.

4.1.3 Battery Operation Regulation

The performance of the battery can be influenced by many factors and one of which is the State of Charge (SoC) of the battery. The SoC, which represents the present capacity of the battery compared to the maximum capacity, is an essential parameter for the battery. For one thing, the SoC is an indicator of the battery's remaining capability for the contribution in future contingencies. For another, if the value of SoC is too high or too low, detrimental damage might be caused to the battery [70]. The SoC of the battery can be calculated by:

$$SoC = SoC_{i=0} - \frac{1}{C_{BESS}} \int P_{BESS} dt \quad (4.1)$$

where $SoC_{i=0}$ is the original value of SoC which is 50% in this research. C_{BESS} is the capacity of the battery. P_{BESS} is the power output of the battery.

In order to maintain the safety operation of the battery, the SoC regulation method is required to control the SoC within a desired range. The control block for SoC regulation is shown in Fig 4. 3 (a), which can be expressed by [71]:

$$PoC^I = K_{SoC} \times \frac{SoC - SoC_{Ref}}{SoC_{Ref}} \times S_{Battery} \quad (4.2)$$

where PoC^I is the power command for SoC regulation. K_{SoC} is the control gain of SoC regulation. SoC_{Ref} is the reference for SoC which is 50%. $S_{Battery}$ is the capacity of the battery. The SoC error is amplified by the control gain and leads to the adjustment of the battery output. Since the SoC is the integration of battery power output, the SoC can be regulated to SoC_{Ref} without steady-state error. The SoC regulation gain should be determined with considerations of both cost and performance. In this project, the value of K_{SoC} is set as $1/(50-20)$.

Fig 4. 3 The control blocks for battery regulation

Besides, the control block for battery operation regulation is shown in Fig 4. 3 (b). The power command, which is the sum of the power requirements from the primary control, the secondary control as well as SoC regulation, is used as the input signal. Apart from the function of SoC calculation, the operation limitations considering the values of the input signals can be provided by two switches at the left side of this control block. The operation principle of this block is as follows:

When the SoC is equal to or smaller than 20%, the upper bound is set as 0, which means that the battery cannot respond to the input signal until a negative value is sent. The negative value represents the charging state of the battery, through which the SoC can be increased. On the contrary, when the SoC is equal to or larger than 80, the lower bound is set as 0. Under this condition, the battery can only respond to positive input signals, which correspond to the discharging state of the battery, and thus the value of SoC can be decreased.

4.2 Simulation Results and Analysis

4.2.1 Power System Under Study

The control strategy proposed in this chapter can be utilized in multi-area models as shown in Fig 2. 9. In this section, a two-area interconnected power system model is employed to verify the feasibility. The nominal power of this system is 7000 MW. The inertia constant of Area 2 is 4, while in Area 1, this value is only 3 due to the increased penetration of renewable energy. Thus, the HESS is installed in Area 1 to improve the dynamic performance.

Simulations based on normal operation scenarios are investigated in this chapter. In simulations, the 24-hours PV plus load demand variation profile is used as the input signal. Nevertheless, it should be noted that the time interval between each load demand data is half an hour, but for PV, the corresponding interval is only one second. Therefore, the fluctuations of the input power are mainly contributed by the PV output change. Thus, in this section, the following analysis based on the simulation results focuses on the system dynamic performance during the day when the solar radiation changes are more significant, which is from 1.15×10^5 s (about 8 a.m.) to 1.45×10^5 s (about 4 p.m.).

(a) PV plus load demand variation profile

(b) Partial enlarged view of (a)

Fig 4. 4 PV plus load variation file

4.2.2 Simulation Results

4.2.2.1 Frequency Performance When With/Without the HESS

In chapter 3, the frequency performance under system contingencies is studied. While in this section, the normal operation scenarios are investigated. Apart from the system parameters introduced previously, in simulation, the sizes of the battery and the supercapacitor are 100 MW and 20 MW respectively. The other control parameters used in the simulation model are listed in Table 4. 1.

Table 4. 1 Controller tuning for the filtered ACE method

Controller tuning							
Time constant of the high pass filter				30s			
Low-frequency part				High-frequency part			
PI controller				PI controller			
K_P	0.5	K_I	0.5	K_P	1	K_I	0.5
Time constant of delay		2s		Time constant of delay		2s	

The simulation results for system dynamics when with/without the HESS are shown in Fig 4. 5. From Fig 4. 5 (a) and (b), the frequency deviations are remarkably decreased by the implementation of the HESS. For example, when without the HESS, the maximum frequency deviation is 0.214 Hz. However, based on [4], this value needs to be limited within ± 0.2 Hz. After employing the HESS, this value is successfully reduced to 0.146 Hz. Besides, the RoCoF is also decreased. The maximum value of RoCoF is reduced from 0.1122 Hz/s to 0.0701 Hz/s. Therefore, it can be concluded that the dynamic performance of this power system is significantly improved. The stability of this system is also enhanced. Thus, the effectiveness of this HESS control method is proved.

Fig 4. 5 Comparison of dynamic performance when with/without HESS

Fig 4. 6 SoC profile of the battery

Besides, the SoC profile of the battery is shown in Fig 4. 6. It can be observed that the battery SoC is limited between 49.4% and 50.6%. Thus, the effectiveness of the SoC regulation method is verified.

4.2.2.2 Investigation on HESS Performance

The performance of the HESS is influenced by many factors, including the battery size and capacity, the cut-off frequency of the high-pass filter and the parameter tuning of the PI controller. In this section, a series of simulations are conducted to investigate these effects.

A. The Influence of Battery Size and Capacity

One of the most important factors that influence system frequency performance is the battery size. To visualize this impact, the frequency performance and RoCoF under different battery sizes ($S_{Battery} = 50, 100$ MW) are shown in Fig 4. 7. The size of the supercapacitor is 20 MW in both situations.

(a) Frequency performance

(b) RoCoF

Fig 4. 7 The comparison of dynamic performance under different battery sizes ($S_{Battery} = 50, 100$ MW)

From Fig 4. 7, an improvement on the system dynamic performance with the increase of battery size can be noticed. For both the frequency and RoCoF curves, the fluctuation ranges are decreased. The reason is that with the increase of battery size, the power compensation contributed by the battery is also increased.

To further investigate the influence of battery sizes, more simulations are conducted to find the trend of the maximum values for frequency deviations and RoCoF when the battery size changes from 50 MW to 150 MW. The corresponding results are shown in Table 4. 2. It can be found that these two values are decreasing with the increase of battery size. A better system dynamic performance is guaranteed by a larger battery size.

Table 4. 2 Dynamic performance under different battery size

BESS size (MW)	Maximum Frequency deviation (Hz)	Maximum RoCoF (Hz/s)
50	0.172	0.0814
60	0.167	0.0778
70	0.163	0.0736
80	0.157	0.0725
90	0.152	0.0714
100	0.146	0.0701
110	0.139	0.0687
120	0.132	0.0671
130	0.125	0.0654
140	0.117	0.0632
150	0.109	0.0600

Apart from the battery size, the energy capacity of the battery may also influence system dynamics. To account for the influence of battery capacities, the long-term simulations of frequency regulation with a time-scale of several hours have been conducted. For illustration, the curves of SoC, frequency, and RoCoF as functions of battery capacities ($C_{Battery} = 50, 75, 100, 125, 175$ MWh) are shown in Fig 4. 8. Different capacities are indicated by the suffix of the corresponding legend. For example, SoC_50 represents the curve for the battery SoC when the capacity is 50 MWh. It can be noticed from Fig 4. 8(c)-(f) that the differences among all the curves are quite small. Specifically, the maximum differences of frequency deviation and RoCoF are less than 1.5% and 0.6%, respectively. However, relatively significant differences among SoC curves can be observed from Fig. 4. 8(a)-(b). The reason is that the influence of battery capacities, which is often reflected by the values of SoC, is compensated by the SoC regulation method adopted here. Since the SoC

regulation method is rapid and effective, the SoC limitations will never be reached and the frequency regulation will not be influenced.

(a) SoC profile

(b) Partial enlarged view of (a)

(c) Frequency performance

(d) Partial enlarged view of (c)

(e) RoCoF

(f) Partial enlarged view of (e)

Fig 4. 8 System dynamic performance under different battery capacity

($C_{Battery} = 50, 75, 100, 125, 175$ MWh)

B. The Influence of Cut-Off Frequency

In this section, the influence of the time constant for the high-pass filter on the system dynamic performance is discussed. Two groups of simulations are conducted, in which the time constants are 3s/30s and 30s/60s respectively.

The cut-off frequency is inversely associated with the time constant of the high-pass filter, which means that when the time constant increases, the cut-off frequency will decrease. Thus, a higher proportion of the ACE signals will be assessed as the “high-frequency” ones, as shown in Fig 4. 9 (e) and Fig 4. 10 (e). Therefore, the power compensation contributed by the HESS for frequency control is also increased. Owing to the fast response of ESS, a slight decrease of frequency deviations can be seen in Fig 4. 9 (a)-(b) and Fig 4. 10 (a)-(b). Also, a slight improvement of RoCoF can be observed. But some special cases where the dynamic performance is weakened by the increased time constant can be noticed, as circled in the figures. And this phenomenon becomes more serious when the time constant further increases. The possible reason is that the battery is more sensitive to fast fluctuating signals than the generators, thus when these signals are responded by the battery, excessive power output may be caused.

(a) Frequency performance

(b) Partial enlarged view of (a)

(c) RoCoF

(d) Partial enlarged view of (c)

(e) Partial enlarged view of the filtered ACE signal

Fig 4. 9 Comparison of dynamic performance under different cut-off frequency ($t=3s, 30s$)

(a) Frequency performance

(b) Partial enlarged view of (a)

(c) RoCoF

(d) Partial enlarged details view of (c)

(e) Partial enlarged view of filtered ACE signal

Fig 4. 10 Comparison of dynamic performance under different cut-off frequency (t=30s, 60s)

C. The Influence of PI Controllers Tuning

In this part, the influence of PI controller tuning on system dynamic performance is investigated. The system frequency dynamics when the parameters of the PI controller used in the secondary control provided by the battery are $K_p = 1$ & $K_i = 0.5$ or $K_p = 10$ & $K_i = 5$ and $K_p = 10$ & $K_i = 5$ or $K_p = 50$ & $K_i = 25$ are compared through simulations respectively.

The input signal is amplified by the P controller and integrated by the I controller. Therefore, for the same input signals, the output of PI controller will be increased by the increase of the P/I gain values. The power compensation provided by the battery is thus increased. From Fig 4. 11 (a)-(b) and Fig 4. 12 (a)-(b), it can be seen that the frequency deviations are decreased. Besides, from Fig 4.11 (c)-(d) and Fig 4.12 (c)-(d), the RoCoF is also decreased. Thus, it can be concluded that during most of the time, the system frequency performance can be improved by a higher value for the P/I gain. But some special cases where the system dynamics are weakened by the increased controller gain values, as circled in the figures, can be noticed. This phenomenon becomes more serious when the controller gains further increase. The possible reason is that a larger power output can be provided by the HESS with higher controller gains, as shown in Fig 4. 11 (e) and Fig 4. 12 (e), but

sometimes a relatively small output is already sufficient for the corresponding error signal.

(a) Frequency performance

(b) Partial enlarged view of (a)

(c) RoCoF

(d) Partial enlarged view of (c)

(e) Partial enlarged view of HESS power output

Fig 4. 11 Comparison of the dynamic performance under different PI controller gains ($K_p = 1$ & $K_i = 0.5$, $K_p = 10$ & $K_i = 5$)

(a) Frequency performance

(b) Partial enlarged view of (a)

(c) RoCoF

(d) Partial enlarged view of (c)

(e) Partial enlarged view of HESS power output

Fig 4. 12 Comparison of dynamic performance under different PI controller settings ($K_p = 10 \& K_i = 5$, $K_p = 50 \& K_i = 25$)

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusion

This thesis investigates the issues introduced by decreased system inertia. Under this condition, system dynamics when facing power variations will be weakened and system stability is threatened. Considering different characteristics of the supercapacitor and the battery, they were used together in a HESS to provide the inertial response or primary frequency control and secondary frequency control, respectively, to improve load frequency control performances and to meet the corresponding operation standards.

First of all, under system contingencies, the function of the proposed HESS control scheme used for inertial response and primary frequency control is analyzed through mathematical methods developed in this thesis as well as the implementation of the sizing method for the HESS. Simulation results visualize the effect of the decreased inertia constant and it is demonstrated that the proposed HESS method can improve LFC performances significantly.

After that, under normal power variation scenarios, the filtered ACE method is used in the HESS for secondary frequency control performance improvement. The battery operation regulation considering SoC limitations is also involved. Besides, the influence of different parameters on the HESS performance, including the battery size and capacity, the cut-off frequency of the filter and the PI controller gains, is also investigated.

From the aforementioned works, the proposed HESS method is verified to be quite effective for the improvement of system frequency dynamics.

5.2 Recommendations for Future Work

Until now, the proposed HESS method was only implemented in a two-area interconnected power system model. Different models can be studied for verification purpose. Besides, a generalized model for energy storage devices is used in this project. Specific details of particular types of energy storage technology can be included in future work. In addition, the sizing method of the battery proposed in this thesis only suits for system contingencies. The sizing method for the battery under long-term power variations can also be researched. Several recommendations for future work are listed in the following part.

5.2.1 Virtual Inertia

Using the virtual synchronous generators (VSGs), which aims at adjusting the performance of grid-connected power converters to emulate synchronous generators, is another well-known approach for frequency control [72]. After the implementation of VSGs, the structure of modern power system becomes similar to the traditional one. Based on which, the inertia performance of VSGs can be designed to emulate the synchronous generators [73], [74]. It is also proved that the VSG has a larger inertia than droop control, thus a better frequency performance and system stability can be guaranteed [74]. Normally, the distributed generators will be combined with the ESSs to provide virtual inertia. When without the ESSs, the virtual inertia contributed by the VSGs will be decided by the DC-link energy storage and the relationship of them has been discussed in [75].

Fig 5. 1 Basic control scheme of VSG and droop control [73]

One special advantage of the VSGs is that the virtual inertia of it can be modified dynamically according to the frequency regulation needs. The self-tuning control method can be used to adjust the virtual inertia and the damping of VSGs, through which, both the settling time and the ESS energy output can be reduced [76]. In [77], a self-adaptive inertia and damping combination control (SAIDC) method is proved to be effective for decreasing system frequency deviations.

It is proved that the VSGs can improve the performance of frequency regulation significantly. Thus, future research can be conducted based on this approach. New control algorithms can also be applied to VSGs to further improve the performance.

5.2.2 Virtual Energy Storage System

In this thesis, it is verified that the HESS is effective for LFC enhancement. But one problem of this method is that the ESS is still quite expensive even after the cost decrease in recent years. For example, the cost of 20 MW/20 MWh flywheel energy storage systems (FESS) is about £25 million-£28 million [78]. Therefore, the large-scale utilization of the ESS in the power system cannot be achieved in a short term.

Aggregated demand response (DR), which can adjust the power consumption of loads, can be used to emulate the charging or discharging state of the ESSs.

Furthermore, compared with the cost for the ESS, the cost of DR can be far smaller [79]. Nevertheless, one disadvantage of DR is its uncertain response. Besides, the reaction among different loads may not be simultaneous.

Therefore, the combination of the ESSs and DR, which can make up for the uncertainty of DR response as well as reduce the cost of the ESSs, can be considered.

Fig 5. 2 Combination of flywheel energy storage system and refrigerators in a VESS

Different types of the controllable parts in the power system can be included in the virtual energy storage system (VESS), such as the ESSs, Microgrids, flexible loads, distributed generators, local DC networks and multi-vector energy systems [80]. The VESS can be used for power exchange with the power system based on the frequency control needs. The refrigerators, which can provide DR [81], and the flywheel energy storage system are combined as a VESS to improve frequency control in [80]. It is proved that the VESS can provide low, high and continuous frequency response in a similar way to the ESS. Besides, the economic benefits of this method are also verified.

Future research can be conducted based on the concept of VESS, since many control schemes of the ESSs used in frequency regulation may also suit for the VESS. The

possibility of combining the ESSs and other controllable components in the power system can also be investigated.

Bibliography

- [1] Solar industry data, Solar Energy Industries Association. [Online]. Available: <http://www.seia.org/research-resources/solar-industry-data>.
- [2] Renewable energy statistics. [Online]. http://ec.europa.eu/eurostat/statistics-explained/index.php/Renewable_energy_statistics
- [3] Facilitating the Entry of Solar Energy into Singapore, Energy Market Authority. [Online]. Available: https://www.ema.gov.sg/Solar_Photovoltaic_Systems.aspx.
- [4] Operating Reserve Policy, Energy Market Authority. [Online]. Available: https://www.ema.gov.sg/System_Planning.aspx.
- [5] A. Oudalov, D. Chartouni and C. Ohler, "Optimizing a Battery Energy Storage System for Primary Frequency Control", *IEEE Trans. Power Syst.*, vol. 22, pp. 1259-1266, Aug. 2007.
- [6] UCTE, Operation Handbook 2004-2010. [Online]. Available: www.entsoe.eu.
- [7] H.G. Kwatny et al., "An optimal tracking approach to load-frequency control," *IEEE Trans. Power App. Syst.*, vol. 94, pp. 1635-1643, Sep. 1975.
- [8] C. Concordia and L.K. Kirchmayer, "Tie line power and frequency control of electric power systems - Part I," *IEEE Trans. Power App. Syst.*, vol. 72, pp.562-572, Jan. 1953.
- [9] C. Concordia and L.K. Kirchmayer, "Tie line power and frequency control of electric power systems - Part II," *IEEE Trans. Power App. Syst.*, vol.73, pp.133-146, Jan. 1954.
- [10] N. Cohn, "Considerations in the regulation of interconnected areas", *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-86, No. 12, pp. 1527-1538, Dec. 1967.
- [11] E. V. Bohn and S. M. Miniesy, "Optimum load-frequency sampled-data control with randomly varying system disturbances", *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-91, No. 5, pp. 1916-1923, Sep. 1972.
- [12] A. Delavari and I. Kamwa, "Improved optimal decentralized load modulation for power system primary frequency regulation", *IEEE Transactions on Power Systems*, vol. 33, No. 1, pp. 1013-1025, Jan. 2018.
- [13] C. Mu et al. "Improved sliding mode design for load frequency control of power system integrated an adaptive learning strategy", *IEEE Transactions on Industrial Electronics*, vol. 64, No. 8, pp. 6742-6751, Aug. 2017.
- [14] S. Hanwate, "Adaptive policy for load frequency control", *IEEE Transactions on Power Systems*, vol. 33, No. 1, pp. 1142-1144, Jan. 2018.
- [15] M. A. Sheirah and M. M. Abd-El-Fattah, "Improved load-frequency self-tuning regulator", *International Journal of Control*, vol. 39, No. 1, Jan. 1984.
- [16] K. A. Lee et al. "Self-tuning algorithm for automatic generation control in an interconnected power system", *Electric Power Systems Research*, vol. 20, No. 2, pp. 157-165, 1991.

-
- [17] W. C. Chan and Y. Y. Hsu, "Automatic generation control of interconnected power systems using variable-structure controllers," *IEEE P. C-Gener. Transm. D.*, vol. 128, no. 5, pp. 269-279, 1981.
 - [18] U. Itkis, *Control systems of variable structure*. Halsted Press, 1976.
 - [19] Y. Mi et al. "Decentralized sliding mode load frequency control for multi-area power systems", *IEEE Transactions on Power Systems*, vol. 28, No. 4, pp. 4301-4309, Nov. 2013.
 - [20] Y. Wang et al. "Robust load-frequency controller design for power systems", *IEEE Proceedings C - Generation, Transmission and Distribution*, vol. 140, No. 1, Jan. 1993.
 - [21] Z. Wang and M. Sznaier, "Robust control design for load frequency control using μ -synthesis", *Conference Record Southcon*, Mar. 1994.
 - [22] D. Rerkpreedapong and A. Feliachi, "Decentralized load frequency control using LMI control toolbox", *Proceedings of the 2003 International Symposium on Circuits and Systems*, May 2003.
 - [23] H. Bevrani et al. "Robust frequency in an islanded microgrid: and μ -synthesis approaches", *IEEE Transactions on Smart Grid*, vol. 7, No. 2, Mar. 2016.
 - [24] P. Ojaghi and M. Rahmani, "LMI-based robust predictive load frequency control for power systems with communication delays", *IEEE Transactions on Power Systems*, vol. 32, No. 5, Sep. 2017.
 - [25] W. C. Chan and Y. Y. Hsu, "Automatic generation control of interconnected power systems using variable-structure controllers," *IEEE P. C-Gener. Transm. D.*, vol. 128, no. 5, pp. 269-279, 1981.
 - [26] A.P. Birch et al. "An enhanced neural network load frequency control technique", *1994 International Conference on Control*, Mae. 1994.
 - [27] S. Nag and N. Philip, "Application of neural networks to automatic load frequency control", *Proceedings of the 2014 International Conference on Control, Instrumentation, Energy and Communication*, Feb. 2014
 - [28] D. Chen and L. Wang, "Adaptive automatic generation control based on gain scheduling and neural networks", *2017 IEEE Power & Energy Society General Meeting*, Jul. 2017.
 - [29] H. A. Yousef et al. "Load frequency control of a multi-area power system: an adaptive fuzzy logic approach," *IEEE Transactions on Power Systems*, vol. 29, No. 4, pp. 1822-1830, Jul. 2004.
 - [30] I. Kocaarslan, G. Akalin and T. Erfidan, "Application of fuzzy reasoning to load-frequency control in two area power system," *1999 European Control Conference (ECC)*, pp. 27-31, Sep. 1999.
 - [31] H. A. Yousef, "Load Frequency Control of a Multi-Area Power System: An Adaptive Fuzzy Logic Approach", *IEEE Transactions on Power Systems*, vol. 29, No. 4, pp. 1822-1830, Jul. 2014.
 - [32] S. K. Aditya and D. Das, "Design of Load Frequency Controllers Using Genetic Algorithm for Two Area Interconnected Hydro Power System", *Electric Power Components & Systems*, vol. 31, No. 1, Jan. 2003.

-
- [33] P. Li et al. "Genetic algorithm optimization for AGC of multi-area power systems", *2002 IEEE Region 10 Conference on Computers, Communications, Control and Power Engineering*, Oct. 2002.
 - [34] F. Daneshfar and H. Bevrani, "Load-frequency control: a GA-based multi-agent reinforcement learning", *Iet Generation Transmission & Distribution*, vol. 4, No. 1, pp. 13-26, Jan. 2010.
 - [35] [Online]. Available: <https://www.quora.com/What-are-different-types-of-energy-storage-systems-and-what-is-its-role-in-Smart-Grid>.
 - [36] H. Ibrahim et al. "Energy storage systems—characteristics and comparisons." *Renewable and sustainable energy reviews*, vol. 12, pp. 1221-1250, Jun. 2008.
 - [37] F. Díaz-González et al., "A review of energy storage technologies for wind power applications," *Renewable and Sustainable Energy Reviews*, vol. 16, pp. 2154-2171, May. 2012.
 - [38] D. Kottick et al. "Battery energy storage for frequency regulation in an island power system," *IEEE Trans. Energy Convers.*, vol. 8, pp. 455-459, Sep. 1993.
 - [39] I. Serban and C. Marinescu, "Control strategy of three-phase battery energy storage systems for frequency support in microgrids and with uninterrupted supply of Local loads," *IEEE Trans. Power. Electr.*, vol. 29, pp. 5010-5020, Sep. 2014.
 - [40] S. K. Aditya and D. Das, "Battery energy storage for load frequency control of an interconnected power system", *Electric Power Systems Research* 2001, vol. 58, No. 3, pp.179-185, 2001.
 - [41] C. Lu et al. "Effect of battery energy storage system on load frequency control considering governor deadband and generation rate constraint", *IEEE Transactions on Energy Conversion*, vol. 10, No. 3, pp. 555-561, Sep. 1995.
 - [42] S. Kalyani et al. "Load frequency control using battery energy storage system in interconnected power system", *2012 Third International Conference on Computing, Communication and Networking Technologies*, Jul. 2012.
 - [43] M-u-d. Mufti et al. "Super-capacitor based energy storage system for improved load frequency control", *Electric Power Systems Research*, vol. 79, No. 1, pp. 226-233, Jan. 2009.
 - [44] E. Çam and I. Kocaarslan, "Load frequency control in two area power systems using fuzzy logic controller," *Energy Conversion and Management*, vol.46, pp. 233-243, Jan. 2005.
 - [45] S. Z. N. Dar and M-u-d. Mufti, "Load frequency control in a two-area power system with supercapacitor energy storage system", *2017 International Conference on Intelligent Computing, Instrumentation and Control Technologies*, Jul. 2017.
 - [46] M. Wakihara, "Recent developments in lithium-ion batteries," *Materials Science and Engineering: R: Reports*, vol. 33, pp. 109-134, Jan. 2001.
 - [47] Zhang, Shengqi, Yateendra Mishra, and Gerard Ledwich. "Battery energy storage systems to improve power system frequency response." *Power Engineering Conference (AUPEC), 2014 Australasian Universities. IEEE*, 2014.

-
- [48] Y. Cheng et al. "Dynamic available AGC based approach for enhancing utility scale energy storage performance." *IEEE Transactions on Smart Grid*, vol. 5, No. 2, pp. 1070-1078, Mar. 2014
 - [49] A. Oudalov, D. Chartouni and C. Ohler, "Optimizing a Battery Energy Storage System for Primary Frequency Control", *IEEE Trans. Power Syst.*, vol. 22, pp. 1259-1266, Aug. 2007.
 - [50] P. Kundur et al., *Power Systems Stability and Control*. New York, NY, USA: McGraw-Hill Education, 1994.
 - [51] G. Delille et al., "Dynamic frequency control support by energy storage to reduce the impact of wind and solar generation on isolated power system's inertia," *IEEE Trans. Sustain. Energy*, vol. 3, No. 4, pp. 931-939, Oct. 2012.
 - [52] O. I. Elgerd et al., "Optimum megawatt-frequency control of multiarea electric energy systems," *IEEE Trans. Power App. Syst.*, vol. PAS-89, No. 4, Apr. 1970.
 - [53] T. K. Nagsarkar, and M. S. Sukhija. *Power system analysis*. Oxford University Press, 2007.
 - [54] H. H. Chen et al., "Effect of battery energy storage system on load frequency control considering governor deadband and generation rate constraint," *IEEE Trans. Energy Convers.*, vol. 10, pp. 555-561, Sep. 1995.
 - [55] G. Shirai, "Load frequency control using Lyapunov's second method: Bang-bang control of speed changer position," *Proc. IEEE*, vol. 67, pp. 1458-1459, Oct. 1979.
 - [56] N. Ewart, "Automatic generation control - performance under normal conditions," *Proc. IEEE*, N.H. Henniker, Aug. 1975.
 - [57] N. Cohn, "Some aspects of tie line bias control on interconnected power systems," *IEEE Trans. Power App. Syst.*, vol. 75, pp. 1415-1436, Feb. 1957.
 - [58] J. L. Willems, "Sensitivity analysis of the optimum performance of conventional load-frequency control," *IEEE Trans. Power App. Syst.*, vol. PAS-93, pp. 1287-1291, Sep. 1974.
 - [59] S. K. Aditya and D. Das, "Battery energy storage for load frequency control of an interconnected power system," *Electric power systems research*, vol. 58, pp. 179-185, Jul. 2001.
 - [60] V. Knap et al., "Sizing of an energy storage system for grid inertial response and primary frequency reserve," *IEEE Trans. Power Syst.*, vol. 31, pp. 3447-3456, Sep. 2016.
 - [61] P. Schavemaker and L. van der Sluis, *Electrical Power System Essentials*. New York, NY, USA: Wiley, 2008.
 - [62] L.K. Kirchmayer, *Economic Control of Interconnected Systems*. John Wiley & Sons, 1959.
 - [63] A.J. Wood and B.F. Wollenberg, *Power Generation, Operation, and Control*. John Wiley & Sons, 1984.
 - [64] V. Knap et al., "Grid inertial response with lithium-ion battery energy storage systems," in *Proc. 2014 IEEE Int. Symp. Ind. Electron. (ISIE)*, pp. 1813-1818, Jun. 2014.

-
- [65] P. W. Christensen and G. C. Tarnowski, "Inertial for wind power plants-State of the art review-Year 2011", *Proc. 10th Int. Workshop Large-Scale Integration of Wind Power into Power Systems*, Aarhus, Denmark, Oct. 2011.
 - [66] A. Payman et al., "Energy control of supercapacitor/fuel cell hybrid power source," *Energy Conversion and Management*, vol. 49, pp. 1637-1644, Jun. 2008.
 - [67] J. Morren et al., "Wind turbines emulating inertia and supporting primary frequency control", *IEEE Trans. Power Syst.*, vol. 21, pp. 433-434, Jan. 2006.
 - [68] Amano, Hiroyuki, et al. "Utilization of battery energy storage system for load frequency control toward large-scale renewable energy penetration", *Innovative Smart Grid Technologies (ISGT Europe), 2012 3rd IEEE PES International Conference and Exhibition on. IEEE*, 2012.
 - [69] PJM manual12: Balancing Operations [EB/OL]. [2017-02-01]. [Online]. Available: <http://www.pjm.com//media/documents/manuals/m12.ashx>.
 - [70] S. Piller et al. "Methods for state-of-charge determination and their applications", *Journal of power sources*, vol. 96, No. 1, pp. 113-120, Jun. 2001.
 - [71] Y. Wang et al. "Load frequency control in a two-area power system with supercapacitor energy storage system", *Energy, Power and Transportation Electrification (ACEPT), 2017 Asian Conference. IEEE*, 2017.
 - [72] H.P. Beck and R. Hesse. "Virtual synchronous machine," *Electrical Power Quality and Utilisation, 2007. EPQU 2007. 9th International Conference on. IEEE*, Oct. 2007.
 - [73] H. Wu et al. "Small-signal modeling and parameters design for virtual synchronous generators", *IEEE Transactions on Industrial Electronics*, vol. 63, No. 7, pp. 4292-4303, Mar. 2016.
 - [74] J. Liu et al. "Comparison of dynamic characteristics between virtual synchronous generator and droop control in inverter-based distributed generators", *IEEE Transactions on Power Electronics*, vol. 31, No. 5, pp. 3600-3611, 2016.
 - [75] J. Fang et al. "Distributed Power System Virtual Inertia Implemented by Grid-Connected Power Converters", *IEEE Transactions on Power Electronics*, 2017.
 - [76] M. A. Torres L. et al. "Self-tuning virtual synchronous machine: A control strategy for energy storage systems to support dynamic frequency control", *IEEE Transactions on Energy Conversion*, vol. 29, No. 4, pp. 833-840, Dec. 2014.
 - [77] D. Li et al. "A self-adaptive inertia and damping combination control of VSG to support frequency stability", *IEEE Transactions on Energy Conversion*, vol. 32, No. 1, pp. 397-398, Mar. 2017.
 - [78] G. Strbac et al. "Strategic assessment of the role and value of energy storage systems in the UK low carbon energy future", Report for Carbon Trust 2012, Jun. 2012.
 - [79] M. Cheng et al. "Primary frequency response in the Great Britain power system from dynamically controlled refrigerators", *22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013)*, pp. 0507-0507, 2013.
 - [80] M. Cheng et al. "Benefits of using virtual energy storage system for power system frequency response", *Applied energy*, vol. 194, pp. 376-385, May 2017.

-
- [81] M. Cheng et al. "Availability of load to provide frequency response in the Great Britain power system", *Power Systems Computation Conference (PSCC), 2014. IEEE*, Aug. 2014.

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