Inertia enhancement for power systems with high penetration of renewable energy

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**INERTIA ENHANCEMENT FOR POWER SYSTEMS
WITH HIGH PENETRATION OF RENEWABLE ENERGY**

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INERTIA ENHANCEMENT FOR POWER SYSTEMS WITH HIGH PENETRATION OF RENEWABLE ENERGY

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A thesis submitted to the Nanyang Technological University

in partial fulfillment of the requirement for the degree of

Master of Engineering

2019

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarized materials, and has not been submitted for a higher degree to any other University or Institution.

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Supervisor Declaration Statement

I have reviewed the content and presentation style of this thesis and declare it is free of plagiarism and of sufficient grammatical clarity to be examined. To the best of my knowledge, the research and writing are those of the candidate except as acknowledged in the Author Attribution Statement. I confirm that the investigations were conducted in accord with the ethics policies and integrity standards of Nanyang Technological University and that the research data are presented honestly and without prejudice.

26/3/2019

26-MAR-2019

Tang Yi

TANG YI

Authorship Attribution Statement

This thesis contains material from 3 papers published in the following peer-reviewed journals where I was the first and/or corresponding author.

Chapter 3 is published as J. Fang, **R. Zhang**, H. Li, and Y. Tang, "Frequency Derivative-based Inertia Enhancement by Grid-Connected Power Converters with a Frequency-Locked-Loop," *IEEE Transactions on Smart Grid*, pp. 1-1, 2018 and J. Fang, **R. Zhang**, H. Li, and Y. Tang, "Inertia enhancement by grid-connected power converters with frequency-locked-loops for frequency derivative estimation," in *Proc. PESGM 2018*, Portland, Oregon, USA, 5–9 Aug. 2018.

The contributions of the co-authors are as follows:

The manuscript drafts were prepared by Dr. Fang Jingyang. I revised and proofread the manuscript drafts. Asst/P Tang Yi provided the initial research direction and idea and proofread the manuscript drafts.

The initial study and simulations on the single-phase FLL and three-phase FLL were done by me. Dr. Fang Jingyang and I discussed the differences of the PLL and FLL together, and the differences were summarized by me. The parameters tuning part was finished by Dr. Fang Jingyang and me. The modified single-phase FLL was designed and proposed by Dr. Fang Jingyang. The experimental test-bed was designed by Dr. Fang Jingyang and built by me and Dr. Fang Jingyang. The experiments were designed and completed by me and Dr. Fang Jingyang in Electrical Power Research Lab located at School of Electrical and Electronic Engineering. I also analyzed the simulation and experiment results.

Dr. Li Hongchang assisted in the result analysis.

Chapter 4 is published as **R. Zhang**, J. Fang, and Y. Tang, "Inertia emulation through supercapacitor energy storage systems," in *Proc. ICPE 2019-ECCE Asia*, Bexco, Busan, Korean, 27–31 May 2019, in press.

The contributions of the co-authors are as follows:

The initial research direction is provided by Ast/P Tang Yi.

I wrote the drafts of the manuscript. The manuscript was revised and proofread by Dr. Fang Jingyang.

The testing structure was designed by me with Ast/P Tang Yi and Dr. Fang Jingyang's assistance. The simulations on the two different control structure were designed and done by me. The experiments were prepared and completed by me and Dr. Fang Jingyang in Water and Energy Research Lab located at School of Electrical and Electronic Engineering.

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Table of Contents

Statement of Originality	i
Supervisor Declaration Statement	ii
Authorship Attribution Statement.....	iii
Acknowledgements.....	v
Summary.....	viii
List of Figures.....	x
List of Tables	xiv
List of Abbreviations	xv
Chapter 1 Introduction.....	1
1.1 Background and Motivation.....	1
1.2 Major Contributions of the Thesis	5
1.2.1 Enhancement of Power System Inertia through Battery Energy Storage.....	5
1.2.2 Enhancement of Power System Inertia through Supercapacitor Energy Storage	6
1.3 Organization of the Thesis	6
Chapter 2 Review of Power System Inertia.....	8
2.1 Effect of Inertia on Frequency Control	8
2.2 Existing Inertia Enhancement Methods	11
2.2.1 Synchronous Generators.....	11
2.2.2 PV Systems and Wind Power Generation	12
2.2.3 DC-link Capacitors.....	14
2.2.4 Virtual Synchronous Generators	16
2.3 Summary	18
Chapter 3 Enhancement of Power System Inertia through Battery Energy Storage	20
3.1 Introduction.....	20
3.2 System Configuration	21
3.3 Principle of the Proposed Method.....	21
3.4 Estimation of Frequency Derivative	24
3.4.1 Limitation of the PLL.....	25
3.4.2 Single-Phase FLL.....	27
3.4.3 Three-Phase FLL.....	31
3.4.4 Modified Single-Phase FLL	34

3.4.5 Parameters Tuning.....	37
3.5 Simulation and Experimental Results	42
3.5.1 Introduction to the testing system	42
3.5.2 Simulation and Experimental Results	43
3.6 Summary	47
Chapter 4 Enhancement of Power System Inertia through Supercapacitor Energy Storage .	49
4.1 Introduction.....	49
4.2 System Description	50
4.3 Principle of Inertia Emulation through SESS	52
4.4 Inertia Control Scheme	53
4.4.1 Basic Control Scheme	53
4.4.2 Nonlinear Control Scheme	55
4.5 Simulation and Experimental Results	57
4.6 Summary	61
Chapter 5 Conclusions and Future Works	63
5.1 Conclusions.....	63
5.1.1 Frequency-Derivative based Virtual Inertia	63
5.1.2 Inertia Emulation through Supercapacitor Energy Storage System	64
5.2 Future Works.....	64
Author's Publication.....	66
Bibliography	67

Summary

To reduce carbon footprints, renewable energy sources (RESs) are widely employed to take the place of fossil fuels at present. With the increasing penetration of renewable energy generation in modern electric power systems, power electronic converters have drawn attentions extensively. Power electronic converters, which feature fast response and flexible control, are typically built with several fully controllable semiconductor devices. The functions of power converters are to convert and control the electricity as required. Power electronic converters have a wide range of application, including high voltage direct current (HVDC) transmission systems, uninterruptible power supplies (UPS), static var compensation (SVC), etc. A paradigm shift occurs in power systems with the fast development of power converters, that is, the conventional power systems are transforming to power electronics-dominated power systems. Hence, innovative and proper control strategies are vital to the future more-electronics power systems for stability maintenance, harmonic elimination and high conversion efficiency.

One specific and severe problem which frequently appears in power electronics-dominated power systems refers to the low inertia. In conventional power systems, the power system inertia is provided by the rotor of the synchronous generators, which could release kinetic energy to the power grids or absorb it from the grids by changing the rotor speed to maintain the grid frequency in an acceptable range when there is a frequency disturbance. Large inertia is always desirable for power systems, because large inertia may reduce the power system frequency deviation and slow down the dynamic of frequency change. However, the synchronous generators are gradually replaced by power converters. With the decreasing of the synchronous generators, power system inertia will be significantly reduced. Less damping can be provided to the power system with the reduced inertia. Therefore, the performances of power system frequency regulation will be weakened due to the increasing shares of renewable energy generation, and the grid frequency would be more sensitive to the disturbance caused by the imbalance between generation and demand in the power systems. Low inertia has already challenged the control and frequency stability of small-scale power system. With the continuous integration of renewable energy generation, the large-scale power systems are likely to face the same issues, such as cascading failures, undesirable load shedding, or even massive black-out, in the future.

The focus of this thesis is the inertia enhancement for power systems through energy storage systems. The objectives of the research are the improvement of frequency regulation and enhancement of the power system inertia by emulating the inertia through power converters. Some control schemes for inertia emulation and enhancement will be presented and discussed in detail in the thesis. Specifically, the distributed virtual inertia is generated by different energy storage systems (ESSs). With the proposed methods, the frequency nadir and the rate of change of frequency (RoCoF) can be improved, which means the power system inertia is emulated and the frequency stability is improved.

The other issues brought by the extension of power converters, such as voltage sag, harmonics, low power factor, etc., should be further discussed and solved in the future. The concept of grid-friendly power converters is the potential research direction.

All the control schemes presented in the thesis are verified in simulation using Matlab / Simulink and PLECS. The down-scale experimental test bed has been built for validating the feasibility of the presented methods.

List of Figures

Fig. 1-1. Solar PV capacity and annual additions, 2007-2017 (Renewables 2018 Global Status Report [Online]. Available: http://www.ren21.net) [4].	2
Fig. 1-2. Wind power capacity and annual additions, 2007-2017 (Renewables 2018 Global Status Report [Online]. Available: http://www.ren21.net) [4].	2
Fig. 2-1. Frequency regulation framework.	8
Fig. 2-2. Frequency response and the relevant RoCoF to a 5% step-up load change with different value of H ($D = 1$).	9
Fig. 2-3. Pole-zero map of the system with different H ($D = 0$).	10
Fig. 2-4. Available inertial energy constant of synchronous generators with different minimum frequency.	12
Fig. 2-5. Schematic diagram of a DFIG-based wind generation system [15].	13
Fig. 2-6. Schematic diagram of a PMSG-based wind generation system [15].	14
Fig. 2-7. Virtual inertia coefficient H_p versus the dc-link capacitance C_{dc} , dc-link voltage V_{dc} , and voltage variation ΔV_{dc_max} ($\Delta f_{r_max} = 0.2$ Hz, $f_{ref} = 50$ Hz, and $V_{A_rated} = 1$ kVA) [21].	15
Fig. 2-8. Experimental waveforms of the frequency responses and the dc-link voltage variations under a 3% step-up load change [21].	16
Fig. 2-9. Primary frequency responses under load disturbances [54].	17
Fig. 2-10. Secondary frequency responses under load disturbances [54].	17
Fig. 3-1. System configuration of the battery energy storage.	21
Fig. 3-2. Frequency regulation framework with the proposed virtual inertia.	22

Fig. 3-3. Active power requirement of the GCC $ \Delta P_{c_pu} $ under various conditions of step load changes $ \Delta P_{l_pu} $ and emulated inertia coefficients H_c ($H = 5$ s) [63].	22
Fig. 3-4. Design flowchart of virtual inertia.	23
Fig. 3-5. Frequency controller of the GCC [63].	23
Fig. 3-6. Block diagram of a single-phase PLL [63].	25
Fig. 3-7. The linearized single-phase PLL.	26
Fig. 3-8. Zero-pole map of the closed-loop PLL system with different K_{PLL_p} .	27
Fig. 3-9. Block diagram of a single-phase FLL [63].	27
Fig. 3-10. Block diagram of a three-phase FLL [63].	31
Fig. 3-11. Step changes of the frequency derivative df_g / dt estimated by the PLL, single-phase FLL, and three-phase FLL [63].	33
Fig. 3-12. The block diagram of a modified single-phase FLL.	35
Fig. 3-13. Simulation waveform of a single-phase system with a single-phase FLL...	36
Fig. 3-14. Simulation waveform of a single-phase system with a modified single-phase FLL.	36
Fig. 3-15. Settling time t_{s_SOGI} versus the proportional gain K_{FLL_p} .	38
Fig. 3-16. Bode diagram of $v_{FLL}(s) / v_{ga}(s)$.	39
Fig. 3-17. Settling time t_{s_FLL} versus the integral gain K_{FLL_i} .	40
Fig. 3-18. Frequency response in the presence of a frequency step change (from 50Hz to 60Hz).	41
Fig. 3-19. Schematic diagram of the testing system.	42
Fig. 3-20. A photo of the experimental test-bed [63].	43

Fig. 3-21. Simulation waveforms of AC voltages v_{gabc} , load currents i_{labc} , and DC-link voltages v_{gdc} and v_{cdc} [63].	44
Fig. 3-22. Experimental waveforms of AC voltages v_{gabc} , load currents i_{labc} , and DC-link voltages v_{gdc} and v_{cdc} [63].	44
Fig. 3-23. Simulation waveforms of frequency responses under a 5% step-up load change [63].	45
Fig. 3-24. Experimental waveforms of frequency responses under a 5% step-up load change [63].	45
Fig. 3-25. Simulation waveforms of the GCC power change ΔP_{c_pu} and frequency derivative df_g / dt under a 5% step-up load change [63].	46
Fig. 3-26. Experimental waveforms of the GCC power change ΔP_{c_pu} and frequency derivative df_g / dt under a 5% step-up load change [63].	46
Fig. 3-27. Simulation waveforms of frequency responses under a various RES output [63].	47
Fig. 3-28. Experimental waveforms of frequency responses under a various RES output [63].	47
Fig. 4-1. Schematic diagram of a SESS equipped with virtual inertia.	50
Fig. 4-2. System structure of the SESS.	52
Fig. 4-3. Frequency regulation framework with virtual inertia.	52
Fig. 4-4. Virtual inertia coefficient H_p versus rated supercapacitor voltage V_{es} and capacitance of supercapacitor C_{es} .	55
Fig. 4-5. Frequency waveforms under a 10% step-up load change.	59
Fig. 4-6. Supercapacitor voltage waveforms under a 10% step-up load change.	59
Fig. 4-7. Frequency waveforms under a 10% step-down load change.	60

Fig. 4-8. Supercapacitor voltage waveforms under a 10% step-down load change.	60
Fig. 4-9. A photo of the experimental test-bed.	61
Fig. 4-10. Experimental waveforms of frequency responses under a 5% step-up load change.	61

List of Tables

Table I. Standard on frequency control prescribed by different international grid code.	3
Table II. Parameters of the synchronous generator frequency regulation framework..	10
Table III. Control parameter values.....	24
Table IV. BESS system parameter values.	43
Table V. SESS system parameter values.....	51
Table VI. Control parameters of SESS.....	58

List of Abbreviations

HVDC	High Voltage Direct Current
UPS	Uninterruptible Power Supply
SVC	Static Var Compensation
RES	Renewable Energy Sources
RoCoF	Rate of Change of Frequency
UFLS	Under Frequency Load Shedding
BESS	Battery Energy Storage System
FLL	Frequency-Locked-Loop
PLL	Phase-Locked-Loop
SESS	Supercapacitor Energy Storage System
PV	Photovoltaic
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
DFIG	Double-Fed Induction Generator
PMSG	Permanent Magnet Synchronous Generator
VSG	Virtual Synchronous Generator
VSM	Virtual Synchronous Machine
ESS	Energy Storage System
GCC	Grid-Connected Converter
SOGI	Second-Order-Generalized-Integrator
SoC	State of Charge

Chapter 1 Introduction

In the first chapter, the research background and motivation are discussed. The renewable power generation represents the trend for modern power systems. However, the massive integration of renewable power generation, which should be coupled to the electrical grid through grid-tied power converters, will cause some problems. As power converters do not provide any inertia to the power grids, the power system frequency stability may confront significant challenges, especially under severe frequency events. Hence, the objective of this thesis is to enhance the power system inertia and improve the power system frequency regulation. After introducing the research background and motivation, the significant contributions of the thesis are presented. Finally, the organization of the thesis is provided.

1.1 Background and Motivation

Power systems are changing from the traditional power grids to more reliable, sustainable, high-efficiency and economical smart grids [1]. As one of the most significant features of smart grids, renewable energy sources (RESs) are replacing the fossil fuels for electrical power generation in modern power systems to reduce the carbon emission and operation costs [2]. As observed in Fig. 1-1 and Fig. 1-2, the capacity of solar PV and wind power generation is continuously increasing these years.

As renewable power generation should be coupled to the main grids through power electronic converters, power electronics technologies have become a vital role to modern power systems for expanding the integration of RESs [3]. Power converters have a wide range of applications, such as uninterruptible power supply (UPS), static var compensator (SVC), high voltage DC transmission (HVDC), etc.

Fig. 1-1. Solar PV capacity and annual additions, 2007-2017 (Renewables 2018 Global Status Report [Online]. Available: <http://www.ren21.net>) [4].

Fig. 1-2. Wind power capacity and annual additions, 2007-2017 (Renewables 2018 Global Status Report [Online]. Available: <http://www.ren21.net>) [4].

In conventional power systems, the kinetic energy stored in the rotor of the synchronous generators can provide power system inertia [5]. The rotating masses of the large synchronous generators could release kinetic energy to the main grids or absorb it from the grids when there is an unbalance between the generation and demand so that the frequency can be maintained in an acceptable range. Notwithstanding the grid frequency is expected to keep unchanged at its nominal value, the generation and demand of the

power systems are continuously changing. One issue associated with low-frequency operations of synchronous generators is related to the vibratory stress on the long low-pressure turbine blades, and the other problem is that the output of boiler feed pumps or fans supplying combustion air may reduce so that the generating units would be overheated [5].

Table I. Standard on frequency control prescribed by different international grid code.

Country/Region	Australia [6]	Europe [7]	Great Britain [8]	Singapore [9]
Nominal frequency	50 Hz	50 Hz	50 Hz	50 Hz
Normal operating frequency band	Interconnected system: ± 0.15 Hz Islanded system: ± 0.5 Hz	± 0.2 Hz	± 0.5 Hz Target frequency band: ± 0.05 Hz	± 0.2 Hz
Operational frequency tolerance band	49-51 Hz Extreme frequency tolerance band: 47-52 Hz	49.2-50.8 Hz	49-51 Hz Under frequency load shedding: 48.8 Hz	Under frequency load shedding: 49.7 Hz

However, in modern power systems, conventional synchronous generators are gradually replaced by power converters [10]. Power converters do not possess any rotating mechanical structure as conventional synchronous generators do. Therefore, they will not provide any rotational inertia to the power system [11-13]. With the increase of the power converters, power system inertia would be significantly decreased, and this will inevitably bring some problems. One of the primary concerns of the low inertia is the unceasing increasing level of the frequency dynamics, i.e., rate of change of frequency (RoCoF). The generating units may tend to pole-slipping and protective tripping with the

high level of the RoCoF [14]. Pole slipping usually happens while the RoCoF is ranging from 1.5 Hz/s to 2 Hz/s (over a 500 ms rolling window) [15]. Besides, extremely high-RoCoF may prevent some protection operation such as Under Frequency Load Shedding (UFLS) [16]. For example, the requirement of the RoCoF in the Great Britain is 0.125 Hz/s. However, with the increasing penetration of renewable power generation, National Grid proposed to increase the RoCoF standard to 1 Hz/s to prevent generators from tripping. The second challenge of the low inertia is the significant frequency contingencies. Severe disturbances may result in severe consequences, such as cascading outages and isolation of areas. For example, the large blackout in Taiwan, China, in 1999, was caused by the power mismatch between generation and demand. When the frequency decline reaches a shallow level, it will lead to problems such as tripping of generating units caused by protective relays [5]. As predicted by [17, 18], frequency excursions will cause load shedding, which may occur in Electric Reliability Council of Texas (ERCOT) with the increasing renewable penetrations [19].

In general, more significant challenges would be faced by power system stability, such as changing the ways of frequency regulation, increasing amounts of spinning reserve, and more frequent starting of generation installed to support the system [20]. For example, running extra rotating machines, such as synchronous condensers, which are essentially synchronous generators working without prime movers or loads, in reactive power compensation modes to generate more inertia. However, the high operation cost prevents this approach from widespread application [5].

Fortunately, power converters feature fast response and flexible control; therefore, they can be adequately controlled for the power system stability and performance improvement. Power converters can mimic the rotational inertia of conventional synchronous generators, which is the so-called virtual inertia. Recently, research efforts have been targeted towards utilizing the energy stored in capacitors for inertia emulation [21-27]. Inertia emulation through the capacitors requires the appropriate control of

power converters. Other candidate applications for inertia emulation by capacitors include ultracapacitor storage systems [20], DC microgrids [28, 29] and virtual synchronous generators (VSGs) [30-33], which are essentially grid-connected power converters functioning as synchronous generators.

With the increasing of power converters in modern power systems, energy storage systems (ESSs) are necessary in the power electronic-dominated power systems as the power converters cannot absorbing/releasing any kinetic energy. In terms of the urgent demand for inertia enhancement with the domination of power electronic converters, the theme of this thesis is to design the virtual inertia control schemes for different energy storage systems. In addition to inertia emulation, issues like modeling the power converters, optimizing the topologies, and parameter design are also taken into consideration and discussed in the thesis.

1.2 Major Contributions of the Thesis

Significant contributions of this thesis are listed as follows:

1.2.1 Enhancement of Power System Inertia through Battery Energy Storage

Batteries are generally featured with fast response, high energy density, and moderate costs. Hence, batteries would be considered as a wise choice for frequency regulation. An inertia emulation method through battery energy storage systems has been proposed. This method is achieved by directly linking the of the grid frequency derivative df_g / dt to the active power reference of the grid-connected battery energy storage systems. Therefore, the grid frequency can be maintained in an acceptable range with the energy-releasing or absorbing by the battery energy storage.

However, the frequency derivative estimation might be difficult as the differential calculation is sensitive to the high-frequency noises; hence the differential operator

cannot be used directly in practice. The main contribution of this research project is the accurate estimation of frequency derivative with a frequency-locked-loop (FLL).

The proposed method can avoid high-frequency noises and effectively achieve inertia enhancement and frequency regulation improvement. Moreover, although the proposed method is implemented by a battery energy storage system in the thesis, and it can also be applied to other types of grid-connected energy storage systems.

1.2.2 Enhancement of Power System Inertia through Supercapacitor Energy Storage

Characteristics such as high-power density, long life cycle, and fast charging speed make supercapacitor a promising candidate for inertia emulation. Hence, a supercapacitor energy storage system (SESS) is implemented in this thesis to generate virtual inertia by proportionally linking the voltage reference of the supercapacitor with the grid frequency. The key to this approach is the proper design of the virtual inertia controller. Two different control schemes are discussed in the thesis. The basic control scheme is to use a proportional controller, but this approach is only applicable when the supercapacitor voltage is limited in a minimal range. When there is a relatively large disturbance, the virtual inertia coefficient will no longer remain a constant with the basic control scheme. As a solution, a nonlinear control scheme is an alternative way to generate virtual inertia even with a high frequency and voltage variation.

1.3 Organization of the Thesis

The following of the thesis is organized as follows:

Chapter 2 introduces the basic concept of power system inertia and its significance to power system frequency control. The principle of primary frequency regulation is discussed first, and then existing inertia enhancement methods are summarized.

Chapter 3 introduces a frequency-derivative based inertia emulation method, which is implemented by a battery energy storage system. In the first place, the system configuration is presented. Next, the principle of the proposed method is demonstrated. After that, the frequency derivative estimation by the frequency-locked-loops (FLLs) is introduced. Before investigating the effectiveness of the FLL, the limitation of the phase-locked-loop (PLL) PLL is presented. The parameters tuning of the FLL are also discussed in this chapter.

Chapter 4 considers the inertia emulation through SESSs. The structure of the SESS is illustrated at first. Then, a bidirectional dc/dc converter equipped with supercapacitors is modeled. Following that, the principle of inertia emulation through supercapacitor energy storage systems is presented. The basic virtual inertia controller and its limitations are discussed first, and the nonlinear control scheme is introduced to tackle the issues within the basic control scheme. The parameter design of the virtual inertia controller and supercapacitor are discussed as well.

Chapter 5 concludes the thesis and suggests some possible future research direction.

Chapter 2 Review of Power System Inertia

This chapter offers a review of power system inertia. The effect of inertia on frequency control is demonstrated by introducing the principle of power system frequency regulation. Subsequently, the existing techniques for inertia enhancement are reviewed.

2.1 Effect of Inertia on Frequency Control

Before discussing the significance of inertia to frequency control, the basic principle of frequency regulation should be illustrated first.

Fig. 2-1 demonstrates the frequency regulation framework of conventional generating units with a reheat steam turbine. The mathematical models of speed governor and reheat turbine are provided by [5]. The prefix Δ and subscript pu denote the changes and per-unit values of relevant variables, respectively. The rotor inertia and damping unit can describe the well-known swing equation:

$$\Delta P_{m_pu} - \Delta P_{l_pu} = D\Delta\omega_{o_pu} + 2H \frac{d\Delta\omega_{o_pu}}{dt}, \quad (2.1)$$

where P_m is the input power of power grid, P_l represents the power absorbed by frequency independent loads and ω represents the grid frequency. D denotes the damping factor, and H is the inertia constant, or inertia coefficient.

Fig. 2-1. Frequency regulation framework.

It needs to be emphasized that H is an essential indicator of power system inertia, which is defined as:

$$H = \frac{E_{\text{gen}}}{VA_{\text{rated}}} = \frac{J\omega_{\text{ref}}^2}{2VA_{\text{rated}}}, \quad (2.2)$$

where E_{gen} represents the kinetic energy stored in the rotor of the generating units, VA_{rated} is the system base power and J refers to the moment of inertia. The frequency response to a load change is determined by the rotor inertia and damping unit, which refers to the inertia constant and damping constant.

To visualize the effect of inertia constant H , the frequency responses and their relevant dynamics, i.e., RoCoF, under a 5% step-up load change and the pole-zero map of the system with different H are shown in Fig. 2-2 and Fig. 2-3, respectively, based on the system parameters listed in Table II.

Fig. 2-2. Frequency response and the relevant RoCoF to a 5% step-up load change with different value of H ($D = 1$).

It can be observed from Fig. 2-2 that the increase of the inertia constant H allows the improvement of the frequency nadir and the prolonged frequency dynamics can be expected. It should be mentioned that with a small H , e.g. $H = 1$, the oscillation will occur during the frequency dynamics.

Fig. 2-3. Pole-zero map of the system with different H ($D = 0$).

From Fig. 2-3, with $H = 0.1$ and $D = 0$, the poles of the system will be located at the right-half-plane, which means the system is unstable in this case.

Table II. Parameters of the synchronous generator frequency regulation framework.

Description	Symbol	Value
Frequency-droop coefficient	R	0.05
Speed governor coefficient	T_G	0.1 s
Turbine HP coefficient	F_{HP}	0.3 s
Time constant of reheater	T_{RH}	7.0 s
Time constant of main inlet	T_{CH}	0.2 s
Load damping coefficient	D	0/1.0
Inertia constant	H	0.1 - 5.0 s
Rated frequency	f_{ref}	50 Hz

Fig. 2-2 and Fig. 2-3 indicate that H and D are essential variables to evaluate frequency stability, and H is a critical indicator of power system inertia. It is obvious that the mechanism for inertia enhancement can be translated to increasing the value of H .

2.2 Existing Inertia Enhancement Methods

As inertia enhancement and inertia emulation are essential and common research topics shared among lots of researchers, many attempts have been done.

2.2.1 Synchronous Generators

It would be very straightforward to implement other synchronous generators. The kinetic energy generated by the synchronous generators can be relatively large. However, the available power during the transient process of inertial responses will be smaller than expected as the synchronous generators need to be synchronized with the power grid [34]. The maximum allowable frequency deviation is typically within the range of 0.1 – 1 Hz [5]. Therefore, the actual available energy should be defined as:

$$H_{\text{available}} = \frac{\frac{1}{2} J \omega_{\text{ref}}^2 - \frac{1}{2} J \omega_{\text{min}}^2}{VA_{\text{rated}}}. \quad (2.3)$$

The available inertial energy constant from synchronous generators with different minimum frequency is depicted in Fig. 2-4. As seen in Fig. 2-4, the available inertial energy constant is usually small, thus it is worth finding other methods for inertia enhancement as mentioned in [34].

Also, the most considerable concern of running other synchronous generators is the high operation costs.

Running extra synchronous generators without a prime mover, which is known as synchronous condensers, has been proved that they can provide minimal inertia from the

kinetic energy stored in the rotating masses. Synchronous condensers are usually used to improve power system stability and voltage support [5]. In addition to the good performance of reactive power compensation, synchronous condensers can also contribute to the inertial responses of the power system, where the typical value of H was 2.1 s [35]. However, the high demand for cooling and the slow response to the load change are the main drawbacks of employing synchronous condensers for inertia enhancement.

Fig. 2-4. Available inertial energy constant of synchronous generators with different minimum frequency.

In summary, there are many limitations and drawbacks of running other rotating machines in power systems. The most significant barrier is the high capital and operating costs. The other concerns include the limited available energy, the thermal, and the slow responses.

2.2.2 PV Systems and Wind Power Generation

Photovoltaic (PV) generation and wind generation will gradually replace synchronous generators in power systems, and the RoCoF may be high in the future with the decreasing of synchronous inertia.

As the available area for PV generation is more than other renewable energy generation, PV generation has drawn lots of attentions in modern power systems [36]. Solar photovoltaic installations do not contain any rotating parts and therefore have no natural inertia. Maximum power point tracking (MPPT) control is commonly used and extensively studied for PV systems. However, PV systems with MPPT control will not contribute to the active power regulation of power systems. PV power for inertia emulation or frequency regulation is required to be curtailed, such as the California ISO, which has been discussed in [36-38]. This method is only justified in high-PV generation systems, such as the California power system, or else, the spilled energy may cause a non-trivial opportunity cost, which might impede its development and adoption because PV inverters are expected to operate below the maximum power points (MPPs).

A potential approach for inertia emulation is to utilize the kinetic energy stored in the wind turbines [15, 39-42]. Both the doubly-fed induction generator (DFIG)-based and permanent magnet synchronous generator (PMSG)-based wind generation system can be implemented for the inertial response, but they will not generate inertia naturally [41]. Fig. 2-5 shows the schematic diagram of a DFIG-based wind generation system. It can be observed that the rotor is connected to the grid through a back-to-back converter. The generator-side converter aims to control the speed of the rotor and the active power, while the grid-side converter is designed for regulating the dc-link voltage v_{dc} and the reactive power. By controlling these two converters, the DFIG can be used to absorb from or release power to the grid, thus regulate the grid frequency.

Fig. 2-5. Schematic diagram of a DFIG-based wind generation system [15].

Besides the DFIG-based wind generation system, there is a system called PMSG-based system as illustrated in Fig. 2-6. It can be observed from Fig. 2-6 that the stator is connected to the power grid through a back-to-back converter, which is different from the DFIG-based wind generation system [41, 43, 44].

Fig. 2-6. Schematic diagram of a PMSG-based wind generation system [15].

A control scheme for inertia emulation has been proposed in [42], which is achieved by proportionally linking the grid frequency derivative to the torque reference of the wind turbine. The calculation of the frequency derivative would inevitably introduce high-frequency noises. Another concern of utilizing the wind turbines for providing inertial responses is the speed recovery. Speed recovery can be a critical issue as discussed in [39, 41]. Excessive energy extraction can stall the wind turbines, and too much absorption may cause a second frequency dip [45]. Several studies have been done for the issue of speed recovery which allows the fast and smooth transitions between the MPP tracking mode and inertial response mode [46, 47]. However, the inertia emulated from wind turbines is very different from the inertia provided by the synchronous generators in practice as the relationship between inertial power and frequency will be nonlinear with the proposed schemes. The accurate inertia emulation with the wind turbine is still an ongoing research topic [48-50].

2.2.3 DC-link Capacitors

Since dc-link capacitors are quite common among grid-connected power converters[3, 11-13, 51], utilizing the energy stored in the dc-link capacitors for inertia emulation have

attracted some attentions recently [21-27, 52]. In general, the dc-link voltage should be varied with the grid frequency to generate virtual inertia. This is applicable because of the similarity between the rotor velocities of the synchronous generators and the capacitor voltages of the dc-link capacitors. The dc-link voltage is proportionally linked with the grid frequency in [21, 22].

For illustration, Fig. 2-7 shows the relationship between the virtual inertia coefficient and dc-link capacitance, dc-link voltage and the range of dc-link voltage variation as demonstrated in [21].

Fig. 2-8 illustrates the experimental results of the frequency responses and dc-link voltage variation under a 3% step-up load change without and with the virtual inertia controller proposed in [21]. It is apparent that with the virtual inertia controller, the frequency nadir and the RoCoF can be improved. Without virtual inertia, the dc-link voltage remains unchanged during frequency variation, which means the dc-link will not provide virtual inertia to the grid.

Fig. 2-7. Virtual inertia coefficient H_p versus the dc-link capacitance C_{dc} , dc-link voltage V_{dc} , and voltage variation ΔV_{dc_max} ($\Delta f_{r_max} = 0.2 \text{ Hz}$, $f_{ref} = 50 \text{ Hz}$, and $VA_{rated} = 1 \text{ kVA}$) [21].

Fig. 2-8. Experimental waveforms of the frequency responses and the dc-link voltage variations under a 3% step-up load change [21].

The dc-link capacitors can be considered as “inertia provider”. Utilizing the energy stored in the dc-link capacitors can avoid the calculation of frequency derivative signals, which could prevent the high-frequency noises. The other distinct benefit presented by this method can prevent the installation of extra hardware. One disadvantage of this method is that it applies to the power converters with capacitors in the dc-links only where the dc-link voltage can be modified as needed. Moreover, there are some limitations of effectively implementing this method in high-power applications, such as high voltage direct current (HVDC) systems [23-25].

2.2.4 Virtual Synchronous Generators

The concepts of virtual synchronous generators (VSGs) [30, 53, 54], virtual synchronous machines (VSMs) [55], or synchronverters [56] are proposed for grid-connected power converters to emulate the operation of conventional synchronous generators, so that the well-established theories for large synchronous generators and power systems can be applied the VSGs replace even the synchronous generators. Unlike conventional synchronous generators, the inertia provided by VSGs can be modified dynamically during the frequency events if the controller is well-designed. In [57], the authors proposed a self-tuning algorithm for VSG to continuously regulate the virtual inertia to slow down the dynamics of frequency change and improve the frequency nadir. In [58],

a self-adaptive control method which combined two parameters, i.e., inertia and damping coefficient, has been proposed for frequency stability improvement. Detailed instruction of designing the controller and its settings of VSGs is presented in [54]. The frequency and power controller proposed in [54] allows the VSGs to exhibit similar inertial responses as conventional synchronous generators, including the primary and secondary frequency regulation. As illustrate in Fig. 2-9 and Fig. 2-10, a VSG with the proposed controller has excellent performance under a load disturbance.

Implementing the VSGs in modern power systems for inertia enhancement is very straightforward and useful. However, the implementation of VSGs requires the involvement of energy storage systems (ESSs) [30]. In most of the references, the assumption that the VSGs can release or absorb infinite energy has been made, and VSGs are grid-connected inverters fed by ideal dc sources, which is not the real case. Hence, the ESSs might be a concern of utilizing the VSGs for inertia enhancement.

Fig. 2-9. Primary frequency responses under load disturbances [54].

Fig. 2-10. Secondary frequency responses under load disturbances [54].

2.3 Summary

This chapter first introduced the frequency regulation framework of a conventional generating unit with reheat steam turbines, then the significance of the inertia to frequency regulation was demonstrated. After presenting the importance of inertia, the existing methods for inertia enhancement were reviewed.

The power system inertia can be evaluated by the inertia constant H . Frequency nadir and the RoCoF are two important performance metrics for assessing the power system stability in terms of frequency regulation. Under disturbances, the frequency should be maintained in an acceptable range to avoid the tripping or triggering of interruptible loads. Moreover, the protection relays may be tripped with a high RoCoF level, resulting in an even more considerable disturbance to power systems. The improvement of frequency nadir and RoCoF can be expected with more substantial power system inertia. Hence, the inertia enhancement is necessary for a modern power system with an increasing number of power converters.

It is effortless and straightforward to run other rotating machines in power systems, but the high capital and operation costs would be the most significant barrier of this method. Other methods are utilizing different techniques for inertia emulation and enhancement. The thermal energy of the PV power generation can be a potential way to providing inertia, but it has not been proven by experiments yet, and the high opportunity costs and intermittency of the solar PV cannot be ignored. Utilizing the kinetic energy stored in the wind turbines is another approach for inertia enhancement and its feasibility has been proven. However, speed recovery should be taken into consideration when implementing this method. The energy stored in the capacitors is a relatively ideal way to inertial responses as it is feasible and does not require any extra hardware. The basic approach of achieving inertia emulation is to link the grid frequency to the capacitor voltage. This

method has been verified in many publications, whereas it is only applicable in the case when the dc-link voltage can be fully controlled.

Chapter 3 Enhancement of Power System Inertia through Battery Energy Storage

3.1 Introduction

As discussed previously, there are several approaches for inertia emulation. Batteries feature with high-energy capability, rapid response, and moderate costs, which make battery energy storage an attractive unit for implementing droop control [59]. Some optimization virtual inertia control schemes by batteries have been covered in [60-62], but these methods have been unverified by experiments.

To fill this research gap, the control strategies for battery energy storage systems to emulate inertia have been proposed in this chapter. This can be realized by linking the grid frequency derivative with the active power reference of the grid-tied battery energy storage. The most considerable difficulty of this method is supposed to be the calculation of frequency derivative, since the high-frequency noises will be introduced with the implementation of differential operators. To address the derivative calculation concern, a noise-free frequency derivative estimation method by using a frequency-locked-loop (FLL) is disclosed in this chapter.

In this chapter, the system configuration of a battery energy storage system (BESS) is sketched at first. Furthermore, the essential mechanism of the proposed inertia emulation method is discussed. The accurate estimation of the frequency derivative by the FLL is demonstrated in detail. It should be mentioned that the precise frequency derivative estimation is the main contribution of this chapter. The single-phase FLL, three-phase FLL, modified single-phase FLL and the parameter tuning are included as well. The simulation and experimental results are provided to demonstrate the effectiveness of the proposed method at the end of this chapter.

3.2 System Configuration

The proposed control scheme can be described based on the system structure demonstrated in Fig. 3-1. As observed, the L -filtered grid-connected converter (GCC) is supplied by a battery, hence, it can be identified as a battery energy storage. The control structure of the GCC contains a cascaded controller structure, where the inner-loop current controller is to regulate the GCC as a current source, and the focus of this chapter is on the outer-loop virtual inertia controller. The proposed inertia emulation method should be implemented in the virtual inertia controller [2, 10]. The detailed control mechanism will be discussed in the following sections.

Fig. 3-1. System configuration of the battery energy storage.

3.3 Principle of the Proposed Method

The essential principle of the presented method is expressed by the red dashed lines in Fig. 3-2, which can be described by the following equation:

$$\Delta P_{c_pu} = 2H_c \frac{d\Delta\omega_{o_pu}}{dt}, \quad (3.1)$$

where ΔP_{c_pu} signifies the active power absorbed by the battery energy storage, and H_c represents the virtual inertia coefficient [21]. From Fig. 3-2, it can be derived that the inertia coefficient will change from H to $(H + H_c)$ after $d\Delta\omega_{o_pu} / dt$, and ΔP_{c_pu} are related by the virtual inertia controller.

Fig. 3-2. Frequency regulation framework with the proposed virtual inertia.

Fig. 3-3. Active power requirement of the GCC $|\Delta P_{c_pu}|$ under various conditions of step load changes $|\Delta P_{l_pu}|$ and emulated inertia coefficients H_c ($H = 5$ s) [63].

Fig. 3-3 illustrates the desired active power of the GCC $|\Delta P_{c_pu}|$ under different disturbances $|\Delta P_{l_pu}|$ and various virtual inertia coefficients H_c , where $H = 5.0$ s. As observed, with a larger H_c , the GCC can provide a most significant amount of active power for inertia emulation. With H_c increasing, $|\Delta P_{c_pu}|$ is gradually close to $|\Delta P_{l_pu}|$, indicating the power mismatch between the power generation and demand can be balanced with the implementation of GCC. It is worth mentioning that the design of H_c

should depend on the currently available inertia and the desired inertia requirement of power systems. In general, the increasing of H_c would be helpful for power system frequency stability, however, a very large H_c might slow down the dynamics of the frequency regulation and extend the frequency restoration. Hence, designing H_c can be a trade-off between the improvement of frequency nadir/RoCoF and the settling time of frequency regulation [21]. The flowchart of designing the virtual inertia coefficient is illustrated in Fig. 3-4.

Fig. 3-4. Design flowchart of virtual inertia.

Fig. 3-5. Frequency controller of the GCC [63].

The above-mentioned control parameter values are summarized in Table III. The details of the FLL will be discussed in the following sections.

Table III. Control parameter values.

Description	SG parameter		Description	ESS parameter	
	Symbol	Value		Symbol	Value
Frequency-droop coefficient	R	0.05	Current control proportional gain	K_{cp}	15
Speed governor coefficient	T_G	0.1 s	Current control integral gain	K_{ci}	300
Turbine HP coefficient	F_{HP}	0.3 s	Reactive current reference	I_{cq_ref}	0 A
Time constant of reheater	T_{RH}	7.0 s	Maximum active power deviation	$\Delta P_{c_ref_max}$	± 0.1 kW
Time constant of main inlet volumes	T_{CH}	0.2 s	FLL proportional gain	K_{FLL_p}	1.414
Load damping coefficient	D	1.0	FLL integral gain	K_{FLL_i}	1.414
Inertia constant	H	5.0 s	Virtual inertia coefficient	H_c	5.0 s
AC voltage reference	V_{g_ref}	150 V	Frequency reference	f_{g_ref}	50 Hz

3.4 Estimation of Frequency Derivative

According to the principle of the proposed method which has been mentioned above, the accurate estimation of frequency derivative represents the key to this method.

However, the calculation of the derivative signal through differential operators cannot be applied in practice due to their sensitivity to the high-frequency noises. The frequency-locked-loop (FLL) serves as an optional method for frequency derivative estimation

without introducing any high-frequency noises. This section serves as the main section of this chapter which includes the main contribution.

3.4.1 Limitation of the PLL

To investigate the FLL, the phase-locked-loop (PLL) should be reviewed first. PLLs enable the grid-connected power converters to keep in synchronization with the power grids. Fig. 3-6 demonstrate the block diagram of a single-phase PLL [64], where the K_{PLL_p} and K_{PLL_i} are proportional and integral gain, respectively.

Fig. 3-6. Block diagram of a single-phase PLL [63].

If an integrator (I) is taking the place of the proportional-integral (PI) controller, i.e., $K_{PLL_p} = 0$, the input of the integrator will be proportional to the derivative of the change of grid frequency $\Delta\omega_g$. However, this might introduce instability problems to the system.

Assuming that the input voltage of the PLL is given by:

$$v_{ga}(t) = V_{ga} \cos \theta_o = V_{ga} \cos(\omega_o t), \quad (3.2)$$

where V_{ga} and θ_o represent the amplitude and phase-angle of the grid voltage v_{ga} , respectively. Multiplying with $-\sin\theta_g$, one can be obtained:

$$-v_{ga}(t) \sin \theta_g = -V_{ga} \cos \theta_o \sin \theta_g = 0.5V_{ga} [\underbrace{\sin(\theta_o - \theta_g) - \sin(\theta_o + \theta_g)}_{\text{high-frequency term}}], \quad (3.3)$$

which includes high-frequency terms $\sin(\theta_o + \theta_g)$.

The estimated phase-angle from the PLL θ_g equals to the phase-angle of grid voltage θ_o under steady state. Hence, the trigonometric function $\sin(\theta_o - \theta_g)$ can be approximated to $\theta_o - \theta_g$. Moreover, neglecting the high-frequency term $\sin(\theta_o + \theta_g)$, the input of the PI controller can be expressed as:

$$-v_{ga}(t) \sin \theta_g = 0.5V_{ga} (\theta_o - \theta_g). \quad (3.4)$$

Hence, the block diagram of the single-phase PLL can be linearized as Fig. 3-7.

Fig. 3-7. The linearized single-phase PLL.

The closed-loop transfer function from $\Delta\theta_o$ to $\Delta\theta_g$ can be derived from Fig. 3-7 as:

$$G_{\text{PLL-cl}} = \frac{\Delta\theta_g}{\Delta\theta_o} = \frac{0.5V_{ga} K_{\text{PLL-p}} s + 0.5K_{\text{PLL-i}}}{s^2 + 0.5V_{ga} K_{\text{PLL-p}} s + 0.5K_{\text{PLL-i}}}. \quad (3.5)$$

When an integral controller replaces the PI controller, i.e., substituting $K_{\text{PLL-p}} = 0$ into (3.5), it yields:

$$G_{\text{PLL-cl}} = \frac{\Delta\theta_g}{\Delta\theta_o} = \frac{0.5K_{\text{PLL-i}}}{s^2 + 0.5K_{\text{PLL-i}}}. \quad (3.6)$$

The zero-pole map of the closed-loop PLL system is shown in Fig. 3-8. It can be noted from (3.6) and Fig. 3-8 that the closed-loop poles are located on the imaginary axis when $K_{\text{PLL-p}} = 0$, resulting in a critically stable system, which might be unstable in practice [65]. Hence, the PLL cannot be applied for frequency derivative signal obtaining. It should be emphasized that this instability issue occurs in both single-phase and three-phase PLLs.

 Fig. 3-8. Zero-pole map of the closed-loop PLL system with different K_{PLL_p} .

3.4.2 Single-Phase FLL

Alternatively, the grid frequency can be locked instead of the phase angle to effectively address the instability issues faced by the PLLs. The system order will be reduced to one by changing the single-phase PLLs to the single-phase FLLs. The block diagram of a single-phase FLL is illustrated in Fig. 3-9 [66].

Fig. 3-9. Block diagram of a single-phase FLL [63].

It can be observed from Fig. 3-9(a) that there is a second-order-generalized-integrator (SOGI) in the FLL system, and the specific illustration of the SOGI can be observed in Fig. 3-9(b).

The transfer function from the input of the SOGI f to its outputs d and q can be expressed as:

$$\frac{d}{f} = \frac{\omega s}{\omega^2 + s^2}, \quad (3.7)$$

$$\frac{q}{f} = \frac{\omega^2}{\omega^2 + s^2}. \quad (3.8)$$

Based on (3.7) and (3.8), the transfer function from v_{ga} to v_{FLL} and qv_{FLL} in Fig. 3-9 can be derived:

$$\frac{v_{FLL}(s)}{v_{ga}(s)} = \frac{K_{FLL-p} \omega_g s}{s^2 + K_{FLL-p} \omega_g s + \omega_g^2}, \quad (3.9)$$

$$\frac{qv_{FLL}(s)}{v_{ga}(s)} = \frac{K_{FLL-p} \omega_g^2}{s^2 + K_{FLL-p} \omega_g s + \omega_g^2}. \quad (3.10)$$

Transfer functions (3.9) and (3.10) indicate that the v_{FLL} and qv_{FLL} are band-pass-filtered and low-pass-filtered of v_{ga} , respectively. The bandwidth of the band-pass filter is exclusively set by K_{FLL-p} and is independent of the center frequency ω_g . Moreover, qv_{FLL} lags v_{FLL} by 90° .

In steady state, $\omega_o = \omega_g$ and $v_{FLL} = v_{ga}$ is supposed to be satisfied. Based on the input voltage v_{ga} expressed in (3.2), v_{FLL} and qv_{FLL} take the following forms:

$$v_{FLL}(t) = V_{ga} \cos \varphi, \quad (3.11)$$

$$qv_{\text{FLL}}(t) = V_{ga} \sin \varphi, \quad (3.12)$$

where φ represents the phase-angle of the FLL. Moreover, the input signal to the integrator can be deduced as:

$$\begin{aligned} & -qv_{\text{FLL}}(t)[v_{ga}(t) - v_{\text{FLL}}(t)] \\ &= -V_{ga} \sin \varphi (V_{ga} \cos \theta_o - V_{ga} \cos \varphi) \\ &= 0.5V_{ga}^2 [\sin(\theta_o - \varphi) - \sin(\theta_o + \varphi) + \sin(2\varphi)] \\ &\approx 0.5V_{ga}^2 (\theta_o - \varphi). \end{aligned} \quad (3.13)$$

It is explicit that (3.13) shares the same form with (3.4), which indicate that the FLL has the same fundamental principle as the PLL. However, the FLL tracks the grid frequency rather than the phase-angle, which would be more stable, hence, the transfer function from $\Delta\omega_o$ to $\Delta\omega_g$ should be derived.

Assuming that $\omega_g \approx \omega_o$ and $\omega_g \neq \omega_o$ during system dynamics, and then the magnitude gains and phase shift of (3.9) at ω_o can be represented as:

$$|D(j\omega_o)| = \left| \frac{v_{\text{FLL}}(j\omega_o)}{v_{ga}(j\omega_o)} \right| = \frac{K_{\text{FLL}_p} \omega_g \omega_o}{\sqrt{(K_{\text{FLL}_p} \omega_g \omega_o)^2 + (\omega_g^2 - \omega_o^2)^2}} \approx 1, \quad (3.14)$$

$$\angle D(j\omega_o) = \angle \frac{v_{\text{FLL}}(j\omega_o)}{v_{ga}(j\omega_o)} = \arctan \frac{\omega_g^2 - \omega_o^2}{K_{\text{FLL}_p} \omega_g \omega_o} \approx \arctan \frac{2(\omega_g - \omega_o)}{K_{\text{FLL}_p} \omega_g}. \quad (3.15)$$

Accordingly, (3.11) and (3.12) should be written as:

$$v_{\text{FLL}}(t) = V_{ga} \cos[\omega_o t + \angle D(j\omega_o)], \quad (3.16)$$

$$qv_{\text{FLL}}(t) = V_{ga} \frac{\omega_g}{\omega_o} \sin[\omega_o t + \angle D(j\omega_o)]. \quad (3.17)$$

Furthermore, the input of the integrator can be modified from (3.13) to the following form:

$$-qv_{\text{FLL}}(t)[v_{ga}(t) - v_{\text{FLL}}(t)] \approx \frac{V_{ga}^2}{\omega_o K_{\text{FLL}_p}} (\omega_o - \omega_g). \quad (3.18)$$

Considering the effect of the integrator as shown in Fig. 3-9(a), the closed-loop transfer function from $\Delta\omega_o$ to $\Delta\omega_g$ should be derived as:

$$G_{\text{FLL}_{cl}}(s) = \frac{\Delta\omega_g(s)}{\Delta\omega_o(s)} \approx \frac{V_{ga}^2 K_{\text{FLL}_i}}{\omega_o K_{\text{FLL}_p} s + V_{ga}^2 K_{\text{FLL}_i}}. \quad (3.19)$$

It is evident from (3.19) that the closed-loop FLL system is a first-order system with only one pole, which is always located at the left-half-plane (LHP), indicating the FLL system is invariably stable. Hence, for the FLL, the frequency derivative signal can be easily obtained from the input of the integrator as shown by the red lines in Fig. 3-9(a).

After being normalized, $d\Delta f_g / dt$ will be sent to the proposed frequency controller, as visualized in Fig. 3-5.

Although the testing system is a three-phase system, it is worth mentioning that the proposed virtual inertia control scheme can be applied to both single-phase and three-phase systems.

However, $d\Delta f_g / dt$ contains the double-line frequency ripple terms when applying the single-phase PLL and FLL. The double-line frequency terms were ignored in the previous analysis, as indicated by (3.3) and (3.13). These ripple terms should be eliminated, otherwise, they will have a negative influence on the estimation accuracy and inertia enhancement.

3.4.3 Three-Phase FLL

As discussed in section 3.4.2, the second order harmonics in $d\Delta f_g / dt$ from the single-phase FLL should be eliminated. Fortunately, the three-phase FLL serves as a possible solution for ripple elimination.

The block diagram of a three-phase FLL is presented in Fig. 3-10, which is implemented in the $\alpha\beta$ -frame.

Fig. 3-10. Block diagram of a three-phase FLL [63].

The block $abc/\alpha\beta$ transforms the signals from the abc -frame to the $\alpha\beta$ -frame, which can be mathematical described by the following matrix:

$$T_{abc-\alpha\beta} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}. \quad (3.20)$$

The input signals v_{gx} ($x = a, b, c$) can be represented as:

$$v_{gabc}(t) = \begin{bmatrix} v_{ga}(t) \\ v_{gb}(t) \\ v_{gc}(t) \end{bmatrix} = V_{ga} \begin{bmatrix} \cos \theta_o \\ \cos(\theta_o - \frac{2}{3}\pi) \\ \cos(\theta_o + \frac{2}{3}\pi) \end{bmatrix} = V_{ga} \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t - \frac{2}{3}\pi) \\ \cos(\omega_o t + \frac{2}{3}\pi) \end{bmatrix}. \quad (3.21)$$

When expressed in $\alpha\beta$ reference frame, (3.21) becomes:

$$v_{g\alpha\beta}(t) = T_{abc-\alpha\beta} v_{gabc}(t) = V_{ga} \begin{bmatrix} \cos \theta_o \\ \sin \theta_o \end{bmatrix} = V_{ga} \begin{bmatrix} \cos \omega_o t \\ \sin \omega_o t \end{bmatrix}. \quad (3.22)$$

From Fig. 3-10, it can be observed that there are two SOGIs in the three-phase FLL system. The two SOGIs are used to tracking v_{ga} and $v_{g\beta}$ including their quadratic signals, respectively. According to (3.16) and (3.17), the estimated signal can be expressed as:

$$v_{\text{FLL}\alpha}(t) = V_{ga} \cos \varphi, \quad (3.23)$$

$$qv_{\text{FLL}\alpha}(t) = V_{ga} \frac{\omega_g}{\omega_o} \sin \varphi, \quad (3.24)$$

$$v_{\text{FLL}\beta}(t) = V_{ga} \sin \varphi, \quad (3.25)$$

$$qv_{\text{FLL}\beta}(t) = V_{ga} \frac{\omega_g}{\omega_o} \cos \varphi. \quad (3.26)$$

Hence, the input signal of the integrator of the three-phase FLL system can be further derived as:

$$\begin{aligned}
 & -0.5qv_{\text{FLL}\alpha}(t)[v_{g\alpha}(t) - v_{\text{FLL}\alpha}(t)] \\
 & -0.5qv_{\text{FLL}\beta}(t)[v_{g\beta}(t) - v_{\text{FLL}\beta}(t)] \\
 & = 0.5V_{ga}^2 \frac{\omega_g}{\omega_o} \sin(\theta_o - \varphi) \approx 0.5V_{ga}^2 \frac{\omega_g}{\omega_o} (\theta_o - \varphi).
 \end{aligned} \tag{3.27}$$

As compared with (3.3) and (3.13) which include high-frequency terms, (3.27) excludes the double-line frequency ripple terms without any ignorance.

(a) Overall view

(b) Zoom-in view

Fig. 3-11. Step changes of the frequency derivative df_g/dt estimated by the PLL, single-phase FLL, and three-phase FLL [63].

To visualize the high-frequency ripple terms, Fig. 3-11 illustrate the frequency derivative signals estimated by the PLL, single-phase FLL and three-phase FLL, respectively. The

frequency derivative df_g / dt changes at 0.5 s from 0 Hz / s to 1 Hz / s and restore at 1.5 s. It can be clearly observed that the PLL and single-phase FLL offers improper results due to the associated instability issues and double-line frequency terms, and only the three-phase FLL provide an accurate estimation of the frequency derivative df_g / dt . Hence, the three-phase FLL is applied to get the frequency derivative signal and is included in the proposed frequency controller in the GCC.

It should be mentioned that implementing the three-phase FLL in the $\alpha\beta$ -frame allows the simplification of the structure. One more SOGI is necessary, and this will make the structure of the FLL more complicated if implementing the three-phase FLL in the abc -frame [67]. After being normalized, $d\Delta f_g / dt$ in Fig. 3-10 will be linked with the active power reference by the frequency controller as shown in Fig. 3-5. Hence, the inertia enhancement can be achieved.

3.4.4 Modified Single-Phase FLL

As presented above, the grid frequency locked by the single-phase FLL will contain double-line frequency ripple terms, and the three-phase FLL serves as one solution for the ripple issue. However, $abc/\alpha\beta$ transformation is required for the three-phase FLL, and it is only applicable in the three-phase systems.

To implement the proposed control scheme in the single-phase systems, the modified single-phase FLL as shown in Fig. 3-12 is recommended to remove the $abc/\alpha\beta$ transformation and eliminate the high-frequency ripple components.

As it can be observed from Fig. 3-12 that the structure of the modified single-phase FLL is quite similar with that of the three-phase FLL, and the only difference lies into the input signals. For the three-phase FLL, the β -axis voltage reference is obtained from three-phase grid voltages through the $abc/\alpha\beta$ transformation. In contrast, the β -axis voltage reference of the modified single-phase FLL is derived from the single-phase grid voltage v_{ga} through a 90-degree time-delay unit. It is worth mentioning that applying a

90-degree time-delay unit in the modified single-phase FLL is only for the rotation of the input voltage reference.

Fig. 3-12. The block diagram of a modified single-phase FLL.

In general, the modified single-phase FLL follows the same operating principle as the three-phase FLL, and thus, it is free of frequency ripple components.

To illustrate the feasibility of the modified single-phase FLL, the simulation waveforms of a single-phase system with the single-phase FLL and with the modified single-phase FLL have shown in Figs. 3-13 and 3-14, respectively. It can be observed that the ripple components can be attenuated through the modified single-phase FLL.

(a) Overall view

(b) Zoom-in view

Fig. 3-13. Simulation waveform of a single-phase system with a single-phase FLL.

(a) Overall view

(b) Zoom-in view

Fig. 3-14. Simulation waveform of a single-phase system with a modified single-phase FLL.

3.4.5 Parameters Tuning

As observed from Figs. 3-9, 3-10 and 3-12, there are two parameters in the FLL system, i.e. the proportional gain K_{FLL_p} and integral gain K_{FLL_i} . In the first step, the proportional gain K_{FLL_p} should be designed. According to (3.2), the input voltage can be expressed in the s domain as:

$$v_{ga}(s) = V_{ga} \frac{s}{s^2 + \omega_o^2}. \quad (3.28)$$

Assuming that FLL have locked the grid frequency, v_{FLL} and qv_{FLL} can be expressed in the s domain based on (3.9) and (3.10):

$$v_{\text{FLL}}(s) = V_{ga} \frac{s}{s^2 + \omega_o^2} \cdot \frac{K_{\text{FLL}_p} \omega_o s}{s^2 + K_{\text{FLL}_p} \omega_o s + \omega_o^2} = \frac{V_{ga} s}{s^2 + \omega_o^2} - \frac{V_{ga} s}{s^2 + K_{\text{FLL}_p} \omega_o s + \omega_o^2}, \quad (3.29)$$

$$qv_{\text{FLL}}(s) = V_{ga} \frac{s}{s^2 + \omega_o^2} \cdot \frac{K_{\text{FLL}_p} \omega_o^2}{s^2 + K_{\text{FLL}_p} \omega_o s + \omega_o^2} = \frac{V_{ga} \omega_o}{s^2 + \omega_o^2} - \frac{V_{ga} \omega_o}{s^2 + K_{\text{FLL}_p} \omega_o s + \omega_o^2}. \quad (3.30)$$

By using the inverse Laplace transformation, v_{FLL} and qv_{FLL} in the time domain can be derived as:

$$v_{\text{FLL}}(t) = V_{ga} \cos(\omega_o t) - V_{ga} e^{-K_{\text{FLL}_p} \omega_o t / 2} [\cos(\lambda \omega_o t) - \frac{K_{\text{FLL}_p}}{2\lambda} \sin(\lambda \omega_o t)], \quad (3.31)$$

$$qv_{\text{FLL}}(t) = V_{ga} \sin(\omega_o t) - \frac{V_{ga}}{\lambda} e^{-K_{\text{FLL}_p} \omega_o t / 2} \sin(\lambda \omega_o t), \quad (3.32)$$

where $\lambda = \sqrt{1 - K_{\text{FLL}_p}^2} / 4$. It is clear from (3.31) and (3.32) that v_{FLL} and qv_{FLL} contain both steady-state and transient components. For evaluating the dynamics of the SOGI, the settling time has been defined as [67]:

$$t_{s_SOGI} = \frac{10}{K_{FLL_p} \omega_o}. \quad (3.33)$$

Fig. 3-15 plots the relationship with the settling time t_{s_SOGI} versus the proportional gain K_{FLL_p} . As it can be observed, the higher the value of the proportional gain K_{FLL_p} , the faster the response of the SOGI.

However, the value of K_{FLL_p} would affect the harmonics attenuation capability of the SOGI. Fig. 3-16 shows the bode diagram of $v_{FLL}(s)/v_{ga}(s)$.

It is evident from Fig. 3-16 that a very high value for K_{FLL_p} will reduce the immunity of the SOGI in front of the harmonics. Hence, the selection of the proportional gain K_{FLL_p} is a trade-off between the dynamic response and harmonics attenuation capability of the SOGI. In this report, K_{FLL_p} is chosen as 1.414 to maintain the settling time around one-line period.

Fig. 3-15. Settling time t_{s_SOGI} versus the proportional gain K_{FLL_p} .

 Fig. 3-16. Bode diagram of $v_{FLL}(s) / v_{ga}(s)$.

After selecting the proportional gain, the next step is to design the integral gain K_{FLL_i} . To achieve this objective, it is necessary to reorganize the closed-loop transfer function of the FLL expressed in (3.19) as:

$$G_{FLL_cl}(s) = \frac{\Delta\omega_g(s)}{\Delta\omega_o(s)} \approx \frac{V_{ga}^2 K_{FLL_i} / (\omega_o K_{FLL_p})}{s + V_{ga}^2 K_{FLL_i} / (\omega_o K_{FLL_p})}. \quad (3.34)$$

Taking the inverse Laplace transformation, the above equation becomes:

$$G_{FLL_cl}(t) = \frac{V_{ga}^2 K_{FLL_i}}{\omega_o K_{FLL_p}} e^{-\frac{V_{ga}^2 K_{FLL_i}}{\omega_o K_{FLL_p}} t}. \quad (3.35)$$

Similar to (3.33), the settling time of the FLL can be approximated to:

$$t_{s_FLL} = \frac{5\omega_o K_{FLL_p}}{V_{ga}^2 K_{FLL_i}}. \quad (3.36)$$

Fig. 3-17 visualizes the relationship between the settling time of the FLL t_{s_FLL} and integral gain K_{FLL_i} . It is clear that the increase of K_{FLL_i} leads to a decrease of t_{s_FLL} . As has been pointed out in [66], $t_{s_FLL} \geq 2t_{s_SOGI}$ should be guaranteed to decouple the responses of the SOGI and the integrator.

Fig. 3-18 shows the time response of the FLL system with $K_{FLL_p} = 1.414$ and different K_{FLL_i} , where the green dashed lines show the ideal waveforms and the red lines show the waveforms estimated by the FLL. The frequency of the input signal changes from 50 Hz to 60 Hz at 0.5 s, and restore at 1.0 s. It can be observed that higher K_{FLL_i} allows a faster response, but the fluctuation would occur.

It is worth mentioning that the SOGI and the FLL have been studied by considering separated variations in both the amplitude and the frequency of the input signal [66]. In this project, K_{FLL_i} is eventually designed to be 1.414. In this case, $t_{s_FLL} \approx 3t_{s_SOGI}$ can be satisfied, which ensures successful dynamic performances of the FLL. $K_{FLL_p} = 1.414$ and $K_{FLL_i} = 1.414$ offer a good tradeoff between the bandwidth and the dynamics.

Fig. 3-17. Settling time t_{s_FLL} versus the integral gain K_{FLL_i} .

(a) $K_{FLL_i} = 0.5$

(b) $K_{FLL_i} = 1.414$

(c) $K_{FLL_i} = 2.5$

Fig. 3-18. Frequency response in the presence of a frequency step change (from 50Hz to 60Hz).

3.5 Simulation and Experimental Results

3.5.1 Introduction to the testing system

To verify the validity of the proposed method, simulations and experiments have been conducted based on the testing system shown in Fig. 3-19, where the system and control parameters are listed in Tables II and III, respectively.

The LC -filtered power converter is regulated as a virtual synchronous generator (VSG). The VSG takes the responsibility for frequency regulation and voltage support, where the detailed parameter designing steps can be found in [54]. The VSG is controlled by a cascaded control structure, where the inner loop is a voltage/current controller for the AC output voltage support, while the outer loop is a frequency/power controller for frequency regulation. The VSG is employed to emulate the operation of conventional synchronous generators, hence the feasibility of inertia emulation by the GCC can be validated.

Fig. 3-19. Schematic diagram of the testing system.

The proposed method will be verifying through the simulations under Matlab/Simulink (R2016b) environment. After the simulation, the experimental testing should be carried out. Fig. 3-20 shows a photo of the experimental test platform. It can be observed the

VSG and GCC were supplied by two DC power supplies and controlled by a dSPACE (Microlabbox) control platform.

Table IV. BESS system parameter values.

Description	VSG parameter		Description	GCC parameter	
	Symbol	Value		Symbol	Value
DC-link voltage reference	V_{gdc_ref}	360 V	DC-link voltage reference	V_{cdc_ref}	360 V
Filter inductance	L_{gf}	1 mH	Filter inductance	L_{cf}	7 mH
Filter capacitance	C_{gf}	50 μ F	Rated reactive power	Q_{c_ref}	0 kW
Rated active power	P_{g_ref}	1 kW	Rated active power	P_{c_ref}	1 kW
Sampling / switching frequency	f_{gsw}	10 kHz	Sampling / switching frequency	f_{csw}	10 kHz

Fig. 3-20. A photo of the experimental test-bed [63].

3.5.2 Simulation and Experimental Results

To verify the feasibility of the VSG, the waveforms of grid voltages v_{gabc} , load currents i_{labc} , and DC-link voltages v_{gdc} and v_{cdc} under steady state are illustrated in Figs. 3-21 and 3-22. As observed, the waveforms of grid voltages are clean sinusoidal, indicating the effectiveness of the VSG control. As the loads are purely resistive, the current waveforms can follow the voltage waveforms. Moreover, it is worth mentioning that the grid

frequency is maintained as its nominal value, i.e., 50 Hz.

Fig. 3-21. Simulation waveforms of AC voltages v_{gabc} , load currents i_{labc} , and DC-link voltages v_{gdc} and v_{cdc} [63].

Fig. 3-22. Experimental waveforms of AC voltages v_{gabc} , load currents i_{labc} , and DC-link voltages v_{gdc} and v_{cdc} [63].

The simulation and experimental waveforms of the grid frequency responses to a 5% step-up load change are presented in Figs. 3-23 and 3-24. It can be observed that the minimum value of the frequency, i.e. frequency nadir can be improved from 49.73 Hz into 49.77 HZ with activating the proposed method. Also, the proposed method can also arrest the fast frequency decline. As a result, a 15% improvement of the frequency nadir can be expected.

Note that a 5% load step change should be considered as a significant disturbance in power systems [5, 68]. Although the 5% step-up load change is not a real case, the effect of this event is quite similar to that of generation or load tripping in real power system,

which represents a severe frequency event [63]. It should be noted that the settling time of primary frequency responses is in the range of tens of seconds.

Fig. 3-23. Simulation waveforms of frequency responses under a 5% step-up load change [63].

Fig. 3-24. Experimental waveforms of frequency responses under a 5% step-up load change [63].

Under a 5% step-up load change, the simulation and experimental results of the BESS power change ΔP_{c_pu} and the frequency derivative df_g / dt are illustrated in Figs. 3-25 and 3-26. It should be highlighted that one of the expectations of inertia enhancement effect is the prolonged frequency dynamics. In other words, the RoCoF is also an essential indicator for power system frequency regulation. As observed from Figs. 3-25 and 3-26, the RoCoF is improved from -0.25 Hz / s to -0.125 Hz / s with the proposed inertia emulation method.

The frequency nadir and the RoCoF can further be enhanced with a more significant H_c . The design of the virtual inertia coefficient H_c should depend on the inertia requirement and existing inertia of the power system.

Fig. 3-25. Simulation waveforms of the GCC power change ΔP_{c_pu} and frequency derivative df_g / dt under a 5% step-up load change [63].

Fig. 3-26. Experimental waveforms of the GCC power change ΔP_{c_pu} and frequency derivative df_g / dt under a 5% step-up load change [63].

Moreover, it is clear from Figs. 3-25 and 3-26 that the GCC can absorb or inject power in proportion to df_g / dt during frequency deviation. After the frequency dynamics, the output power of the GCC will restore to its normal value. It can be concluded that the proposed method will not influence the nominal operation of the grid-connected power converter, i.e., to regulate the grid-connected power converter as a current source. It should be noticed that the GCC should provide sufficient energy for generating desired amount of inertia; otherwise the expected inertia enhancement and frequency regulation improvement cannot be achieved.

In addition to load changes, the intermittency of renewable power generation should also consider as a factor of frequency deviation. The proposed method can also deal with the

issues brought by the RESs. To illustrate this effect, Figs. 3-27 and 3-28 demonstrate the simulation and experimental results of the frequency responses with a randomly generated output power of RESs. It is clear that the frequency deviation can be effectively reduced and the improvement RoCoF can be expected. These effects of increasing the power system inertia agree well with the theoretical analysis [5, 21].

Fig. 3-27. Simulation waveforms of frequency responses under a various RES output [63].

Fig. 3-28. Experimental waveforms of frequency responses under a various RES output [63].

3.6 Summary

In this chapter, the background and objectives have been given firstly. Next, the principle of virtual inertia has been presented in detail. Then, the frequency derivative estimation through the FLL was introduced, and the simulation and experimental results were given. In this chapter, a novel inertia emulation method implemented in the battery storage system has been proposed. The proposed method is also applicable to other types of grid-

tied energy storage systems without introducing any extra hardware. Three main conclusions can be made:

- (1) This method is achieved by proportionally linking the time derivative of grid frequency to the active power reference of the battery energy storage system, thus the energy can be interchanged by the battery energy storage system when there is a load disturbance.
- (2) The core of this method is the frequency derivative estimation. However, the calculation of the frequency derivative may introduce high-frequency noises. To tackle this problem, the FLL has been employed for accurate estimation of the frequency derivative signal, which serves as the main contribution of this chapter.
- (3) The single-phase, three-phase and modified single-phase FLL have been presented in detail, and the limitation of the PLL has been reviewed. The detailed mathematical model and system analysis have shown its feasibility. The objectives of inertia enhancement and frequency regulation improvement have been successfully met through grid-connected power converters as verified by the simulation and experimental results.

Chapter 4 Enhancement of Power System Inertia through Supercapacitor Energy Storage

4.1 Introduction

Fossil fuels are increasingly replaced by renewable energy sources (RESs) in modern power systems with a view of reducing greenhouse gas emissions and carbon footprints. As discussed in the previous chapter, RESs are typically coupled to the electrical grids via grid-connected power converters, hence power converters become indispensable in modern power systems. However, the extensive application of power converters in place of large synchronous generators reduces the power system inertia significantly, because power converters possess no kinetic energy which varies as the grid frequency changes as mentioned before. As a result, significant challenges will be faced by modern power systems in terms of frequency control.

As discussed in the previous chapters, energy storage systems (ESSs) can be considered as a reliable candidate for inertia emulation by exchanging energy with the grid when the grid frequency deviates from its nominal value. The battery storage systems for inertia emulation and frequency regulation improvement have been presented and verified in the previous chapter. While the battery storage systems can effectively achieve the goal of inertia enhancement, there are several limitations related to the ESSs equipped with batteries. The very first concern involves the chemical kinetic, which prevents the cells from operating at a very high-power level for a long time. Also, the environmental problems due to the toxic gas emission during charge/discharge period cannot be ignored as well [69].

Due to the high-power density, long life cycle and fast charging speed of supercapacitors, supercapacitor energy storage systems (SESSs) are promising candidates for inertia emulation [30].

In this chapter, the basic control scheme for inertia emulation through SESSs is discussed. It is implemented by proportionally linking the grid frequency and supercapacitor voltages through a frequency controller. It should be emphasized that it is different from the method discussed in Chapter 3, as utilizing SESSs for inertia emulation does not require the estimation of frequency derivative, which could simplify the control structure of the system. More importantly, this chapter discloses that the basic control scheme introduces inertia emulation errors under large frequency disturbances. As a solution, a nonlinear inertia control scheme, which ensures fair inertia emulation in all cases, is further discussed.

4.2 System Description

Fig. 4-1 details the schematic diagram of a grid-connected SESS, which consists of an L -filtered grid-connected converter (GCC) equipped with dc-link capacitor C_{dc} , a bidirectional dc/dc converter, and a supercapacitor C_{es} . The parameters of the testing system are listed in Table V.

Fig. 4-1. Schematic diagram of a SESS equipped with virtual inertia.

A cascaded controller controls the GCC. The outer-loop voltage controller aims to regulate the dc-link voltage v_{dc} following its reference v_{dc_ref} , while the inner-loop current

controller serves to regulate the ac output currents, where the outer-loop controller provides the d -axis current reference i_{d_ref} , and the q -axis current reference i_{q_ref} depends on the requirement of reactive power compensation [2]. The control parameters of the GCC can be found in [70].

Table V. SESS system parameter values.

Description	DC/DC Converter		Description	DC/AD Converter	
	Symbol	Value		Symbol	Value
Supercapacitor voltage	V_{es_ref}	300 V	DC-link voltage	V_{dc_ref}	400 V
Filter inductance	L_c	10 μ H	Filter inductance	L_g	10 mH
Supercapacitance	C_{es}	2.96 F	Rated active power	P_{g_ref}	1 MW
Rated active power	P_{c_ref}	1 MW	AC output voltage	V_{gabc}	110 $\sqrt{2}$ V
Sampling / switching	f_{csw}	10 kHz	Sampling / switching	f_{gsw}	10 kHz

Also, the bidirectional dc/dc converter aims to regulate the supercapacitor voltage and implement the inertia control schemes. The supercapacitor voltage v_{es} can be regulated to its reference v_{es_ref} by controlling the inductance current reference i_{l_ref} . Moreover, the virtual inertia controller serves to generate virtual inertia by providing the supercapacitor voltage reference v_{es_ref} . The details of inertia control schemes will be presented in the following sections.

The control structure of the SESS and the block diagram of the voltage/current controller of the dc/dc converter is illustrated in Fig. 4-2. K_{PWM} denotes the proportional gain of the PWM which is $K_{PWM} = 1$ in this case. The objective of the inner loop current controller is to control the inductor current i_l follow its reference value i_{l_ref} , while the outer loop voltage controller is used to manage the supercapacitor voltage v_{es} track its reference value v_{es_ref} provided by the virtual inertia controller. The detailed control parameter design procedure can be found in [71, 72].

Fig. 4-2. System structure of the SESS.

4.3 Principle of Inertia Emulation through SESS

Fig. 4-3 presents the frequency regulation framework with the virtual inertia for supercapacitors, where the mathematical models of the reheat turbine and speed governor have been discussed in chapter 2.

Fig. 4-3. Frequency regulation framework with virtual inertia.

In essence, the inertia emulation by SESSs is to utilize the energy stored in supercapacitors. Similar to H represented by equation (2.2), i.e. $H = E_{\text{gen}} / VA_{\text{rated}} = J\omega_{\text{ref}}^2$

/ $2VA_{\text{rated}}$, the inertia coefficient of a supercapacitor H_c can be defined as the ratio of the electrical energy stored in the supercapacitor to the system base power, represented as

$$H_c = \frac{E_{\text{cap}}}{VA_{\text{rated}}} = \frac{C_{\text{es}} v_{\text{es}}^2}{2VA_{\text{rated}}}, \quad (4.1)$$

where E_{cap} signifies the energy stored in the supercapacitor, C_{es} refers to the capacitance of the supercapacitor, and v_{es} denotes the voltage of the supercapacitor. It is clear that (2.2) and (4.1) share similar forms. That is, the inertia coefficients of synchronous generators and supercapacitors are proportional to the squares of grid frequency ω_o (f_o) and supercapacitor voltage v_{es} , respectively. Hence, the supercapacitor voltage can be linked to the grid frequency for inertia emulation.

The dashed-line can represent the mechanism for inertia emulation in Fig. 4-3, where $G_{\text{clv}}(s)$ denotes the closed-loop transfer function from $v_{\text{es_ref_pu}}$ to $v_{\text{es_pu}}$. With the frequency controller, the equivalent total inertia coefficient will change from H to $H + H_c G_{\text{clv}}(s) G_{f_pu}(s)$, where the second term $H_c G_{\text{clv}}(s) G_{f_pu}(s)$ represents the virtual inertia coefficient. As the dynamics of voltage control usually are much faster than those of frequency control, $G_{\text{clv}}(s)$ can be approximated to 1 [2].

4.4 Inertia Control Scheme

The implementations of inertia control schemes refer to the designs of the frequency controller $G_f(s)$. In this section, two control schemes, i.e. the basic control scheme and the nonlinear control scheme, will be separately discussed.

4.4.1 Basic Control Scheme

When the grid frequency change Δf_o and supercapacitor voltage change Δv_{es} are sufficiently small, it is possible to implement a proportional controller $K_{\omega v_pu}(s)$ for inertia emulation:

$$v_{es_pu} = K_{\omega v_pu} \cdot \Delta f_{o_pu} + 1, \quad (4.2)$$

where the proportional gain should be represented as

$$K_{\omega v_pu}(s) = \left(\frac{\Delta V_{es_max}}{V_{es}} \right) / \left(\frac{\Delta f_{o_max}}{f_{ref}} \right), \quad (4.3)$$

where ΔV_{es_max} is the maximum allowable capacitor voltage change, which is defined as $\Delta V_{es_max} = (V_{es_max} - V_{es_min}) / 2$, and Δf_{o_max} is the maximum allowable grid frequency change.

Substitution of (4.3) into the expression of the virtual inertia coefficient, it yields

$$H_p = \frac{\Delta V_{es_max} f_{ref}}{V_{es} \Delta f_{o_max}} \cdot \frac{C_{es} V_{es}^2}{2VA_{rated}}, \quad (4.4)$$

where V_{es} denotes the rated supercapacitor voltage. It should be highlighted that the supercapacitor voltage v_{es} is approximated to its rated value V_{es} for the inertia coefficient of supercapacitor, hence, the virtual inertia coefficient H_p will be a constant only if the voltage change is limited in a small range [21].

From (4.4), it can be concluded that the virtual inertia coefficient depends on the following factors: the capacitance of supercapacitor C_{es} , the rated supercapacitor voltage V_{es} , the maximum allowable variation of supercapacitor voltage $\Delta V_{es_max} / V_{es_max}$ and maximum permissible variation of grid frequency $\Delta f_{o_max} / f_{o_max}$. When the maximum frequency deviation is set as $\Delta f_{o_max} = 0.2$ Hz and maximum permissible voltage deviation is set as $\Delta V_{es_max} / V_{es_max} = 0.15$, the virtual inertia coefficient H_p versus rated supercapacitor voltage V_{es} and capacitance of supercapacitor C_{es} for this 1-MVA system is illustrated in Fig. 4-4. Hence, according to (4.3), $K_{\omega v_pu} = 37.5$.

Fig. 4-4. Virtual inertia coefficient H_p versus rated supercapacitor voltage V_{es} and capacitance of supercapacitor C_{es} .

Hence, when designing the frequency controller, the desired virtual inertia coefficient H_p should be decided first. Then, the system parameters including system base power VA_{rated} , grid frequency f_o and maximum frequency deviation Δf_{o_max} should be considered. Following that, the capacitor of supercapacitor C_{es} , rated supercapacitor voltage V_{es} and maximum voltage deviation ΔV_{es_max} should be designed according to Fig. 4-4 and [21]. The detailed design procedure is discussed in [21].

4.4.2 Nonlinear Control Scheme

There are limitations of designing the frequency controller as a proportional controller [23]. In particular, when there are significant frequency disturbances, grid frequency and voltage changes will also become excessively large. In this case, the virtual inertia coefficient will no longer be constant. This is because the supercapacitor inertia coefficient H_c will change during frequency dynamics.

To tackle this issue, the nonlinear control scheme would be a solution by letting the power response of the supercapacitor exactly follow the power response of synchronous generators.

According to (2.1), the inertial power absorbed by the rotors of synchronous generators can be expressed as

$$\Delta P_{k_pu} = 2H \cdot \frac{d\Delta\omega_{o_pu}}{dt} = 2H \cdot \frac{d\Delta f_{o_pu}}{dt}. \quad (4.5)$$

The inertial power absorbed by the supercapacitor can be derived by differentiating (4.1) on both sides as

$$\Delta P_{es_pu} = \frac{C_{es} v_{es}}{VA_{rated}} \cdot \frac{d\Delta v_{es}}{dt}. \quad (4.6)$$

To generate a desired virtual inertia coefficient H_p , one may replace H in (4.5) by H_p and then let (4.5) equal to (4.6), i.e.

$$2H_p \cdot \frac{d\Delta f_{o_pu}}{dt} = \frac{C_{es} v_{es}}{VA_{rated}} \cdot \frac{d\Delta v_{es}}{dt}. \quad (4.7)$$

Integrating (4.7) on both sides, one obtains

$$2H_p \cdot \frac{\Delta f_o}{f_{ref}} = \frac{C_{es} v_{es}^2}{2VA_{rated}} + K, \quad (4.8)$$

where K is a constant determined by the capacitance of supercapacitor C_{es} , rated supercapacitor voltage V_{es} , and system base power VA_{rated} through the following equation:

$$K = -\frac{C_{es} V_{es}^2}{2VA_{rated}}. \quad (4.9)$$

Substituting of (4.9) into (4.8) the full nonlinear control scheme can yield as:

$$2H_p \cdot \frac{\Delta f_o}{f_{\text{ref}}} = \frac{C_{\text{es}}}{2VA_{\text{rated}}} (v_{\text{es}}^2 - V_{\text{es}}^2). \quad (4.10)$$

The virtual inertia coefficient can be obtained from (4.10) as:

$$H_p = \frac{1}{2} \cdot \frac{C_{\text{es}} V_{\text{es}}^2}{2VA_{\text{rated}}} \cdot \frac{f_{\text{ref}}}{\Delta f_o} \left[\left(\frac{\Delta v_{\text{es}}}{V_{\text{es}}} \right)^2 + 2 \frac{\Delta v_{\text{es}}}{V_{\text{es}}} \right]. \quad (4.11)$$

It can be observed from (4.11) that if the voltage variation Δv_{es} is sufficiently small, the second order term $\Delta v_{\text{es}} / V_{\text{es}}$ can be ignored, then the (4.11) shares the same form with (4.4). The design procedure of the nonlinear control scheme can be found in [23].

Equation (4.10) can be written in another form which derives the desired expression of the ultracapacitor voltage as follows:

$$v_{\text{es_ref}} = \sqrt{\frac{4VA_{\text{rated}} H_p}{C_{\text{es}} f_{\text{ref}}} \cdot \Delta f_o + V_{\text{es}}^2}. \quad (4.12)$$

The relationship between supercapacitor voltage reference and grid frequency will be nonlinear according to (4.12). This nonlinear controller guarantees that the virtual inertia coefficient can always be maintained as a constant even under significant frequency disturbances.

4.5 Simulation and Experimental Results

To validate the effectiveness of the SESS and nonlinear control scheme, a simulation model was built under the PLECS environment based on the system frequency regulation framework in Fig. 4-2(a), and system parameters based on Table VI and control parameters in Table VI.

Table VI. Control parameters of SESS.

Description	SG parameter		Description	ESS parameter	
	Symbol	Value		Symbol	Value
Frequency-droop coefficient	R	0.05	Maximum voltage (basic controller)	V_{es_max}	345
Speed governor coefficient	T_G	0.1 s	Minimum voltage (basic controller)	V_{es_min}	255
Turbine HP coefficient	F_{HP}	0.3 s	Basic frequency controller	K_{ov} / K_{ov_pu}	225 / 37.5
Time constant of reheater	T_{RH}	7.0 s	Rated supercapacitor voltage	V_{es_ref}	300 V
Time constant of main inlet volumes	T_{CH}	0.2 s	Maximum frequency deviation	Δf_{o_max}	0.2 Hz
Load damping coefficient	D	1.0	Maximum voltage deviation	ΔV_{es_max}	45 V
Inertia constant	H	5.0 s	Virtual inertia	H_p	5.0 s
Power rating	VA_{rated}	1MVA	Frequency reference	f_{ref}	50 Hz

The virtual inertia coefficient H_p is designed as 5.0 s. which is identical to the inertia coefficient of synchronous generators, i.e. $H = 5$ s. Fig. 4-5 illustrates the frequency responses of two control schemes under a 10% step-up load change, and Fig. 4-6 sketches the relevant supercapacitor voltage waveforms. It should be mentioned that a 10% load change should be considered as a huge disturbance in power systems.

In the beginning, the frequency and voltage differences between the two cases are minimal. However, as the frequency drop continues, the frequency and voltage changes will significantly change the virtual inertia coefficient H_p . As a result, the proportional controller cannot generate the desired amount of virtual inertia, leading to a lower frequency nadir. In contrast, the nonlinear controller generates a fixed amount of inertia

under significant frequency disturbances. With the nonlinear controller, the frequency nadir can be improved from 49.52 Hz to 49.54 Hz. It can be observed that the nonlinear control features a larger supercapacitor voltage change. In this way, the supercapacitor releases more energy to improve frequency regulation.

Fig. 4-5. Frequency waveforms under a 10% step-up load change.

Fig. 4-6. Supercapacitor voltage waveforms under a 10% step-up load change.

The frequency responses under a 10% step-down load change are illustrated in Fig. 4-7 and its relevant voltage waveforms are demonstrated in Fig. 4-8. It can be observed that the frequency and voltage responses are similar to the previous case as shown by Figs. 4-5 and 4-6, that is, the differences between the two control schemes are minimal at the beginning, and the frequency and voltage changes differently as the grid frequency

continues rising. This is because with the basic control scheme, the virtual inertia coefficient H_p becomes more significant than its desired value as the supercapacitor voltage variation Δv_{es} exceed its maximum allowable amount.

Fig. 4-7. Frequency waveforms under a 10% step-down load change.

Fig. 4-8. Supercapacitor voltage waveforms under a 10% step-down load change.

Fig. 4-9 shows a photo of the experimental test-bed. In the experimental test-bed, the conventional synchronous generator is emulated by the virtual synchronous generator (VSG). As observed, the testing system is regulated by the dSPACE (Microlabbox) control platform. Fig. 4-10 demonstrates the experimental waveforms of the frequency response under a 5% step-up load change. With the virtual inertia control, the frequency nadir can be improved from 49.73 Hz to 49.77 Hz, and 50% improvement of the rate of

change of frequency (RoCoF) can be expected. The experimental results have verified the feasibility of the virtual inertia control scheme.

Fig. 4-9. A photo of the experimental test-bed.

Fig. 4-10. Experimental waveforms of frequency responses under a 5% step-up load change.

4.6 Summary

In this chapter, the motivation and the objective of this project have been presented first. Following that, the supercapacitor energy storage system has been sketched and modeled, and the principle and feasibility of inertia enhancement through SESS were then discussed in detail. Additionally, two different control schemes, the basic control scheme and the nonlinear control scheme, were disclosed separately. The voltage reference of

the supercapacitor is directly linked with the grid frequency by the frequency controller to generate virtual inertia. The frequency controller can be designed as a proportional controller or a nonlinear controller, which will lead to different results, mainly when a significant frequency disturbance occurs. Three main conclusions can be generalized from this chapter:

- (1) Supercapacitor energy storage systems (SESSs) can effectively be employed for inertia emulation and frequency regulation as demonstrated by the experimental results. The feasibility of the virtual inertia control schemes has been verified by the experimental results.
- (2) The problem that battery energy storage systems cannot operate at a high-power level for a long time can be solved. Also, the overmodulation issues which may appear in the case that the dc-link capacitors are employed for inertia emulation can be addressed as well.
- (3) The voltage reference of the supercapacitor can be linked with the grid frequency by different virtual inertia controllers for inertia enhancement. The basic control scheme can be applied when the frequency deviation is sufficiently small only. Otherwise, the virtual inertia coefficient will no longer be a constant. Fortunately, the nonlinear control scheme can tackle this issue. The virtual inertia coefficient can remain as a constant when the nonlinear controller is employed for the frequency controller, which is validated by the simulation results.

Chapter 5 Conclusions and Future Works

This chapter concludes the significant contribution of the thesis and provides some possible research directions with regards to power system stability improvement with high penetration of renewable generation.

5.1 Conclusions

This thesis focuses on the issue of power system inertia decreasing when power systems are transforming from conventional power systems to more sustainable, environmental-friendly and high-efficiency smart grids. This kind of paradigm shift will introduce some problems to power system stability. Specifically, the power system frequency stability is discussed in the thesis.

Through careful analysis and discussion, one way to addressing the frequency instability concern is to emulate the power system inertia through power converters. Several inertia emulation methods have been presented in this thesis to improve frequency regulation. Some conclusions can be derived as follows:

5.1.1 Frequency-Derivative based Virtual Inertia

As discussed in Chapter 3 that the power system inertia can be emulated and enhanced by the battery energy storage systems. It is achieved by proportionally linking the time derivative of grid frequency with the active power reference of the grid-connected power converter (GCC). Consequently, when there is a load change, the GCC can absorb energy from the grid or release it to the grid with necessary.

The key to this approach is the frequency derivative estimation as the differential operator will inevitably introduce high-frequency noises. The frequency derivative obtained from the frequency-locked-loop (FLL) can avoid high-frequency noises.

The single-phase and three-phase FLL have been discussed carefully in Chapter 3. The three-phase FLL can eliminate double-line frequency ripple terms while estimating the frequency derivative. Thus, the three-phase FLL is applied in this thesis.

The simulation and experimental results validate the feasibility of the proposed method. The proposed method is a promising method for inertia enhancement and frequency regulation improvement.

5.1.2 Inertia Emulation through Supercapacitor Energy Storage System

As battery storage system cannot operate in high-power level for a long time and the model of the battery will limit the effectiveness of the method, the supercapacitor would be a promising energy storage source for inertia emulation. Hence, inertia emulation through supercapacitor energy storage systems (SESSs) is discussed in this thesis.

Two different virtual inertia control schemes have been discussed in Chapter 4. The basic control scheme can only be employed when the supercapacitor voltage and grid frequency variations are sufficiently small, otherwise, the virtual inertia coefficient will no longer be a constant. However, the nonlinear control scheme can be applied even under a relatively large load disturbance where the supercapacitor voltage and grid frequency vary in a broad range.

The simulation and experimental results have shown the effectiveness of the inertia emulation through SESS and the differences between the two different control schemes.

5.2 Future Works

This thesis only focuses on the frequency stability issues faced by power systems with high penetration of renewables. However, with the growing penetration of renewable power generation in modern power systems, many issues other than inertia reduction

may be introduced due to the significant differences of power converters with conventional power systems.

Different control schemes have been proposed for power converters operation for various control objectives, such as power quality improvement, cost reduction, and efficiency improvement, etc. [73-78]. Controlling the power converters is still an ongoing research topic as power converters are expected to provide more ancillary services to modern power systems, such as active power support, reactive power support, and grid-fault ride-through [25, 32, 37, 79]. These functions may dramatically change the way that power systems operate and control. Hence, some future research directions may be recommended as follows.

Under weak grid conditions with large grid impedances, virtual inertia may introduce instability issues, which has been disclosed in [80]. This is caused by the inherent differential operator brought by the virtual inertia controller. There might be many instability issues with reactive power controller as well. With the reactive power control, the instabilities may be caused due to the coupling between d -axis and q -axis. The mechanism of the instability issues and the solutions to them could be the future research direction.

A concept of grid-friendly power converters is proposed for future power systems. Grid-friendly power converters are supposed to provide not only active power support and virtual inertia but also the reactive power control and voltage support. The modeling and control of grid-friendly power converter would also be a potential research direction for power grids with high penetration of renewable power generation.

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