・論文タイトル：Design and Control of Energy Storage System for a Linear Generator to Maximize Electric Output Power for Ocean Power Plant

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Design and Control of Energy Storage System for a Linear Generator to Maximize Electric Output Power for Ocean Power Plant

リニア波力発電機電気出力最大化に必要なエネルギー蓄積システム設計と制御

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Abstract

1. Characteristic of generator output power is important in analysis of capacity of inverter and storage system at starting of experiment of this ocean power plant system.

2. For real ocean power plants, all units are paralleled in the sea, with the same DC voltage, output power is summarized and transit into power grid. Because power is need to make generator start moving and make DC voltage of different units to be the same. Design of storage system is necessary.

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3.Since the battery has large energy density and long lasting time of charge and discharge, and on the contrary the super capacitor has large power-density and rapid transition between charge and discharge, the combination of SCESS and BESS can be seen as optimal HESS for this wave power generation system.

4.An approach for determining the HESS capacity is proposed to make it autonomously started separated from grid. And also match the characteristic and performance of the generator. For this unique structure of LMSG, new parameter test method is proposed.

5. Applying HESS in real-time control strategy for fluctuation, target power control strategy meeting the requirement of power grid is researched. After analyzing LPF algorithm and its application in power distribution, optimal LPF algorithm is proposed to meet fluctuation limitation and make cost of storage minimum.

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Chapter 1 Introduction

1.1 Background

The development of wave power, which is a clean and renewable energy[1], has shown an extremely rapid speed in integration of wave energy into the overall electricity supply. However, the wind is interment, which limits the application of wave power in the power grid and affects the stability and power quality of the grid. Due to the randomness and variability of wave speed, large-scale wave power grid voltage and frequency of the existing power grid, causing a great impact to the safe and stability of operation of the grid. Energy storage system, as an energy buffer device, can improve power quality, optimize the operation of OPT. However, features are different in a variety of energy storage systems. How to effectively use energy storage system to make effective regulation of OPT is currently researched.

1.2 Standard of connected power grid and characteristic of wave power generation

1.2.1 Restrictions for wave power fluctuations based on power grid connection standards

Wave power generation system generally operate in maximum power generation mode and wave power output is mainly determined by the real-time wave excitation. With the installed capacity of generation system increases, wave itself has such randomness, volatility, leading to random fluctuations of wave power generation. So it will caused a great impact of existing power grid power quality (including voltage and frequency) and power grid dispatching when wave power generation system is connected into the grid. In 2006 Germany's largest grid operator E. ON company [2] published power grid connection standard, in which for wind farms and other renewable energy power generation system there is a series of technical indicators requirements, including active power, frequency, and fault recovery, etc. Although there is less standard for wave power generation, the standard for wind farm can be a good reference. Denmark Eltra and Elkraft [3] suggested that active power control target wind farm: Average output power per minute does not exceed 5% of maximum output power by different frequency and voltage range.

1.2.2 Comparison of different type power generations

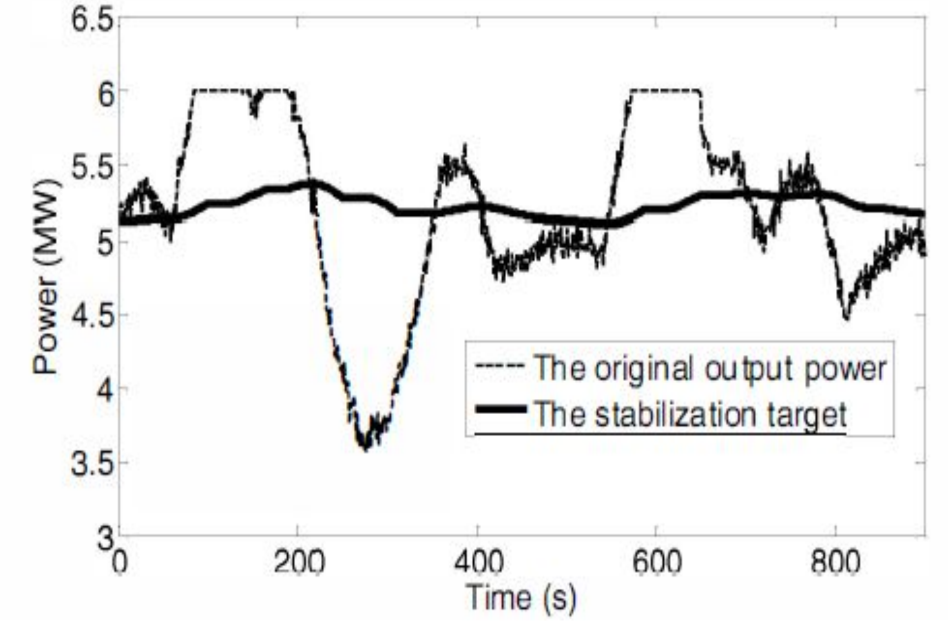


Fig.1.1 The power of wind power generation system

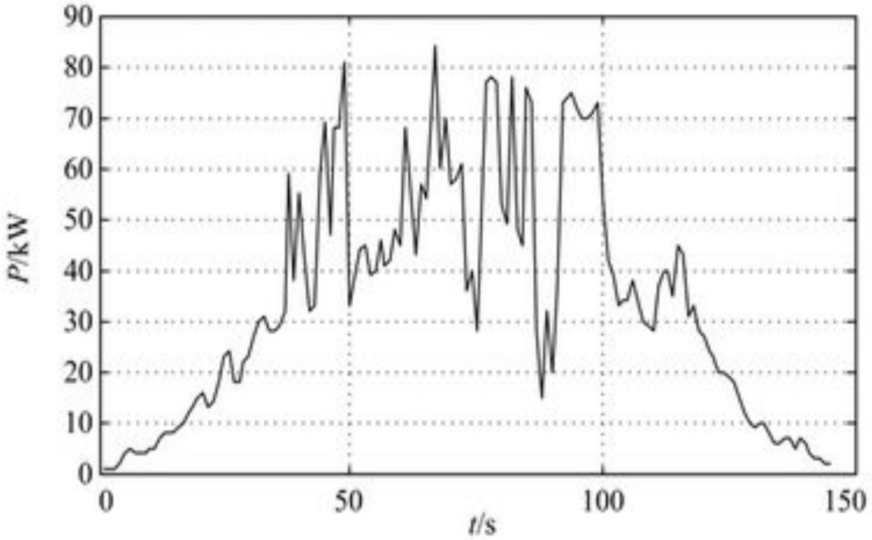


Fig.1.2 Output power waveform of PV(photovoltaic) power generation system

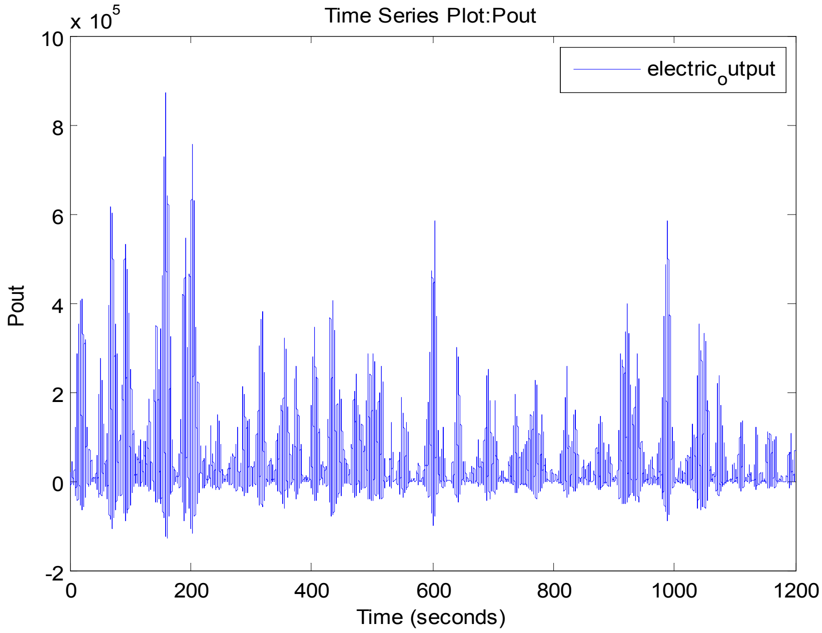


Fig.1.3 Output power waveform from ocean power generation system

From Fig 1.1 and Fig 1.2, it can be seen that, in wind power generation system and PV generation system, output power from generator is all positive, which means that generator just operates on generating power[4][5]. But in Fig 1.3, it can be observed that, in this generator control strategy, some time generator operates in generating mode, but some time, generator acts as a motor, which means that power needed to be transferred back to generator. In starting operation period, when output voltage is unstable which has not reached bus voltage, generation system can not be connected to the grid, which means that it is an isolated system. So it needs power to start into normal operation mode. After generation system connected to the power grid, big fluctuation of output power from generator will have bad effect to the grid system, so a buffer system is necessary for smoothing power.

1.3 Development of energy storage technology and its application in wave power generation

Due to the randomness of and unpredictability wave speed , the current wave power prediction error still can not achieve real-time scheduling requirements to run the power grid, so the grid adjustment in real-time has hidden danger in security and stability. Energy storage system, as an energy buffer, aim to dynamically absorb and release energy. Due to its large capacity connection, it can promote the optimization of the grid structure to solve the volatility and randomness problems. In addition, due to the nature of this linear synchronous motor Maximum output power system strategy, real-time power conversion between positive and negative, that is, the period of time beginning to run generators, energy storage systems needed as the initial power to the generator provide energy to conform to the maximum output power requirements.

1.3.1 Development of energy storage technology

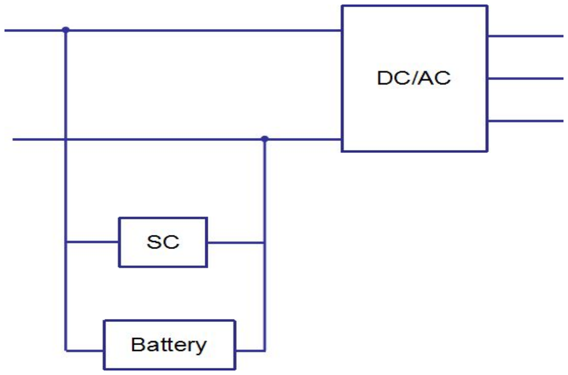
Currently energy storage technology is still in the diversified development stage, there is no single storage method play a full role can take care of both performance and cost. According that storage technology can change electrical energy into different storage form, it is divided into four categories: physical (mechanical) energy storage, chemical energy storage, magnetic storage and phase change storage. Physical (mechanical) energy storage includes pumped storage, compressed air energy storage and flywheel energy storage. Pump storage is relatively mature, so it is mostly used in electricity regulation. But by its large geographical constraints, it is not suitable for distributed energy adjustment. Chemical energy storage includes: Sodium-sulfur Battery, Lead-acid Battery, Lithium Lon Battery and so on[6]. Electromagnetic energy storage is the the recently emerging energy storage technology changing electric energy into electromagnetic energy, which includes: Super-capacitor and Superconductor Storage. Phase-change energy storage includes: electrical heat storage technology, molten salt heat storage and ice storage technology.

According to the charge-discharge performance characteristics of energy storage technology, it is divided into energy type and power type. Energy storage type has high energy storage density, long charge and discharge time, which is mostly used for high energy demand occasions, including compressed air energy storage, sodium sulfur batteries, lead-acid batteries and lithium ion batteries. Power-type storage has power density, fast response, which is mostly used for high power demand occasions, including super capacitor, flywheel energy storage and superconducting magnetic energy storage[7]. Due to different characteristics of energy storage system rated power, continuous charge and discharge capacity, efficiency and cycle life, its applications are also changed. In table it shows characteristic parameters of typical storage technology for distributed energy[7][8][9].

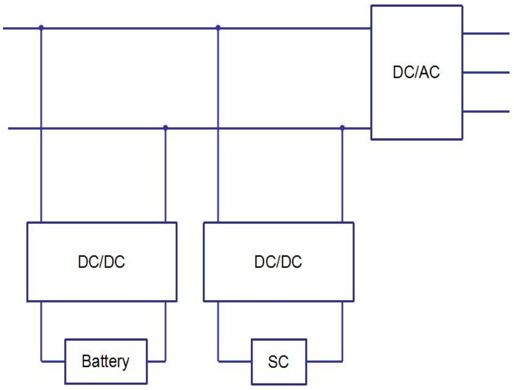
Table 1.1 Characteristic parameters of typical storage technology

Electrical Energy Storage Technology		Charge /Discharge Duration	Power Density (W/kg)	Energy Density (Wh/kg)	Cycle Efficiency (%)	Cycle Life (h)
Mechanical Energy Storage	Compressed air Storage	Minute-hour Level	_	_	_	>10000
	Flywheel Storage	Minute Level	400-1600	5-130	85-90	>100000
Electromagnetic Energy storage	Super Capacitor	Second-minute Level	3000	0.05-5	95	>50000
	Superconductor Storage	Millisecond-second Level	500-2000	0.5-5	90	>100000
Chemical Energy Storage	Sodium-sulfur Battery	Hour Level	90-200	150-240	75	2000-4500
	Lead-acid Battery	Minute-hour Level	75-300	30-50	70-90	100-5000
	Lithium Ion Battery	Minute-hour Level	150-315	75-250	80-95	5000

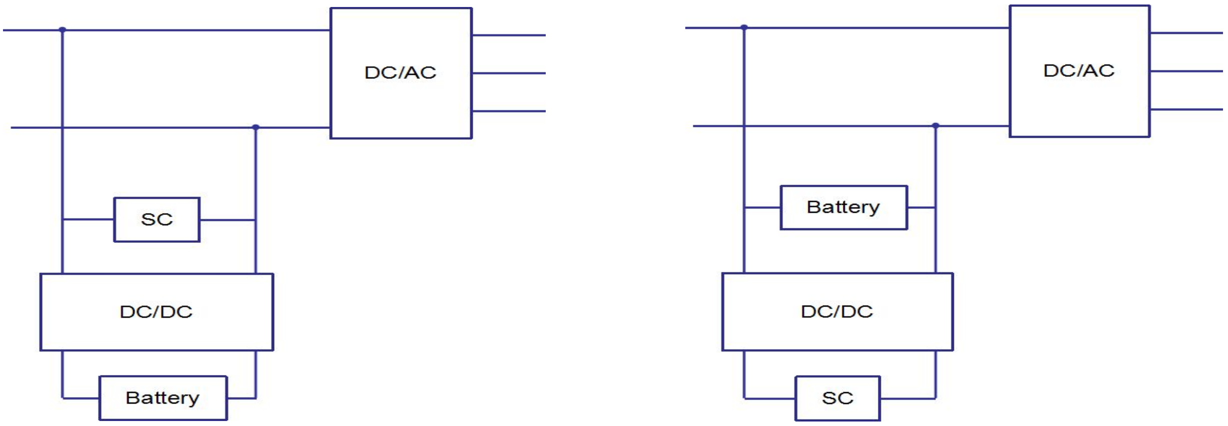
1.3.2 Different topology structure of HESS



(a)



(b)



(c) (d)

Fig 1.4 Different topology structures of HESS control system

Super capacitors and batteries can share the same DC / AC converter if they are in parallel on the DC side.[4]. Through the control of the DC bus voltage power regulation, they are connect to the grid, which is a relatively simple control. We need to increase the DC / AC converter power to meet the power needs of the super capacitor.

In Fig (a) Super capacitors and batteries are directly in parallel. This topological structure is simple,with low cost, high system efficiency and fast response. But the capacity of the energy storage system can not be fully utilized. Current is automatically distributed between the two energy storage devices, depending on their resistance size. Therefore power of each energy storage can not controlled. In addition, the super capacitor voltage and the battery voltage is the same. For this voltage is not controlled, it varies with the SOC of battery, which limits the optimal use of super capacitors and also limits the selection of super-capacitor cells. In order to achieve the same voltage, it requires more capacitance elements connected in series. It is adapted in occasion that change range of DC bus voltage is small or no strict requirements of battery charging and discharging.

In Fig (c), battery is connected to DC / DC and super capacitor is directly connected in parallel to the DC link. In this topology battery power is controllable , battery charge and discharge current can be optimized in controlled, which can extend its life cycle.Power of super capacitor directly changes with changing of DC bus voltage which has fast response. But the disadvantage is that the super capacitor requires a lot of cells in series to obtain a high bus voltage. In addition, in pulse load current range, the terminal voltage of the super capacitor will decrease. If connected inverter requires a stable or normal operation minimum voltage to generate correct AC side voltage, the voltage will drop too much that will cause problems. So DC voltage must be controlled within an appropriate range.

In Fig (d), Super capacitor is connected to DC / DC, and battery is directly connected to the DC bus in parallel. In this topology super capacitor energy storage can be fully utilized, so we can optimize the design of rated capacity. But the battery power is not controllable, and its charge and discharge current can not be optimized. DC bus voltage changes with changing of battery SOC change , which can not be directly controlled and must be maintained within a given range. So the operation of system is limited.

In Fig (b), super capacitor and battery are connected in parallel through the DC / DC power converter. The technological advantages of this topology is obvious that DC / DC converters has function like, so that through two different energy storage element with different terminal voltage can be connected. Each storage device can be directly controlled, meanwhile DC bus voltage can be maintained constant. Also battery charge/discharge current can be optimized so that its life can be extended. Battery and super capacitor can deeply charge/discharge so that they can be fully utilized and the design of system rated capacity can be optimized. The use of DC / DC can also enable configuration of energy management system to be more flexible. However, compared with direct parallel, using of DC / DC will make power loss generated, production system costs increased and efficiency reduced. Therefore, we must consider a compromise between technological advantage of this topology and increasing economic costs of the system.

1.3.3 Application of HESS in Ocean Power Plant

When energy storage system is used in wave power generation three problems should be considered: (1) The selection of energy storage system: single type storage or hybrid type storage. (2) In actual operation: charging and discharging strategy of energy storage system. (3) In planning of ocean power plant system: capacity configuration issues.

First problem is the selection of energy storage system. Usually storage system is selected according to requirement of wave power generation, characteristics of energy storage system and economic of system. In my research, hybrid storage system is selected to be the combination of battery and super-capacitor. And for their different characteristics, power fluctuation can be smoothed.

Second problem is the charge/discharge control strategy of storage system. For the constraint of output power from generation system when it connected to power grid, output power from generator cannot directly connected to the grid. So it is necessary that an optimal real-time control strategy of storage system will help to smooth power fluctuation into target range. Zhang kun [10]used fuzzy policy control strategy to control charge/discharge of storage system, smoothing power fluctuation under the situation that battery is not overcharged/over-discharged. But when target power is defined, low pass filter algorithm with constant coefficient is used that it will increase output power so that cost of operation will be increased. Mid-Eum[11] make the reduction of energy loss of storage system to be optimization target when considering the real-time control strategy hybrid energy storage system. So life of battery will be extended. But by this method, only inner workings of the energy storage system is considered, which is not applied to the actual power combined stabilization.

Third problem is the optimal definition of capacity figuration of storage system. Micheal used expert system based on prior knowledge to make comparison of micro-grid system construction ans maintenance cost under different capacity configurations. However expert system requires a certain historic accumulation which can not be applied in wave power generation system. Zhang Kun[12] used different filter time constant to stabilize fluctuation. at different rated power and capacity of battery conditions And in accordance with the genetic algorithm to evaluate the economy, the optimal configuration of power, capacity, and filter time constant are found. But due to that only battery is consider, it can not be applied to the application of this research. In my research, when I make optimization of capacity configuration, make storage system meet requirement of normal operation and also considered about economy.

1.4 Main work in this research

Because of volatility of wave power generation, when generation system is connected to power grid system, current and frequency will have significant effect on power grid. By the application of energy storage system, problems in connection to power grid can be solved, especially the problem, real-time fluctuation smoothing problem. Now real-time control strategy of storage system and capacity optimization in wave power generation is rare researched. So it will be well discussed in this research. Wherein the hybrid energy storage system, combination of super-capacitor and battery, has merits of complementary of power characteristic and energy characteristic. Requirement of fluctuation smoothing can be satisfied and optimal capacity can be designed.

(1) In Chapter1, development situation and significance of wave power generation is introduced. And the grid connection standards, connection problems are described when generation system is connected to power grid system. Finally, the present situation of the development of energy storage technology, as well as in solving the difficulties in wave power applications, including energy storage system selection, real-time control strategy and capacity configuration three questions.

(2)In Chapter 2 design of wave power generator and storage system is introduced, so that characteristic of wave power generation system can be analyzed by equivalent model. Parallel system consists of different generation units. Analysis of one unit and relation to parallel system is explained. Due to target of fluctuation constraint and design of storage system, case study strategy is described and will be the direction of analyzing the control strategy for whole generation system step by step.

(3)In Chapter 3 control strategy for constant target power is introduced. As basic sample to observe power and energy characteristic of generation system, with ideal storage system, rated power should be large enough to absorb power peak to achieve smoothing target. Also capacity requirement of storage system is high, so realistic hybrid storage is necessary for this generation system. Power distribution control strategy is based on low pass filter algorithm. By comparison of cases using different filter coefficient, it can be known that larger filter coefficient will be better for smoothing generator power fluctuation.

(4) In Chapter 4 control strategy for fluctuation target is introduced. Aim at making power stored in storage system as small as possible, target power control strategy is proposed. Because fluctuation target is applied for parallel system, for each unit fluctuation range can be wider if optimal control between different units is operated. But in this research single unit is analyzed, so strict fluctuation constraint range and wider range are both analyzed which can be reference for research of parallel system.

(5) In Chapter 5 according to case study in chapters before, rated power and rated capacity of storage equipment are analyzed and defined which should be able to meet peak points in fluctuation smoothing control strategy.

Chapter 2 Design of Wave Power Generation Structure and Design of Storage System

2.1 Structure of wave power generation system

2.1.1 Structure of wave power generator

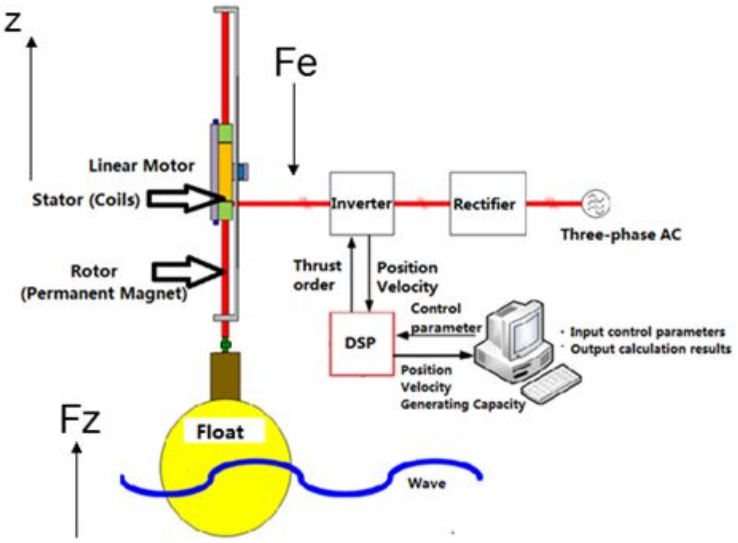


Fig 2.1 Structure of wave power generator

In this research, permanent magnet linear synchronous generator (LSG) is used as energy converter to change wave energy into electric energy. The float is connected to the mover part of LSG, so they will move together. Due to the relative motion between mover and stator, power can be generated. Because output power from generator will be transported to power grid through the bus, so first the generator will be connected with AC/DC converter. And before power grid, DC/AC converter is used to convert DC voltage into AC voltage.

If there is no control strategy for the generator, maximum power from the generator can not be generated. So in our program, we use active motion control for this LSG to give response to movement of mover. Which means we control the thrust of generator due to different velocity and position of mover, so that we have to control the current of generator. Because output voltage is constant as voltage of bus bar, if we have good control of the power, it means the current will be controlled.

To make active motion control of generator and observe the characteristic of output power from generator, characteristic test-method of LSG is necessary. But now there is less research of test method for LSG, so in appendix I introduced my proposed test-method for LSG.

2.1.2 Structure and characteristic of unit generation system

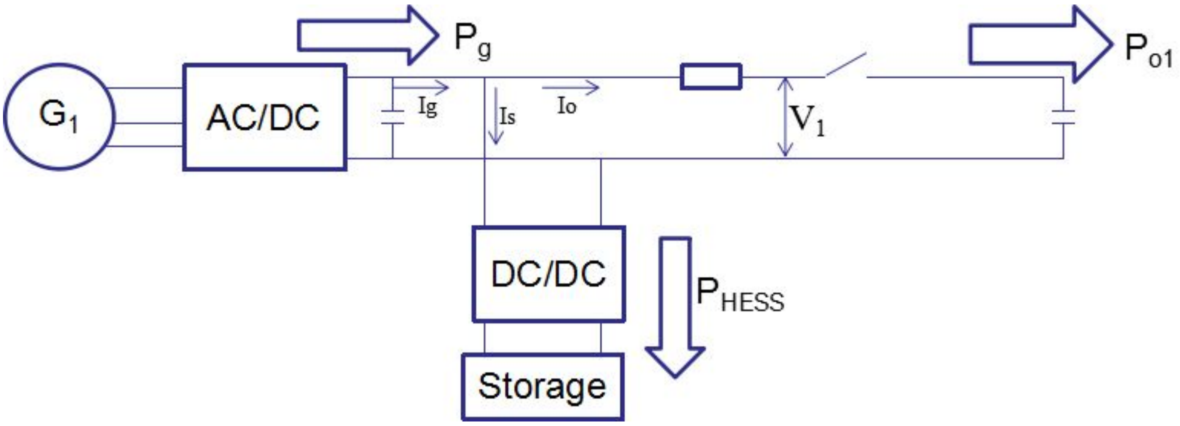


Fig 2.3 Equivalent mode of wave power generation system

From Fig 2.3, relationship between current and power can be described.

$$I_g = I_s + I_o \tag{2.1}$$

$$P_g = P_{HESS} + P_o \tag{2.2}$$

$$P_o = i_o * V \tag{2.3}$$

I_g --- Current from generator

I_s --- Current of storage system

I_o --- Current into power grid

P_g --- Power output from generator

P_{HESS} --- Power absorbed by storage system

P_o --- Power into power grid

V --- Voltage of bus

Power from one generator will be transported into storage system and power grid system. After action of storage system as a buffer system, smoothing power will be transported into grid system.

All the parallel generation systems are the same. After power from different units are gathered, total power from generator units can be obtained. One unit generator power Pg can be calculated according to the generator force and generator velocity that using ACL control strategy applying for this LSG.

2.1.3 Structure and characteristic of parallel system

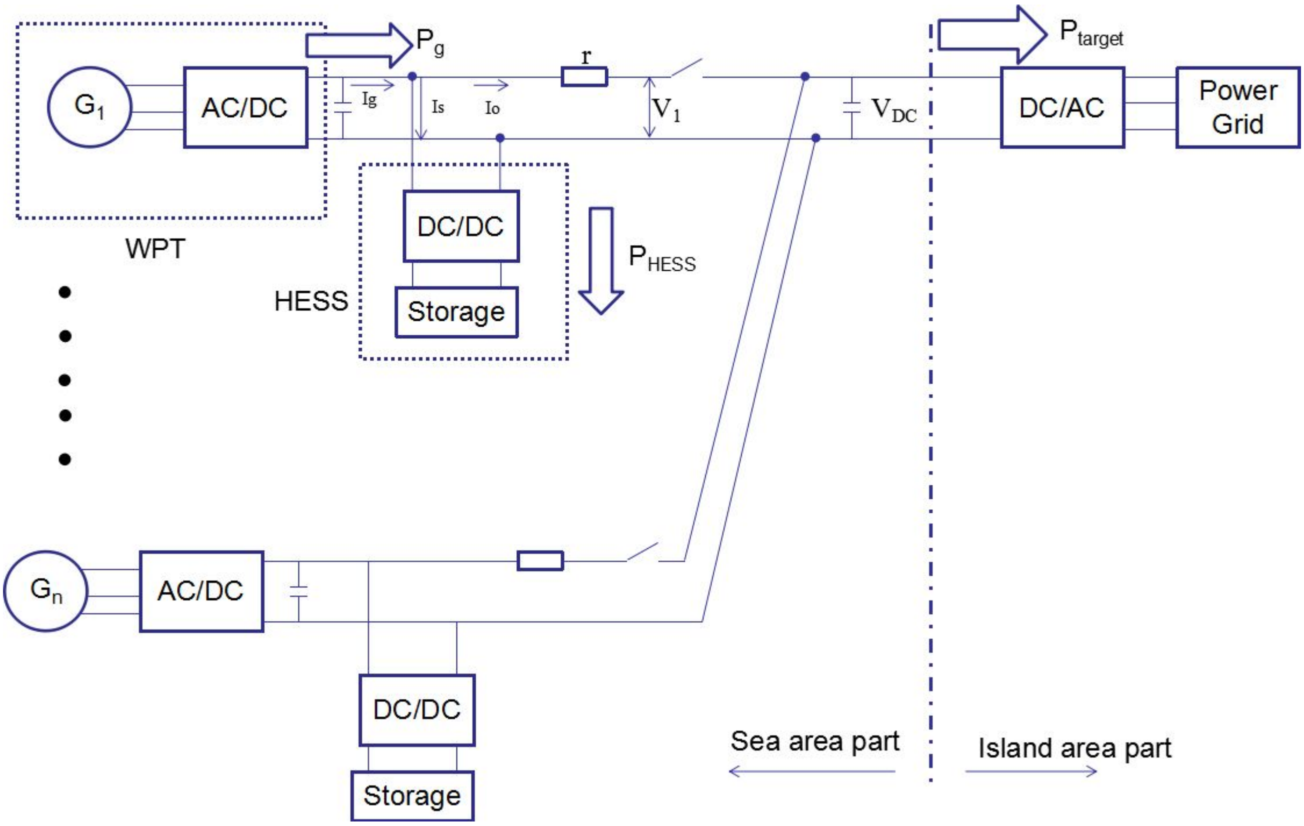


Fig 2.2 Structure of wave power generation system connected to grid

$$P_{target} = P_{o,1} + P_{o,2} + \ldots + P_{o,n} \tag{2.4}$$

Ptarget --- Target power transported into power grid under fluctuation constraint

Po,1 ... Po,n --- Output power from different generation system units

Structure of ocean power plant system can be described as Fig.2.2, which is mainly constructed with wave power generation and energy storage system. In sea area part, wave power generation units are connected parallel with the same DC voltage. In the starting period, storage system work as power source to make generator begin to operate until output voltages are the same and generators work in normal generation mode.

2.2 Analysis structure of control strategy for energy storage system

Real-time control strategy of this energy storage system consists of two problems: (1) According to the power characteristics, power distribution of realistic storage system can be determined. (2) Determine real-time target power meeting the requirement of grid connected power so that required real-time power of storage system can be determined.

In ideal single storage system, capacity is unlimited, so that it can be the basic sample to observe characteristic of power and energy. But for realistic storage system, capacity has limit, so that structure of hybrid storage system will be analyzed.

For ideal target power as the constant value of average generator power, storage system will have strict requirement of power and capacity range. But due to grid connection standards, target power can be under the range without over 5% of average power. So in this situation, requirement of power and capacity range of storage equipment will be reduced.

Fluctuation should be under 5% of average power. But this constraint is for parallel units system, which means that if we have different orders of different units to meet target power range, for every unit, requirement of power and capacity range of storage equipment can be more reduced. In this research, I just had case study base on one unit, so if it can meet strict situations, it must meet requirement when it is in parallel system.

Table 2.1 Analysis Structure of control strategy

Target Ripple Storage	0%	5%	10%
Single ideal storage	Case1	Case3	Case5
Realistic storage	Case2	Case4	Case6

2.3 Summary of Chapter 2

Design of wave power generator and storage system is introduced, so that characteristic of wave power generation system can be analyzed by equivalent model. Parallel system consists of different generation units. Analysis of one unit and relation to parallel system is explained. Due to target of fluctuation constraint and design of storage system, case study strategy is described and will be the direction of analyzing the control strategy for whole generation system step by step.

Chapter 3 Real-time Control Strategy for Ideal Mode

3.1 Case1 Constant output power with single ideal storage system

3.1.1 Analysis of output power from generator

The output power data is under the situation that excitation wave period is 7s and wave height is 2m which is most happened wave excitation mode in historic data. By using active motion control, output power can be calculated. In basic situation, target power for power grid is constant, it should be the average value of power in this time range 200s.

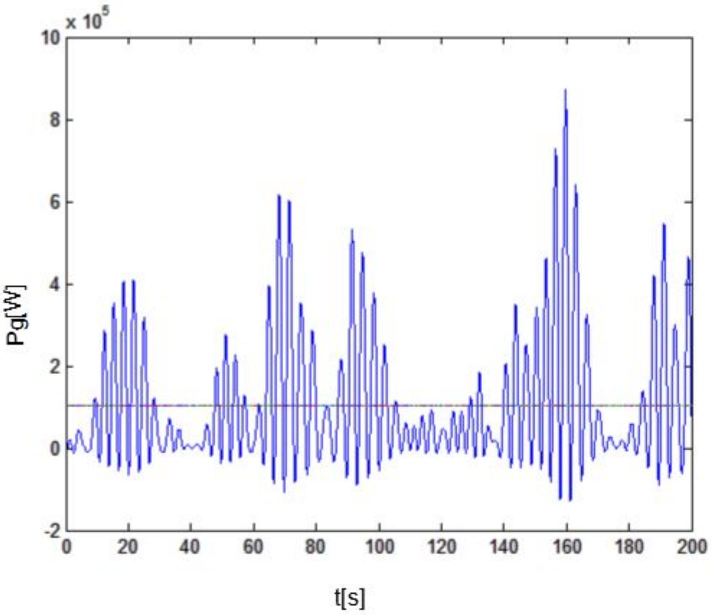
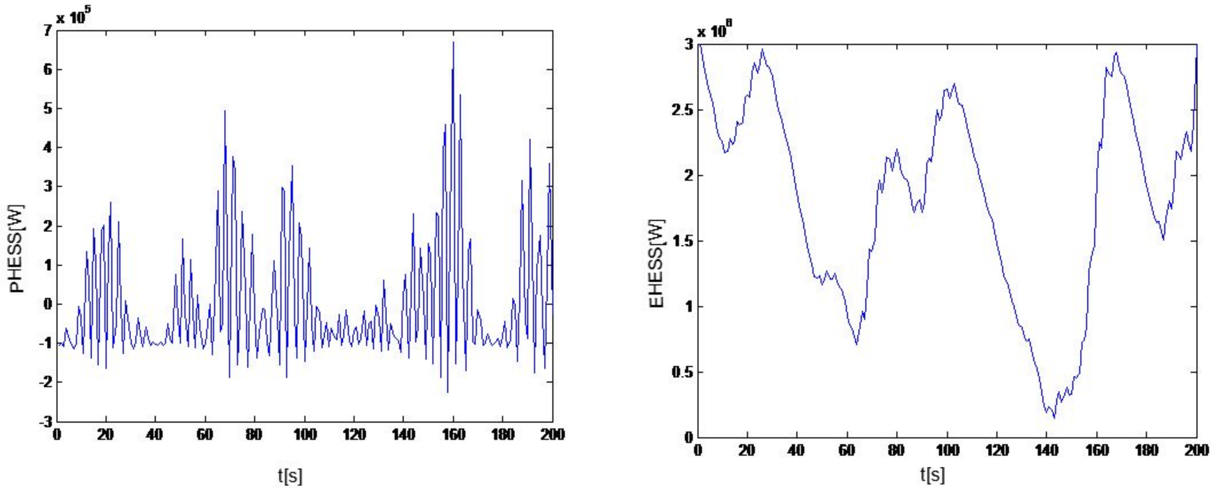


Fig 3.1 case 1 Output power from wave power generator and average power

The original output power and the stabilization target are shown together in Figure 3.1, we can see the stabilization target is the average value of the original output power. It can be observed that 100kW,which is defined as rated power of generation system, but maximum power point is 890kW. The maximum power is about 9 times of average power, so that if target power is wanted, large power should be stored in storage system which means that rated power of storage system is very big.

3.1.2 Analysis of power and energy requirement of ideal storage system

Output power is target power, so the different between output power of generator and target is stored in storage system.



(a) (b)

Fig 3.2 case 1 (a)Power stored in storage system (b) Energy change in storage system

From Fig 3.2(a), if rated power and rated capacity of this single real storage system is large enough, maximum power should be bigger than 680kW. And also in Fig 3.2(b) capacity of storage is about 3MWs to make sure it is large enough to make energy change not under 0 and in starting period, there should be energy storage to act as source to make generator operate into normal situation.

It can be observed that both of rated power and rated energy requirements of this storage system are very big. Due to high frequency power generation ingredient, storage should have high power density. Also high energy density of storage is required. So single ideal storage system is impossible to have both characteristics and hybrid storage system should be proposed to solve this problem.

3.2 Case 2 Constant output power with realistic hybrid storage system

3.2.1 Design of realistic storage system

In this work, we attempt to propose a type of HESS by using the SCESS as the key component to stabilize the power fluctuation over time of wave power generation due to its intermittent nature. The HESS system structure is showed in Figure . It is a brief structure diagram, so the devices between the generation system and the grid, such as transformers, are ignored.

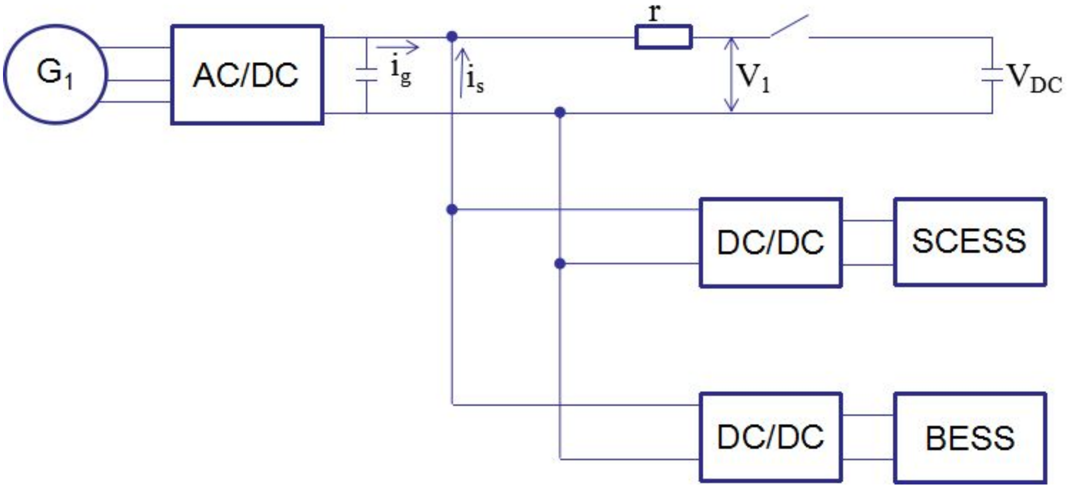


Fig.3.3 The system structure of HESS

In HESS, the SCESS and BESS are organized through a bus connection. With such structure, once the output power of generator is lower than the stabilization target, HESS compensates the error. Otherwise, HESS absorbs the excess power generated from the win In this way, the wind power can be improved to the standard to be connected to the power distribution grid.

In this work, we consider that the studied HESS consist of the SCESS as a component to absorb high frequency power component, while BESS works as a component to absorb low frequency component and provide energy that super-capacitor can not provide. The super-capacitors have many advantages as follows: (1) Higher power density: The power density of super-capacitors is about 10 to 100 times higher than batteries, and could reach 10 kW/kg. This feature makes super-capacitors can be used for scenarios that requires high output power in short time; (2) Faster charging speed: It may only cost dozens of seconds to several minutes to complete the charging process, while the battery needs several hours; (3) Longer lifetime: The cycle lifetime can be over 100000 times of charging, which is 10 to 100 times more than the lifetime of battery; (4) More environmental friendly: The charging and discharging of super-capacitors are physical processes which has limited affections to the environment. But energy density of super-capacity is small that rated capacity of it should be reduced by using battery as the compensate component.

Based on the above recognition, we propose an approach of power energy dispatch which works as follows: SCESS has higher priority when power is needed for compensating the power output of generator. If the power for compensation is high and changing frequently, SCESS can complete the compensation task as main component. However, if the power for compensation is small, but the capacity of SCESS cannot be enough for the large power throughput. In this case, BESS works as main component to work to compensate the power.

3.2.2 Operating principle and system model of power distribution of hybrid storage system based on Low Pass Filter Algorithm

The hybrid storage structure combining battery and ultra-capacitor together has merit as complementary of storage characteristic and power characteristic, so that fluctuation can be smoothed. According to that battery and ultra-capacitor absorb power with different frequencies, select low-pass filter algorithm as basic algorithm. For its great flexibility, filter coefficients can be real-time adjusted according to desired effect of storage.

For low-pass filter method, according to 1-order low-pass filter:

$$RC\frac{dU_o}{dt}+U_o=U_i \tag{3.1}$$

RC --- Filter time constant

U_i --- Input signal

U_o --- Filter output signal

Power filter can be described as:

$$\tau \frac{dP_o}{dt} + P_o = P_g \tag{3.2}$$

τ --- Power filter time constant

P_g(t) --- Power output from generator at sampling time t

P_o(t) --- Target power output from generation system at sampling time t

Power filter can be described as:

$$\tau \frac{dP_{BESS}}{dt} + P_{BESS} = P_{HESS} \tag{3.3}$$

τ --- Power filter time constant
P_{HESS}--- Power provided by hybrid storage system
P_{BESS} --- Power provided by battery

By changing time constant, calculate power provided by battery to make it meet battery SOC.
Input and output power can be got by sampling, so after discrete, it can be described as:

$$P_{BESS}(t) = ((\frac{2\tau}{Ts} - 1)P_{BESS}(t-1) + P_{HESS}(t) + P_{HESS}(t - Ts))/(1 + \frac{2\tau}{Ts}) \tag{3.4}$$

Ts --- Sampling time
P_{HESS}(t) --- Power should be provided by HESS at sampling time t
P_B(t) --- Power should be provided by battery at sampling time t

So it can be observed that power provided by battery at this moment is not only related to HESS total power, but also related to battery power at last moment. Set ω_c to be cut-off angular frequency of LPF.

$$\omega_c = \frac{1}{\tau} \tag{3.5}$$

Set T_{min} to be minimum charge-discharge cycle time of battery.

$$\omega_c = 2\pi f_{\max} = \frac{2\pi}{T_{\min}} \tag{3.6}$$

$$\tau = \frac{T_{\min}}{2\pi} \tag{3.7}$$

Filter time constant range is [0,∞).

It can be observed that if filter effect is smaller, role of generator power is more important. If filter effect is bigger, battery power at last moment is more important, power is more stable.

Real-time power provided by hybrid storage system: (3.8)

$$P_{HESS}(t) = P_G - P_O(t)$$

Through the power to grid and the power output from generator, the power which should be provided by hybrid system per second can be calculated.

When $P_B(t) \geq 0$, $P_{SC}(t) \geq 0$, it is in charge.

When $P_B(t) < 0$, $P_{SC}(t) < 0$, it is in discharge.

3.2.3 Simulation Cases

(1) Power distribution between super-capacitor and battery with filter coefficient τ=60

Table 3.1 Situation of Case 2

Length of data	200s
Time Intervals of Data	1 second
Rated power of generation system	100kW

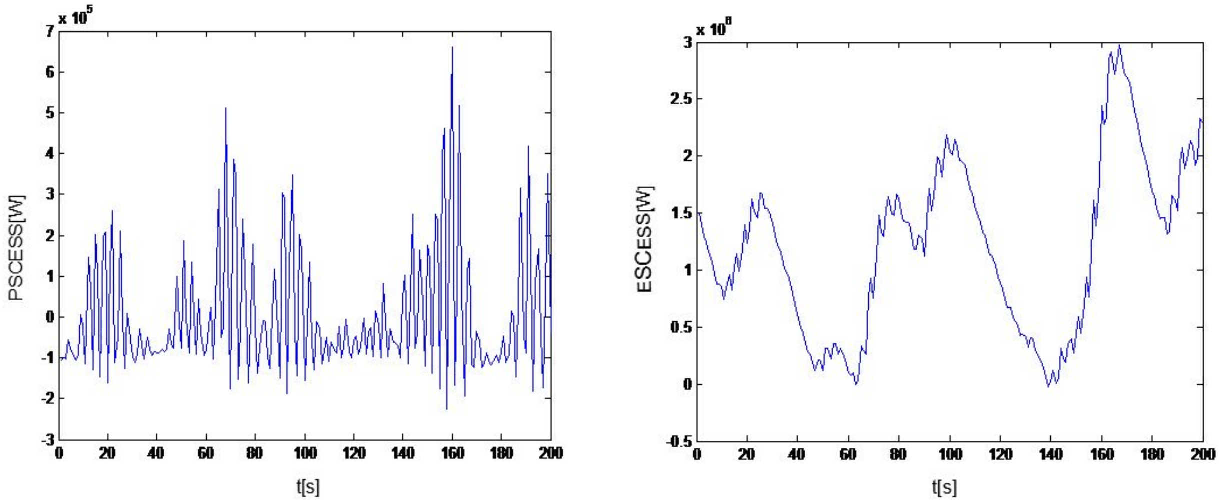


Fig 3.5 case 2 τ=60 (a)Power stored in super-capacitor (b) Energy change in super-capacitor

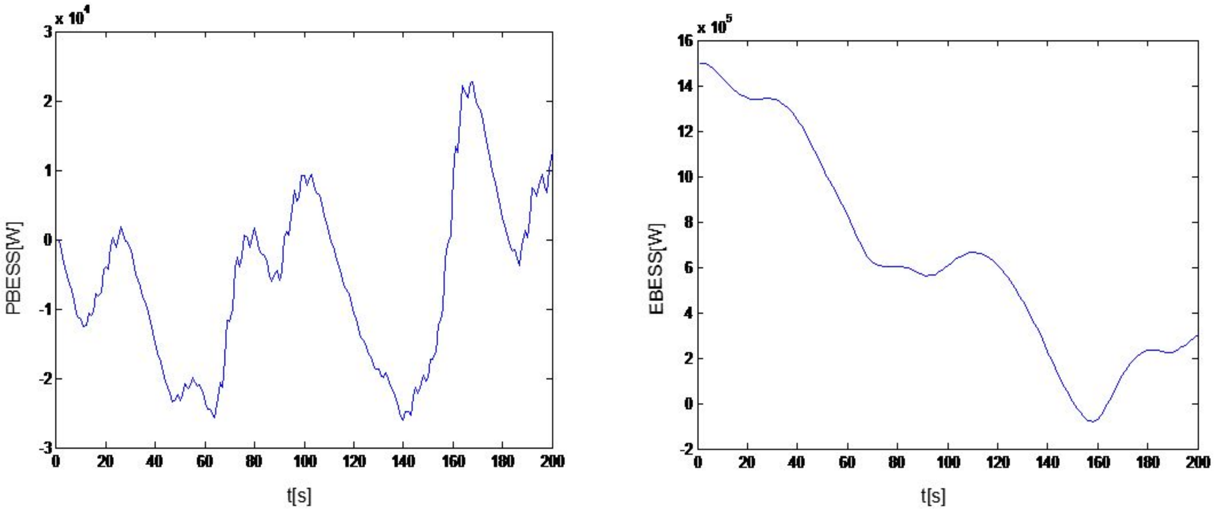


Fig 3.6 case 2 $\tau=60$ (a)Power stored in battery (b) Energy change in battery

The power task of HESS is showed in Figure 3.2. From the figure 3.2, we can easily find that the power task fluctuates from -200 to 680 KW. And it includes low-frequency part whose power value is relatively large and high-frequency part which changes fast. This task can be completed by SCESS and BESS with the help of the strategies and algorithms proposed in this chapter. We can estimate the capacity and the maximum power of SCESS and battery based on theses figures.

The power tasks of SCESS is showed in Figure 3.5(a). It can be observed that super-capacitor charge/discharge frequently with same power change trend of ideal storage power trend, which means that super-capacitor can successfully stored high frequency component of fluctuation power. Especially at the second 160s, super-capacitor stored maximum power point 680kW to make this largest fluctuation smoothed. In Fig 3.5(b), requirement of energy range is smaller than range in ideal storage system because of the compensation of battery.

In addition, from the power task of BESS in Fig 3.6(a), we know that SCESS almost absorb and release the high frequency power. In Fig 3.6(b) it can be observed that BESS works as device to compensate with SCESS, and it deals with the low frequency power part because of the characteristic that the ramp rate power of BESS is very small. The suggested method that using the BESS as a backup device decreases scale of BESS and saves the cost of SCESS. Also it's good for extending the lifetime of BESS and friendly to the environment.

(2) Power distribution between super-capacitor and battery with filter coefficient τ=30

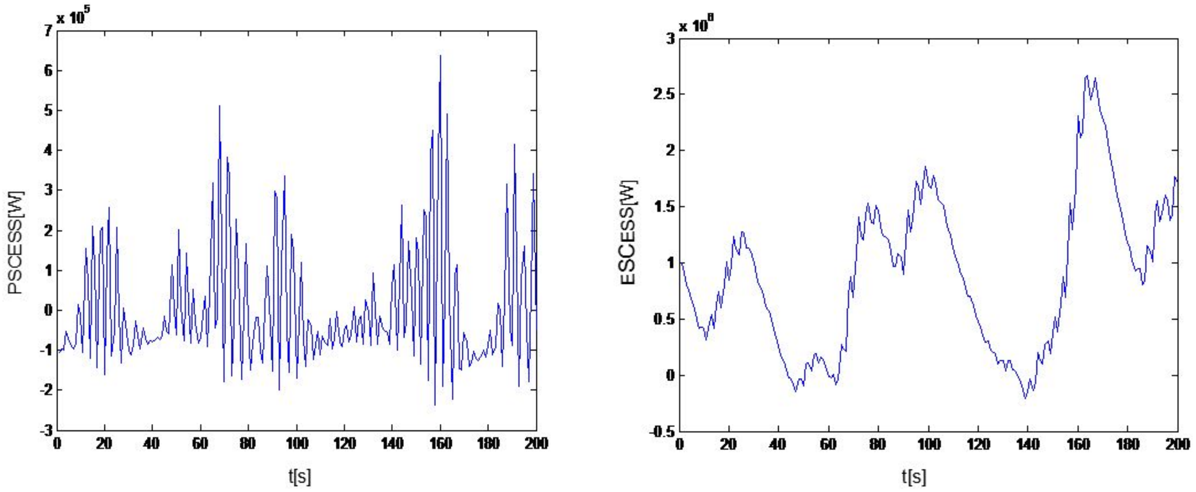


Fig 3.7 (a) case 2 τ=30 Power stored in super-capacitor (b) Energy change in super-capacitor

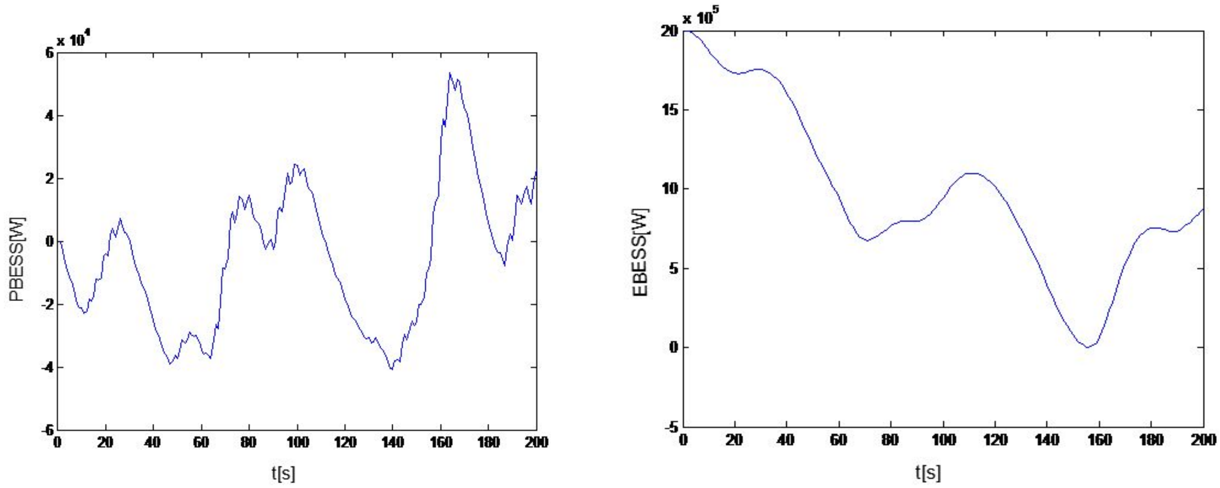


Fig 3.8 (a) case 2 τ=30 Power stored in super-capacitor (b) Energy change in super-capacitor

Due to comparison between Fig 3.5(a) and 3.7(a), it can be observed that when filter coefficient is bigger, power component of super-capacity is smaller. Especially at maximum power point, requirement of super-capacitor is a little reduced. So in Fig 3.7(b), it can be known that capacity requirement of super-capacitor is also reduced.

But from comparison of Fig 3.6(a) and Fig 3.8(a), it can be observed that when filter coefficient is bigger, power component of battery is bigger, which is not good for its power density characteristic and not good for stability of battery. Also from Fig 3.8(b), it can be known that capacity requirement of battery is largely increased so that scale of battery is increased and cost will be larger.

From comparison between these two cases with different filter coefficient, it can be observed that when filter coefficient is smaller, frequency range of component that battery can compensate is more narrow and power peak is bigger. Also switching of battery charge/discharge is more frequently which is not good for extend of battery life. So it is better to choose bigger filter coefficient.

3.3 Summary of Chapter 3

Control strategy for constant target power is introduced. As basic sample to observe power and energy characteristic of generation system, with ideal storage system, rated power should be large enough to absorb power peak to achieve smoothing target. Also capacity requirement of storage system is high, so realistic hybrid storage is necessary for this generation system. Power distribution control strategy is based on low pass filter algorithm. By comparison of cases using different filter coefficient, it can be known that larger filter coefficient will be better for smoothing generator power fluctuation.

Chapter 4 Real-time Control Strategy in Fluctuation Target Mode

4.1 Principles and system model of hybrid storage system with target fluctuation

4.1.1 Definition of smoothed wave power generation fluctuation in parallel system

When wave power generation system is connected to large power grid, active power fluctuation is main considered. Here active wind power fluctuations definition will be introduced. In this paper, the sampling time is *Ts*, wave power fluctuation ratio after smoothing is defined as the ratio of difference between maximum/minimum power and rated power and rated power.

$$\begin{cases} \Delta P_o\%(t) = (P_o(t) - \mathrm{P_r}) / \mathrm{P_r}, Po(t) \geq \mathrm{Pr} \\ \Delta P_o\%(t) = (\mathrm{P_r} - P_o(t)) / \mathrm{P_r}, Po(t) \leq \mathrm{Pr} \end{cases} \tag{4.1}$$

P_o --- Smoothed power transported to the grid

P_r --- Rated power of wave power generation system (equal to average power of output power from generator)

From the definition of one minute power fluctuation, power fluctuation constraint should be considered when target power is determined.

Target smoothing power must meet the requirement of 1min fluctuation limitation.

$$0 \leq \Delta P_o\%(t) \leq \gamma\% \tag{4.2}$$

$\gamma\%$ --- Maximum wave power fluctuation rate by grid connection standards requirement

In this research, $\gamma\%$ is defined as 5%. This fluctuation constraint is applied for parallel system, which means that after summary of power from every generation system unit, total power transported to power grid can have power margin under 5% bigger or smaller than rated power. So power from every generation unit may have larger margin like 10% if there is good compensation among different units. But in this research, only one unit mode is researched so that 5% and 10% margin will be applied in single unit system which will be good reference for analysis of parallel system.

4.1.2 System model of control strategy for realistic generation system

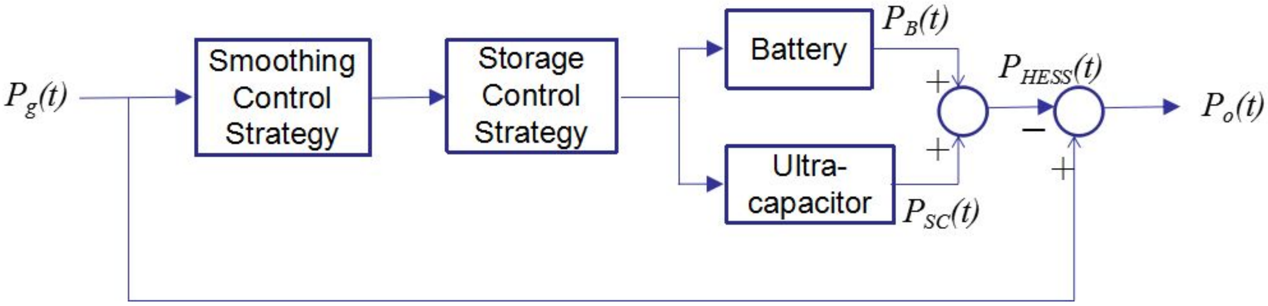


Fig 4.1 Control strategy of HESS for smoothing wave power generation fluctuation

The control strategy of HESS for mitigating power generation fluctuation is shown in Fig 4.1. Firstly, the direct output power of generator is obtained, and then it is calculated to derive the expected smoothed output power in which power stored by storage system is as small as possible. Secondly, the expected compensation power by HESS is allocated between the battery and the super-capacitor considering that the super-capacitor is suitable to accommodate the most fluctuations with its high power density and the battery is for those super-capacitor couldn't bear. Finally, the combined power from generation system is achieved satisfying the requirement of grid connection.

One of the key benefits of the proposed approach is that the control strategy can be carried out in real-time. More specifically, the finding of stabilization target, and charging discharging process are implemented in real-time. According to the real-time output power, Pg , and the stabilization target power, Po, we can easily obtain the power task of HESS P_{HESS}.

Through the suggested strategies and algorithms, we can compute the stabilization target power, Po, by the requirement fluctuation we want to obtain. and get the optimal power task of SCESS and BESS, P_{SCESS} (t) and P_{BESS} (t) in real-time. DC-DC (A) controls the actual charging or discharging power of SCESS, P_{SCESS} (t) and DC-DC (B) controls the actual charging or discharging power of BESS, P_{BESS} (t) . In order to control P_{SCESS} (t) and P_{BESS} (t) accurately, we must measure the terminal voltage in real-time. Take SCESS for example, the terminal voltage of SCESS is Usc (t) , then the control target of the current is:

$$I_{SC}(t)=\frac{P_{SCESS}(t)}{U_{SC}(t)} \tag{4.3}$$

Through the close-loop control to the current, we can control the power accurately. The high-voltage side of DC-DC connects to three-phase converter to guarantee the voltage stable.

4.1.3 Stabilization strategy and algorithm design of target power

The power task of HESS is described by decision of target power transported to grid system. When the system need the target power fluctuation to be under 5% of rated power, from eq(3.8), HESS releases or absorbs power to smooth the power output from generator to be target power in constraint. To make power stored by storage system as small as possible to make operation and maintenance cost as small as possible, we use different strategies in different situations:

$$\begin{cases} P_o(t)=(1+\Delta P_o\%(t))*\mathrm{P_r}, P_g(t)>\mathrm{P_r} \\ P_o(t)=(1-\Delta P_o\%(t))*\mathrm{P_r}, P_g(t)<\mathrm{P_r} \\ P_o(t)=\mathrm{P_r}, P_g(t)=\mathrm{P_r} \end{cases} \tag{4.4}$$

$$\begin{cases} P_{HESS}(t)=P_g(t)-(1+\Delta P_o\%(t))*\mathrm{P_r}, P_g(t)>\mathrm{P_r} \\ P_{HESS}(t)=P_g(t)-(1-\Delta P_o\%(t))*\mathrm{P_r}, P_g(t)<\mathrm{P_r} \\ P_{HESS}(t)=0, P_g(t)=\mathrm{P_r} \end{cases} \tag{4.5}$$

(1) When P_g(t) > P_r, set P_o(t) to be maximum value in constraint range. So that from eq(4.5), power that needed to be absorbed by storage system can be calculated to be as small as possible.

(2)When P_g(t) < P_r, set P_o(t) to be minimum value in constraint range. So that from eq(4.5), power that needed to be released by storage system can be calculated to be as small as possible.

(3)When P_g(t) = P_r, set P_o(t) to be equal value of real-time generator power value. So that from eq(4.5), power that needed to be absorbed by storage system can be calculated to be 0.

4.2 Case3 Smoothing power in fluctuation target with single ideal storage system

4.2.1 Analysis of output power from generator

According to target power definition algorithm, grid-connection target power can be calculated after real-time smoothing. Rated value of generator output power is defined to be 100kW, and fluctuation constraint of grid-connection active power is defined to be under 5% of WPT rated power.

Table 5.1 Situation of Case 3

Length of data (s)	200
Rated power of generation system(kW)	100
Sampling time (s)	1
fluctuation (%)	5
Filter coefficient in power distribution	60

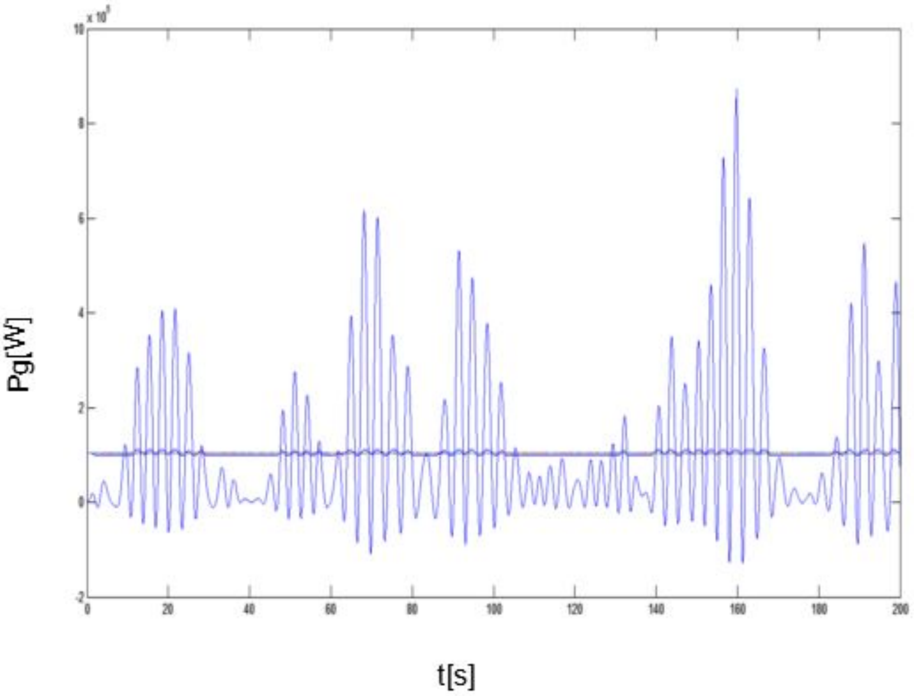


Fig 4.1 case 3 ΔP_o%max=5% Output power from generator and target power

From comparison of Fig 3.1 and Fig 4.1, it can be observed that target power transported to power grid changes beneath/under average power of generator according to target power definition control strategy.

4.2.2 Analysis of power and energy requirement of ideal storage system

Output power is target power, so the different between output power of generator and target is stored in storage system.

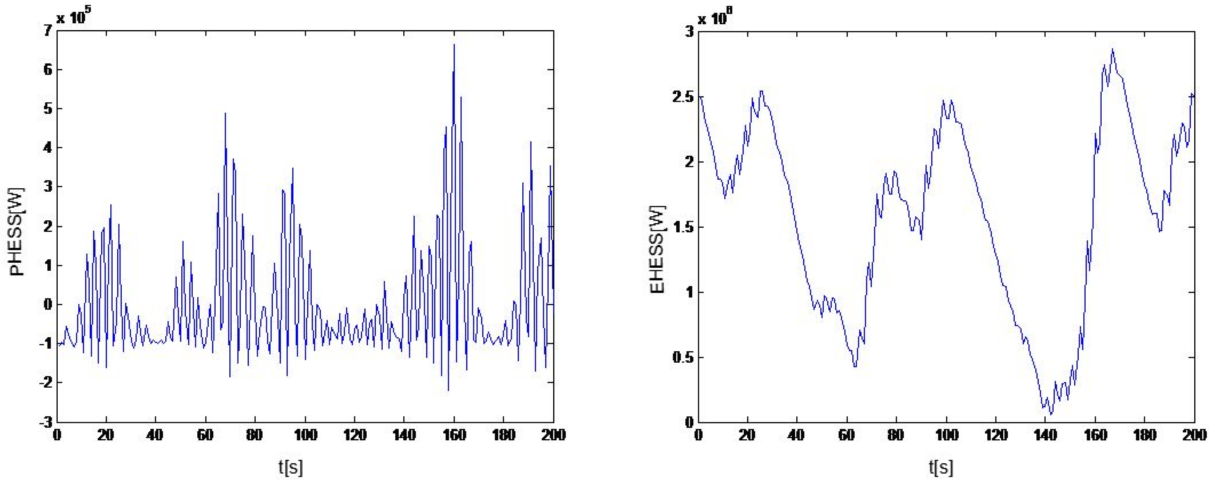


Fig 4.2 case 3 ΔP_o%max=5% (a) Power stored by single ideal storage system (b) Energy change in single ideal storage system

From comparison of Fig 3.2(a) and Fig 4.2(a), power peak that needed to be stored in storage system is decreased when target power control strategy is used.Because at this second, 160s, output power of generator is bigger than maximum target power range so that target power should be set to be maximum value.

From comparison of Fig 3.2(b) and Fig 4.2(b), capacity requirement of storage system is decreased from 300 kWs to 250 kWs as about 15% of rated capacity. By using target power definition control strategy it will be less strict requirement of storage system which will make cost of equipment and maintenance decreased.

4.3 Case 4 Smoothing power in fluctuation target 5% with realistic hybrid storage system

According to power distribution control strategy introduced in chapter 3, power is optimal distributed between super-capacitor and battery.

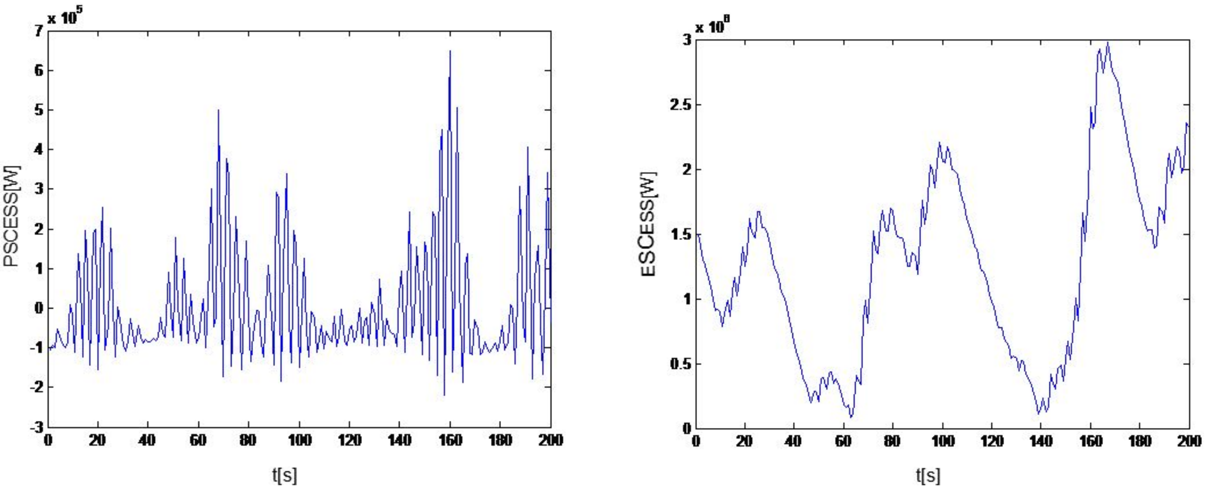


Fig 4.3 case 4 ΔP_o%max=5% (a) Power stored by super-capacitor (b) Energy change in super-capacitor

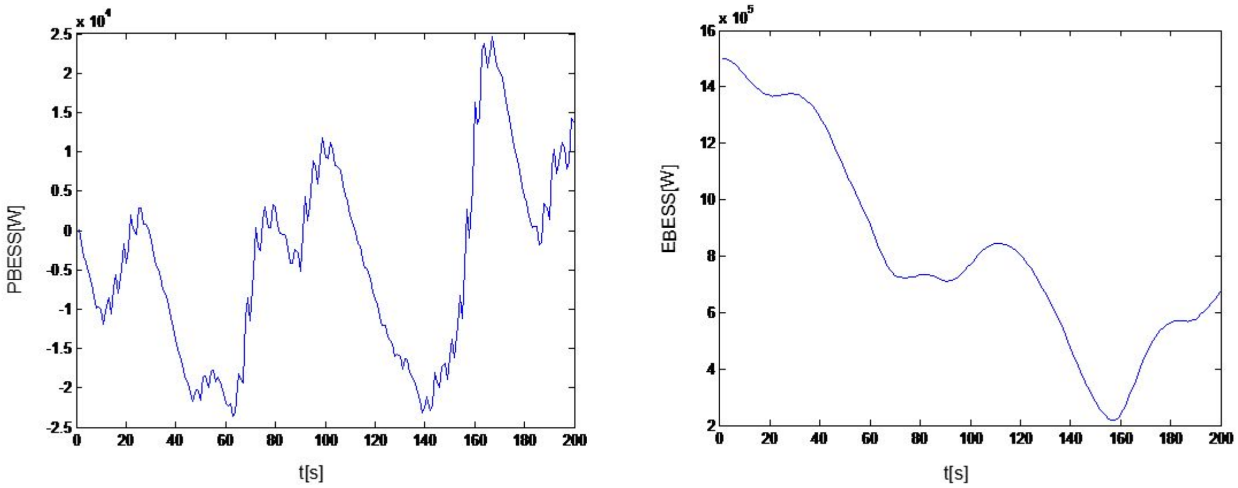


Fig 4.4 case 4 ΔP_o%max=5% (a) Power stored by battery (b) Energy change in battery

From the figure 4.2(a), we can easily find that the power task fluctuates from -200 to 680 KW. And it includes low-frequency part whose power value is relatively large and high-frequency part which changes fast. This task can be completed by SCESS and BESS with the help of the strategies and algorithms proposed in chapter 3. We can estimate the capacity and the maximum power of SCESS and battery based on theses figures.

The power tasks of SCESS is showed in Figure 4.3(a). It can be observed that super-capacitor charge/discharge frequently with same power change trend of ideal storage power trend, which means that super-capacitor can successfully stored high frequency component of fluctuation power. Especially at the second 160s, super-capacitor stored maximum power point 660kW to make this largest fluctuation smoothed which is smaller than that in case 2 that target power is the average power. In Fig 4.3(b), requirement of energy range is smaller than range in ideal storage system because of the compensation of battery, and also smaller than that in case 2.

In addition, from the power task of BESS in Fig 4.4(a), we know that SCESS almost absorb and release the high frequency power. In Fig 4.4(b) it can be observed that BESS works as device to compensate with SCESS, and it deals with the low frequency power part because of the characteristic that the ramp rate power of BESS is very small. Also compared with Fig 3.6(b), capacity requirement of battery is decreased so that cost of equipment can be reduced.

4.4 Case 5 Smoothing power for fluctuation target 10% with single ideal storage system

4.4.1 Analysis of output power from generator

According to target power definition algorithm, grid-connection target power can be calculated after real-time smoothing. Rated value of generator output power is defined to be 100kW, and fluctuation constraint of grid-connection active power is defined to be under 10% of WPT rated power.

Table 5.1 Situation of Case 5

Length of data (s)	200
Rated power of generation system(kW)	100
Sampling time (s)	1
fluctuation (%)	10
Filter coefficient in power distribution	60

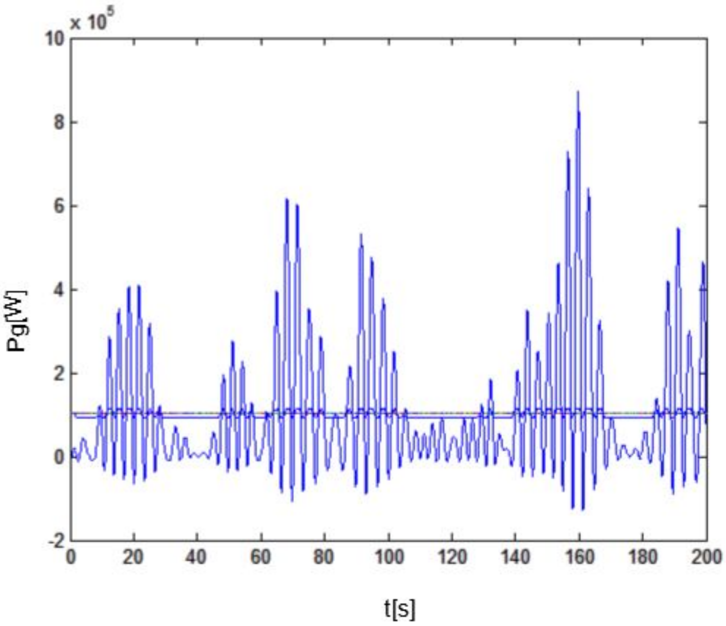


Fig 4.5 case 5 ΔP_o%max=10% Output power from generator and target power

Compared with Fig 4.1, it can be observed that fluctuation range of smoothing power is larger than before in which target power control strategy is also used.

4.4.2 Analysis of power stored in storage system

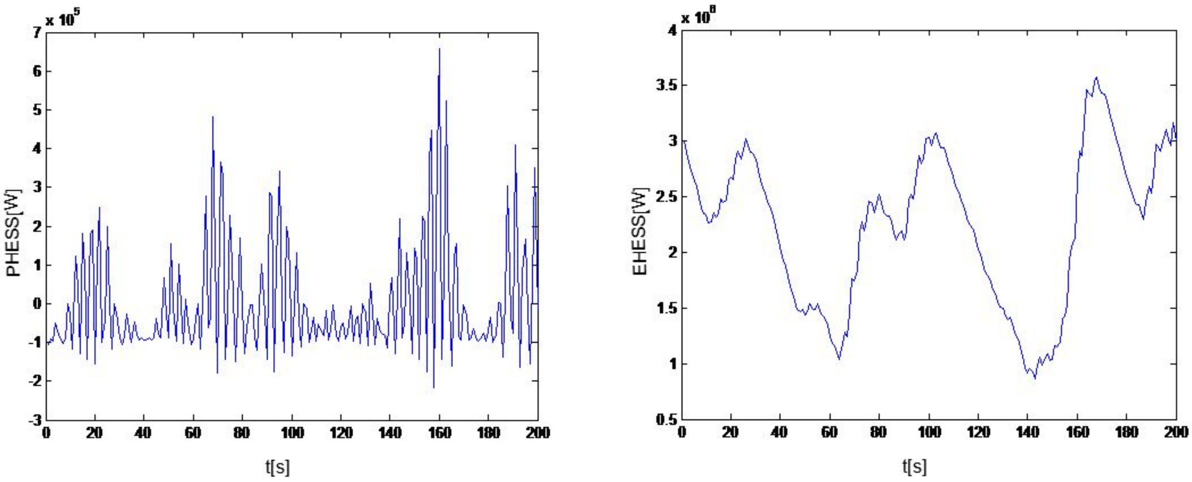


Fig 4.6 case 5 ΔP_o%max=10% (a) Power stored by single ideal storage system (b) Energy change in single ideal storage system

In Fig 4.6(a), power peak that stored by the storage system is 650kW which is smaller than that in fluctuation target range 5%, which means that wider fluctuation target range will release the responsibility of storage system and it is good for requirement of equipment.

In Fig 4.6(b), energy change is in the range from 1MWs to 3.5MWs, which is smaller than the range that in case 3, which means that if there is optimal design of storage system in realistic situation, capacity requirement of storage system can be reduced.

4.5 Case 6 Smoothing power for fluctuation target 10% with realistic hybrid storage system

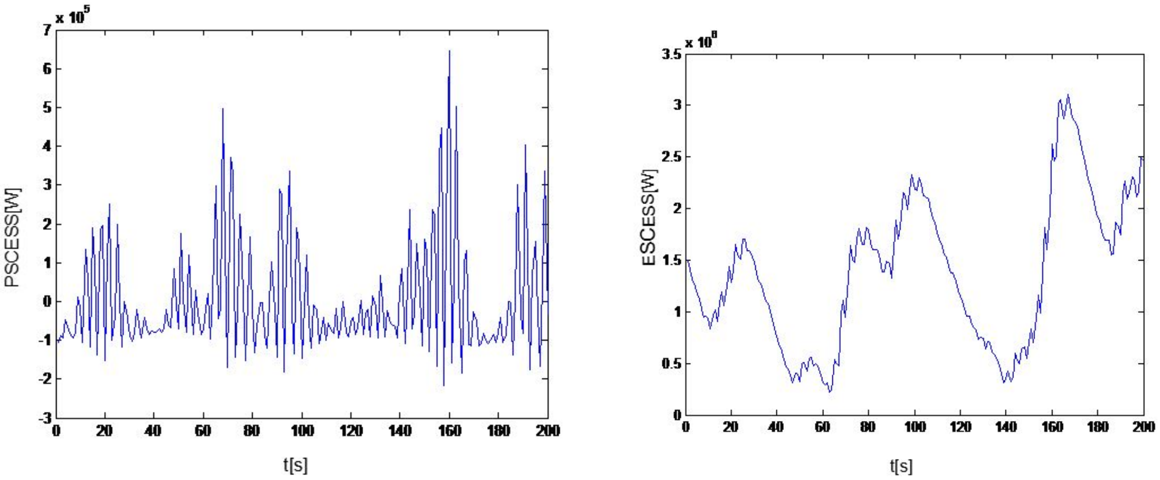


Fig 4.7 case 6 ΔP_o%max=10% (a) Power stored by super-capacitor (b) Energy change in super-capacitor

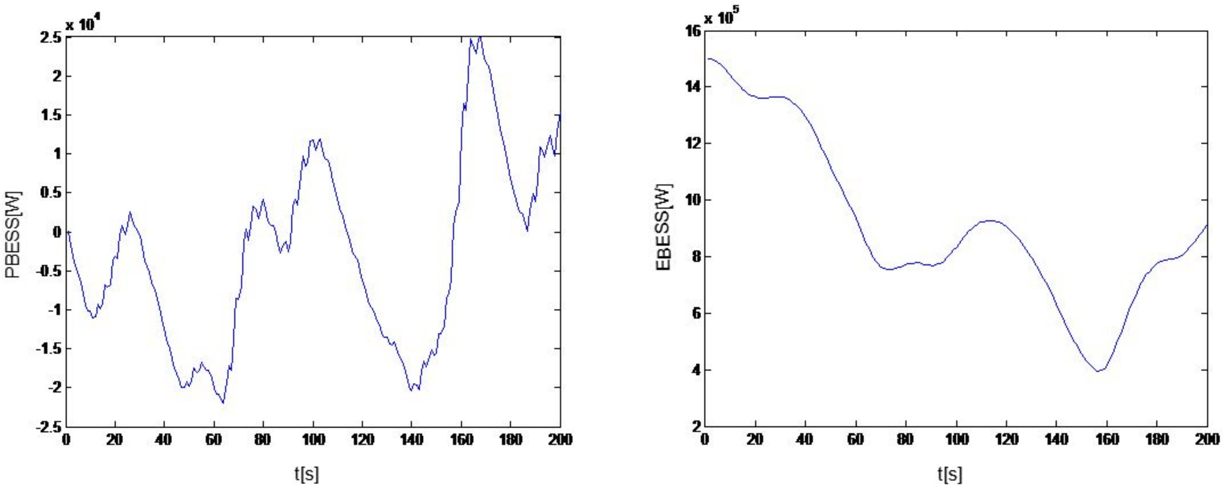


Fig 4.8 case 4 ΔP_o%max=10% (a) Power stored by battery (b) Energy change in battery

In Fig 4.7(a), because super-capacitor act as the component to absorb high frequency power component and power peak, the reduction of power peak under fluctuation target 10% situation will make requirement of super-capacitor decreased. In Fig 4.7(b), capacity requirement of super-capacitor is smaller that that in case 4 which is better for capacity optimization of equipment. In Fig 4.8(a), ramp rate of power change of battery is smaller so that it can be observed that the compensation power curve is more smoothing. In Fig 4.8(b), it can be observed that energy change range is smaller than that in case 4, which means it has potential to be optimized that capacity of battery can be smaller.

4.6 Summary of Chapter 4

Control strategy for fluctuation target is introduced. Aim at making power stored in storage system as small as possible, target power control strategy is proposed. Because fluctuation target is applied for parallel system, for each unit fluctuation range can be wider if optimal control between different units is operated. But in this research single unit is analyzed, so strict fluctuation constraint range and wider range are both analyzed which can be reference for research of parallel system.

Chapter 5 Capacity Configuration Design of Realistic Hybrid Storage System

When wave power generation system is connected to power grid system, power fluctuation attack to the power grid can be efficiently reduced by using storage system. After analysis of real-time control strategy of smoothing power fluctuation with hybrid storage system, which is introduced in chapters before, in this chapter, at start stage for wave power generation system, capacity configuration design of realistic hybrid storage system is analyzed. Because compared to wave power generation cost, cost of energy storage equipment is very expensive that in most research about capacity configuration, storage system cost is still be focused on. But in actual operation, ability of storage system that can make generation system start and operate in normal situation is also necessary to be considered.

Table 5.1 Configuration of storage equipment

Rated power of ideal storage system	690kW
Rated capacity of ideal storage system	3MWs
Rated power of super-capacity	690kW
Rated capacity of super-capacity	3MWs
Rated power of battery	25kW
Rated capacity of battery	1.5MWs

Chapter 6 Summary and Closing Conclusions

6.1 Summary of research

With development of wave power technology and green energy advocates, problem of stability and reliability of power and frequency of grid connection due to randomness and volatility of wave power should be well analyzed. Now there is less research about problem and standard of fluctuation when generation system is connected to power grid, which is the main research content in this thesis. In operation of wave power generation system, energy storage system act as buffer equipment to smooth and meet fluctuation target of grid connection. In my research, real-time control strategy of target power definition and power distribution in hybrid storage system is described:

(1) Development situation and significance of wave power generation is introduced. And the grid connection standards, connection problems are described when generation system is connected to power grid system. Finally, the present situation of the development of energy storage technology, as well as solving difficulties in wave power applications, including energy storage system selection, real-time control strategy and capacity configuration three questions are introduced.

(2)Design of wave power generator and storage system is introduced, so that characteristic of wave power generation system can be analyzed by equivalent model. Parallel system consists of different generation units. Analysis of one unit and relation to parallel system is explained. Due to target of fluctuation constraint and design of storage system, case study strategy is described and will be the direction of analyzing the control strategy for whole generation system step by step.

(3)Control strategy for constant target power is introduced. As basic sample to observe power and energy characteristic of generation system, with ideal storage system, rated power should be large enough to absorb power peak to achieve smoothing target. Also capacity requirement of storage system is high, so realistic hybrid storage is necessary for this generation system. Power distribution control strategy is based on low pass filter algorithm. By comparison of cases using different filter coefficient, it can be known that larger filter coefficient will be better for smoothing generator power fluctuation.

(4) Control strategy for fluctuation target is introduced. Aim at making power stored in storage system as small as possible, target power control strategy is proposed. Because fluctuation target is applied for parallel system, for each unit fluctuation range can be wider if optimal control between different units is operated. But in this research single unit is analyzed, so strict fluctuation constraint range and wider range are both analyzed which can be reference for research of parallel system.

According to case study in chapters before, rated power and rated capacity of storage equipment are analyzed and defined which should be able to meet peak points in fluctuation smoothing control strategy.

6.2 Closing conclusions

(1) In control strategy of target power definition, minimum rated capacity requirement should be also considered and theoretical analysis of relationship between target power and minimum rated capacity requirement should be well considered.

(2) In control strategy of power distribution in hybrid storage system, relationship between equipment cost and charge/discharge should also be considered to make control strategy more efficient and economical.

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Thank you for encouragement and help from Professor Koseki in this master period. I have learned knowledge not only about technology but also the study method to have strategy plan of the research by myself.

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[1] Guo Ruijuan, Takafumi Koseki, "Characteristic Test Method of Permanent Magnet Linear Synchronous

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Appendix A

Characteristic Test Method of PMLSG

When PMLSG is used as WEC (Wave Energy Converter) on ocean power plant, the mover is directly connected with float and move together under wave force. So wave energy can be directly converted into electric energy through mover motion.The advantages of using PMLSG as direct drive WEC[1] are as follows: (1) Simple mechanism due to elimination of intermediate transmission links, weight and volume largely decline. (2) High positioning accuracy: elimination of a variety of positioning errors caused by intermediate links. (3)Fast response: high sensitivity, good follower. (4) High stiffness and low noise.

A.1 Resistant Test

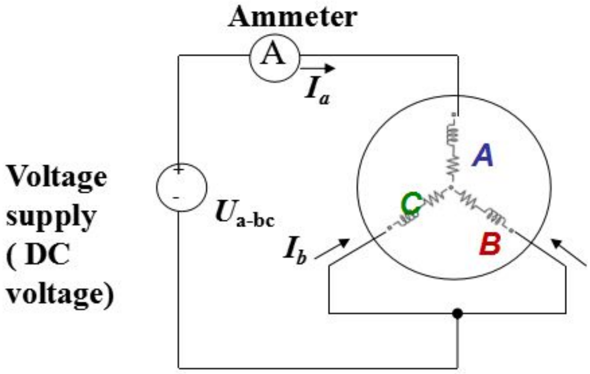

Fig A.1 Equivalent circuit model for resistance test

From equivalent circuit model, resistance can be calculated as:

$$U_{a-bc} = I_a(R_a + R_b // R_c) \tag{A.1}$$

$$R = R_a = \frac{2U_{a-bc}}{3I_a} = 4.24\Omega \tag{A.2}$$

A.2 No-load Test

For ocean plant, mover displacement z(t) [m]can be described as sinusoidal wave with wave angle frequency Ω [rad/s] because mover of generator is connected to float which is driven by wave force. So mover displacement can be written as:

$$z(t) = z_0 \sin \Omega t \tag{A.3}$$

Then electrical angle and Ea can be calculated as follows:

$$\theta(t) = \frac{\pi}{\tau} z(t) = \frac{\pi}{\tau} z_0 \sin \Omega t = \theta_0 \sin \Omega t \tag{A.4}$$

$$\begin{aligned} E_a(t) &= -\frac{d\psi_a}{dt} = N \cdot \phi_r \cdot \sin(\theta(t)) \cdot \frac{d\theta}{dt} \\ &= N \cdot \phi_r \cdot \theta_0 \cdot \Omega \cdot \cos \Omega t \cdot \sin(\theta_0 \sin \Omega t) \end{aligned} \tag{A.5}$$

From equation of EMF, it is obvious that change of Ω directly affects EMF. So different mover displacement with different Ω should be driven to observe how EMF will be.

A.3 d-q Inductance Test

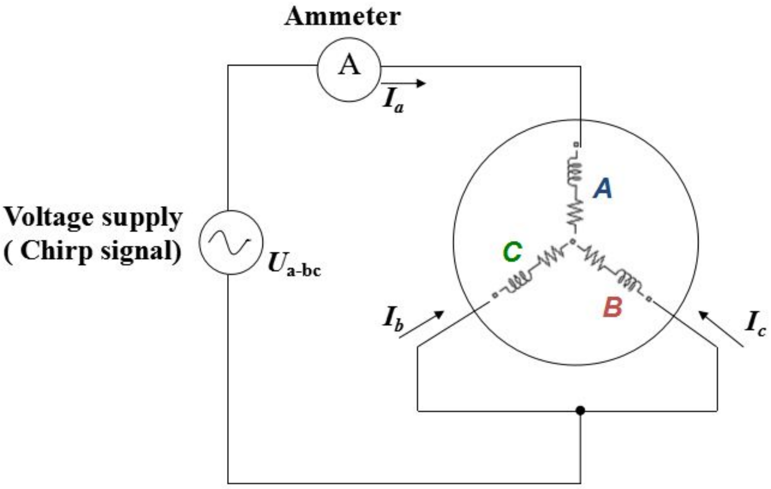

Fig A.2 Equivalent circuit model for d,q inductance test

Table A.1 Comparison of Situation for Different Test Method

Symbol	Defination	Unit

L_{aa}, L_{bb}, L_{cc}	Three-phase self-inductance	mH
L_{aa0}, L_{bb0}, L_{cc0}	Self-inductance caused by fundamental component of air gap flux	mH
L_{a1}, L_{b1}, L_{c1}	Self-inductance caused by armature leakage flux	mH
$Lg2$	Self-inductance casued by rotor Salient Characteristics	mH
θ_e	Electrical degree of rotor position	Rad/s
M_{ab}, M_{bc}, M_{ca} $M_{ba,}$, M_{cb}, M_{ac}	Three-phase mutual inductance	mH
L_{af}, L_{bf}, L_{cf}	Mutual inductance between stator and rotor	mH
ψ_a, ψ_b, ψ_c	Armature magnetic linkage	Wb
i_a, i_b, i_c	Three-phase armature current	A
ψ_r	Magnetic linkage caused by permanent magnet	Wb
i_f	Equivalent excitation current	A

A.3.1 Previous d and q Inductance Measurement

To get d,q inductance, there are three method types: analytical method, finitie element method, and experiment method[2]. Experiment method is a more direct and effective way to obtain d and q inductance of PMSM. Japan J. Nakatsugawa[3] --- Using AC with DC Bias Method has merit of ability to measure saturated nonlinearity of inductance. Australia R. Dutta[4] --- AC Standstill Method is to calculate d,q inductance from separate measurement of phase inductance and mutual inductance. And also some other test methods like finding maximum inductance in different rotor position[5].

A.3.2 Principals of Proposal d and q Inductance Measurement

From Fig.1, proposed circuit is described. There are two main points: short-circuit b-phase and c-phase, and chirp signal as input voltage source between a-phase and b-c-phase. In accordance with the specific wiring diagram of the measured impedance, decoupling analysis of PMLSG is done, then the equivalent impedance model is derived. After measuring inductance between the a-phase and bc-phase in different frequency ranges, from analysis of frequency response, d and q inductance can be calculated.

Compared to previous test method, proposed measurement has its merits: 1) Observation mover magnetic pole position is unnecessary. 2) Measurement of mover magnetic flux is unnecessary. 3) Simple experiment platform using basic measurement equipment.

Inductance and magnetic linkage model of PMLSG eq. (A.6) -(A.9) can be obtained from modification of Electrical Excitation Synchronous Motor[6]. In table.2, definition of symbols is explained.

Three-phase self inductance can be described as:

$$\begin{cases} L_{\mathrm{aa}} = L_{\mathrm{aa0}} + L_{\mathrm{a1}} + L_{\mathrm{g2}}\cos 2\theta_e \\ L_{\mathrm{bb}} = L_{\mathrm{bb0}} + L_{\mathrm{b1}} + L_{\mathrm{g2}}\cos(2\theta_e + 2\pi/3) \\ L_{\mathrm{cc}} = L_{\mathrm{cc0}} + L_{\mathrm{c1}} + L_{\mathrm{g2}}\cos(2\theta_e - 2\pi/3) \end{cases} \tag{A.6}$$

Three-phase mutual inductance

$$\begin{cases} M_{\mathrm{ab}} = M_{\mathrm{ba}} = -L_{\mathrm{aa0}}/2 + L_{\mathrm{g2}}\cos(2\theta_e - 2\pi/3) \\ M_{\mathrm{bc}} = M_{\mathrm{cb}} = -L_{\mathrm{aa0}}/2 + L_{\mathrm{g2}}\cos 2\theta_e \\ M_{\mathrm{ac}} = M_{\mathrm{ca}} = -L_{\mathrm{aa0}}/2 + L_{\mathrm{g2}}\cos(2\theta_e + 2\pi/3) \end{cases} \tag{A.7}$$

Mutual inductance between stator and rotor

$$\begin{cases} L_{\mathrm{af}} = L_{\mathrm{sr}}\cos\theta_e \\ L_{\mathrm{bf}} = L_{\mathrm{sr}}\cos(\theta_e - 2\pi/3) \\ L_{\mathrm{cf}} = L_{\mathrm{sr}}\cos(\theta_e + 2\pi/3) \end{cases} \tag{A.8}$$

When the d axis coincides with one phase, the mutual inductance between this phase of the stator and the rotor reaches the maximum as L_{sr}.

From eq. (A.6), (A.7), (A.8), armature magnet flux can be represented by the following equation:

$$\begin{bmatrix} \psi_{\mathrm{a}} \\ \psi_{\mathrm{b}} \\ \psi_{\mathrm{c}} \end{bmatrix} = \begin{bmatrix} L_{\mathrm{aa}} & M_{\mathrm{ab}} & M_{\mathrm{ac}} \\ M_{\mathrm{ba}} & L_{\mathrm{bb}} & M_{\mathrm{bc}} \\ M_{\mathrm{ca}} & M_{\mathrm{cb}} & L_{\mathrm{cc}} \end{bmatrix} \begin{bmatrix} i_{\mathrm{a}} \\ i_{\mathrm{b}} \\ i_{\mathrm{c}} \end{bmatrix} + \begin{bmatrix} L_{\mathrm{af}} \\ L_{\mathrm{bf}} \\ L_{\mathrm{cf}} \end{bmatrix} i_{\mathrm{f}} \tag{A.9}$$

The magnet flux caused by permanent magnet can be represented by the following:

$$\psi_{\mathrm{f}} = L_{\mathrm{sr}} i_{\mathrm{f}} \tag{A.10}$$

After d q alternation,

$$\begin{cases} L_d = (3L_{aa0} + 2L_{a1} + 3L_{g2})/2 \\ L_q = (3L_{aa0} + 2L_{a1} - 3L_{g2})/2 \end{cases} \tag{A.11}$$

From this equivalent circuit Fig. A.2, equivalent circuit equations can be described as:

$$\begin{cases} U_b = U_c \\ I_a + I_b + I_c = 0 \\ Z_{a-bc} = \dfrac{U_{a-bc}}{I_a} \end{cases} \tag{A.12}$$

Use Equations (A.6),(A.7), in s-domain,

$$Z_{a-bc} = \frac{3(R + sL_d)(R + sL_q)}{2R + s[(L_d + L_q) - (L_d - L_q)\cos 2\theta]} \tag{A.13}$$

When θ=0°,

$$Z_{a-bc} = 1.5(R + sL_d) \tag{A.14}$$

When θ=90°,

$$Z_{a-bc} = 1.5(R + sL_q) \tag{A.15}$$

L_d and L_q can be calculated from above.

A.3.3 Simulation Studies of d,q Inductance Measurement

1) Simulink Test Using Chirp Signal as Voltage Source

In order to set input voltage to be rich in frequency contained, it is a good way to input a chirp signal voltage[7]. Chirp Signal is a sinusoidal wave that increases in frequency linearly over time.

$$f(t) = f(0) + kt \tag{A.16}$$

In spectrum, it has good performance of average energy in frequency scale. According to the frequency spectrum of chirp signal, it can be known that in the frequency scale, amplitude is the same for each frequency.

Chirp signal is set to change from 0.1Hz to 200Hz in 0.1s. Then I can get $I_a(t)$ and $U_a(t)$ in time response. The sampling interval T is 1e-4s, and observation time is 0.2499s.

2)Results of simulation studies

Amplitude of a-phase voltage U_a stays the same because U_a is 2/3 of $U_{a\text{-}bc}$. But amplitude of I_a declines because ωL increases with frequency increase. In order to obviously observe response of I_a, U_a with different frequencies, we use Fast Fourier Transformation to analyze I_a and U_a in frequency domain. Using the frequency response of I_a and U_a, we can draw bode graph showing frequency response of RL-circuit. From Fig.A.3, it can be known that the frequency at -3dB is 36Hz.

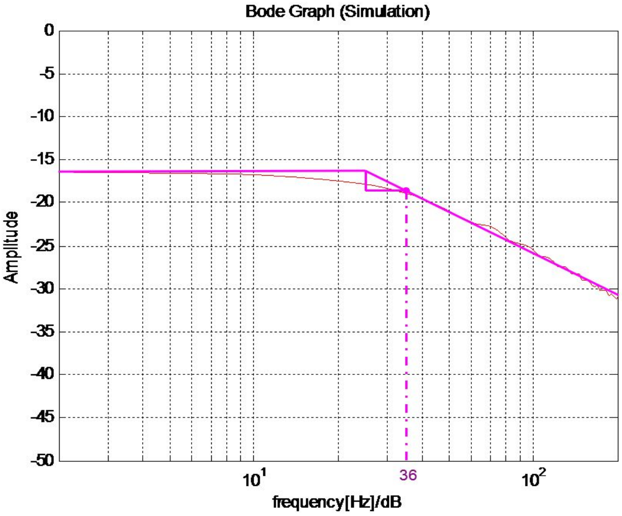

Fig. A.3 Amplitude- frequency characteristics bode graph

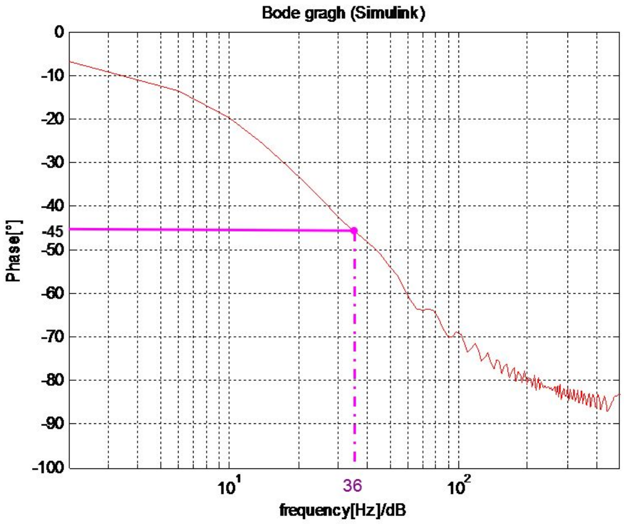

Fig. A.4 Phase- frequency characteristic bode graph

When ω is very small,

$$\omega << \frac{1}{\tau} = \omega_c, L(\omega) = -16\text{dB} \qquad (17)$$

From eq. (A.17), angle frequency which is wanted can be found on minus 3dB point.

$$\omega = \frac{1}{\tau} = \omega_c, L(\omega) = -16\text{dB} - 3\text{dB} = -19\text{dB} \qquad (18)$$

$$\frac{1}{\tau} = \omega_c = 2\pi f = 2\pi * 36 = 226.2 \qquad (19)$$

Because armature resistance is measured to be 4.24Ω, inductance can be calculated:

$$\frac{1}{\tau} = \frac{R}{L} = 226.2 \Rightarrow L = 19\,\text{mH} \qquad (20)$$

In phase bode graph Fig.A.4, phase 45° point also shows wanted frequency is 36Hz. Also for theoretical d and q inductance in simulink set-up is 19mH, it is certified to calculate d and q inductance in required frequency point.

A.3.4 Experiment Studies of d,q Inductance Measurement

1) Comparison Experiment with Previous Test Method

For ACstandstill measurement, mover is fixed on different electric angle position, and d and q inductance are calculated from measuring self-inductance and mutual inductance. As comparison, we just use proposal equivalent circuit but do not use chirp signal and keep same a-phase current with ACstandstill measurement. Both experiments are tested under frequency of 20, 50, 100Hz.

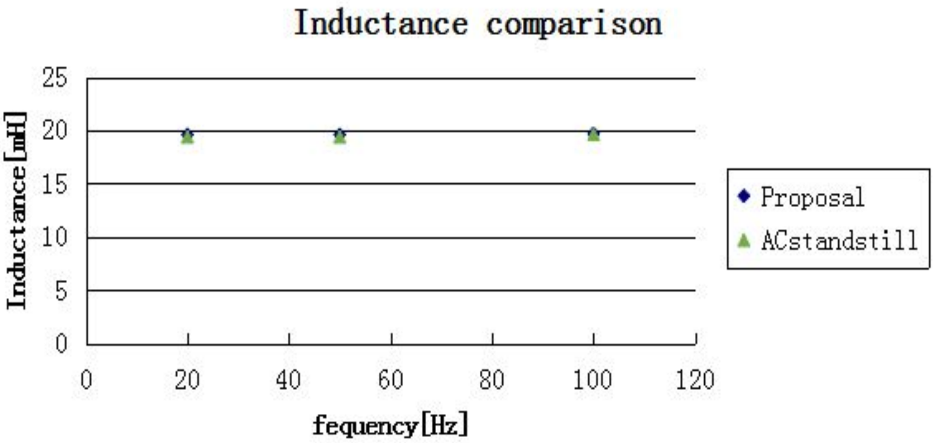

Fig. A.5 Comparison experiment with previous test method

From inductance data, it shows that d inductance and q inductance are almost the same, because for this PMLSM, it has characteristics similar to non-salient motor. From Fig.A.5, it can be observed that d inductance of these two methods are very close under 0.5% of d inductance.

2) Experiment Platform for Proposed Test Method

Experiment Equipment can can be described from main four parts from Fig.A.6:

(1) Function Generator: providing voltage source as chirp signal.

(2) Amplifier: Voltage from function generator is amplified and be put into circuit as $U_{a\text{-}bc}$.

(3) PMLSG: armature coils of b,c phase are short-circuit.

(4)Oscilloscope: Two channels of oscilloscope are used--CH1 shows voltage $U_{a\text{-}bc}$; CH2 shows voltage on added resistance (because I_a cannot be directly observed from oscilloscope, so a very small resistance 0.5Ω is series connected in a-phase to calculate current I_a).

Mover of PMLSG is fixed and chirp signal is set up changing from 0.1Hz to 20, 30, 40, 50, 60, 80, 100, 150, 200Hz in 0.1s. Then $I_a(t)$ and $U_a(t)$ in time response can be obtained. The sampling interval T is 1e-4s, and observation time is 0.2499s.

Table A.2. Comparison of conditions and inductance data in different cases

Case	Condition	d Inductance (mH)
Theoretical	R=4.24Ω	19
Simulation of proposal test method	R=4.24Ω; chirp signal frequency 0.1-200Hz; sampling interval T is 1e-4s, and observation time is 0.2499s	19
Ac Standstill Test	R=4.24Ω; Position on electrical degree of 0°, 45°, 90°; Voltage frequency of 20, 50, 100Hz; Ia= 1A	19
Proposal circuit by point measurement	R=4.24Ω; Position on electrical degree of 0°, 90°; Voltage frequency of 20, 50, 100Hz; Ia= 1A	19
Proposal test method using chirp signal	R=4.24Ω; chirp signal frequency 0.1-20, 30, 50, 60, 80, 100, 150, 200Hz; sampling interval T is 1e-4s, and observation time is 0.2499s	19

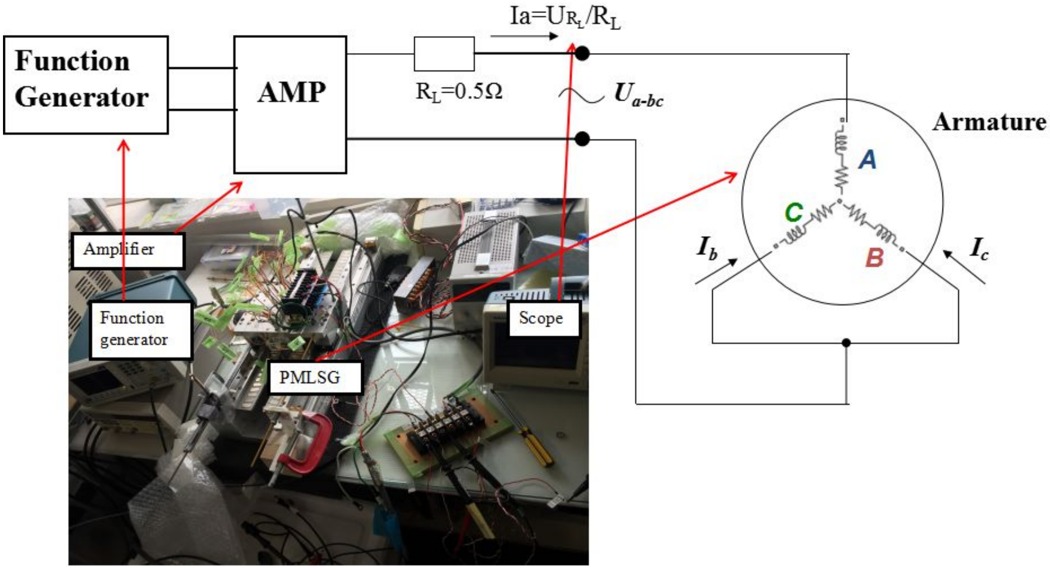

Fig. A.6. Experiment structure of proposed test method

3)Results of Experiment Studies

From Fig.A.7 and Fig.A.8, it shows that if only one curve in one frequency range is used, required frequency point can not be accurately found. But after measuring in big frequency range, the required frequency point can be mostly certain in smaller frequency range, and change maximum chirp signal frequency. If all curves in different frequency ranges are list together, fitting curve can be described and required frequency point can be found at 35Hz.

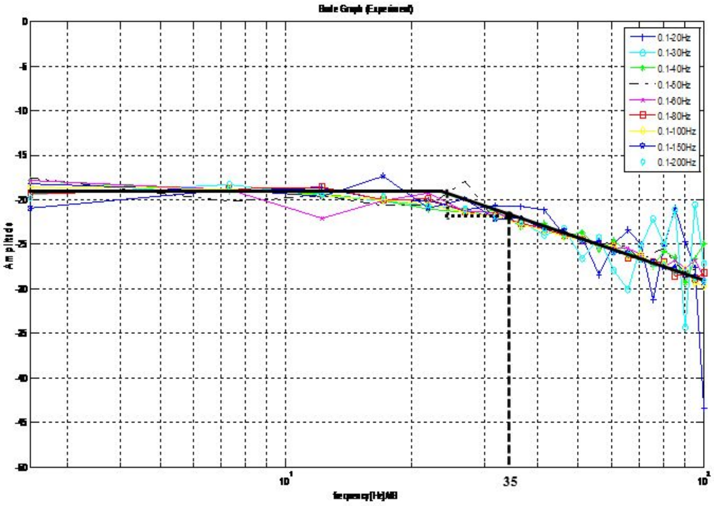

Fig. A.7 Amplitude- frequency characteristics bode graph

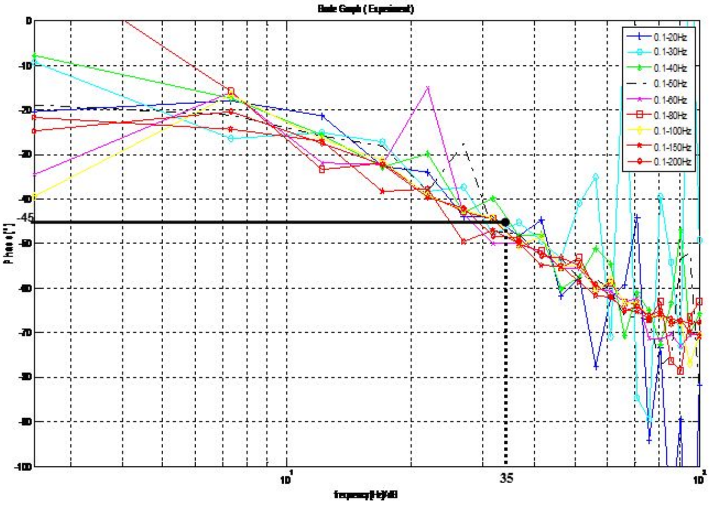

Fig. A.8 Phase- frequency characteristic bode graph

$$\frac{1}{\tau}=\omega=2\pi f=2\pi*35=219.9 \qquad (21)$$

$$\frac{1}{\tau}=\frac{R}{L}=219.9\Rightarrow L=19\mathrm{mH} \qquad (22)$$

In Fig.7, 45° point turns to show that required frequency is 35Hz. The required frequency point can be determined by combination of amplitude bode graph and phase bode graph.

From inductance data comparison table.2, simulation data is only 0.5% bigger than theoretical data, and experiment data is 3% bigger than theoretical data. Measurement error is under permitted.

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