On the design of energy storage systems to achieve wind dispatchability

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**NANYANG
TECHNOLOGICAL
UNIVERSITY**

**ON THE DESIGN OF ENERGY STORAGE
SYSTEMS TO ACHIEVE WIND
DISPATCHABILITY**

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SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING
2014**

On the Design of Energy Storage Systems to Achieve Wind Dispatchability

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Summary

Energy is essential to the growth of modern society, and fossil fuels have been accredited as the prime sources since the industrial revolution for bringing ever new levels of prosperity and human welfare. However, the emissions of greenhouse gases due to the burning of fossil fuels and with the dwindling availability of the fossil fuels, the pace to deploy renewable energy sources has hastened. Among the various renewable energy sources, wind has been shown to enjoy the most rapid growth in recent years. While the technology of wind power generation is now fairly well-established, unfortunately wind power tends to be unsteady and stochastic in nature. This is one reason why higher penetration of this form of power generation into electrical grid systems has been hampered.

Much research attention has been directed toward the mitigation of the negative impacts of the unsteady wind power generation. Various techniques have been examined and one which has shown great promise is the coupling of energy storage systems (ESS) with wind generation. Indeed, ESS can play a role in one of the three major functional categories: of enhancing power quality, providing bridging power and achieving power/energy management. Unfortunately, most ESS would not be economically viable to be applied in all categories. This is because each particular type of ESS has its distinct characteristics in terms of energy capacity and power capability. Hence, the implementation of a particular type of ESS will generally depend on the purpose of the application.

Another recent development in electricity generation is pertaining to the recent decisions by several advanced countries in phasing out nuclear power generation within the next twenty years. It means that the penetration level of wind power in these countries is expected to increase. Should this occur, wind power plant operators will be more than likely to be pressured into committing firm power dispatch in a manner similar to that provided by conventional thermal power stations. When wind power becomes dispatchable, not only less spinning reserve will need to be provided by the utilities, wind farm operators can also expect higher tariff rate from the sale of the dispatchable wind power. Consequently, it will create a more attractive proposition for the investment of the ESS.

For the purpose of achieving firm wind power dispatchability, ESS capable of fulfilling the role of power-energy management will be required.

In this connection, if the ESS is to be effective as an energy buffer to cater for any mismatch between the wind power generation and the committed power dispatch, the power and energy storage capacities of the ESS must be carefully determined during planning or design stage of the ESS. However, as planning and operational planning are closely interrelated, various operational planning issues with regard to wind power forecast error, prevailing power market rules, amongst other factors, must be taken into consideration during the design of the ESS. For example, wind power prediction techniques will be used when planning the operation of the wind farm. This is done so that an estimation of the future wind power production can be obtained since the input wind power is time-varying. Furthermore, wind power generation needs to comply with the various prevailing power market rules. Therefore, the power market rules and the inevitable wind power forecast errors must be taken into consideration during the planning stage of the ESS.

In view of the explained reasons above, a scheme is first proposed in this investigation to integrate a generic ESS within a wind farm so that firm power dispatch can be committed. The task is to determine the required ESS power and energy capacities. For this purpose, a statistical approach is adopted so that the ESS capacities can be related to the confidence level in successful power dispatch. With the ESS capacities so determined, the next focus is on the design of the dispatch strategy which is strongly related to the operational planning aspect of the wind-ESS scheme. The new dispatch strategy takes into consideration the state-of-charge of the ESS. The rationale of this strategy is to utilize the ESS more efficiently and to minimize the occurrences of the ESS being over-charged and over-discharged.

In recognizing the several distinct advantages the batteries ESS (BESS) have over other types of ESS in fulfilling the energy management role, BESS is proposed to be incorporated with wind farm to realize the aim of wind-ESS output power dispatchability. In order to maximize the harnessing of wind energy and to prevent the life span of the BESS from

being reduced to an unacceptable level, supercapacitor (SC) energy storage is used to act as a supplementary short-term ESS working in conjunction with the BESS to form a hybrid energy storage system (HESS). As the HESS expected lifetime and the probability the wind farm-HESS scheme can meet its power commitment will also be impacted by a poorly designed dispatch strategy, it is therefore prudent to design the dispatch strategy and incorporate it into the planning stage when determining the required HESS capacities. Thus, the dispatch strategy should be designed while the HESS capacities are still unknown. In this manner, the viability of the wind-HESS scheme is enhanced as the required HESS capacities so determined have been evaluated based on the designed dispatch strategy and the same dispatch strategy is also to be used later in the operational planning phase when the wind farm-HESS is in operation. Furthermore, in the design of the HESS, a proposed coordinated power flow control strategy between the BESS and SC is used together with a developed statistical method to determine the required HESS capacities and quantify the confidence level the wind farm is capable of meeting its firm power dispatch commitments. Through the minimization of a performance index which aims to reduce the cost of the HESS, the optimal HESS capacities are thereby established.

A new scheme to incorporate the design of the dispatch strategy into the planning of ESS is also proposed in this study for the integration of large-scale wind power generation into the electrical power systems. The scheme exploits the pumped-hydroelectric storage (PHS) inherently larger energy capacity and its ability to store / supply energy over long duration. The objective is again to enable the integrated wind generation-PHS system to be capable of committing firm power dispatch to the grid at specified confidence level. In the proposed scheme, however, a newly designed dispatch strategy allows the PHS to change its operation mode from charging to discharging and vice versa only when the PHS state-of-charge has reached stipulated design limit. Hence, the PHS shall undergo charge-discharge operation cyclically. In this manner, the PHS energy storage capacity is fully utilized and the expected lifetime of the PHS will not be adversely affected as a result of frequent transition between the pumping and generating modes.

The proposed approaches are therefore useful planning tools to achieve dispatchability of wind power generation so that the output power of the wind-ESS schemes can be scheduled and committed under the condition of varying and uncertain input wind power.

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List of Abbreviations

ACF	Autocorrelation function
Ah	Amp-hour throughput
BESS	Battery energy storage system
CAES	Compressed air energy storage
CDF	Cumulative probability function
DOD	Depth of discharge
ERCOT	Electric reliability council of Texas
ESS	Energy storage system
FES	Flywheel energy storage
HESS	Hybrid ESS
Hz	Hertz
Li-ion	Lithium-ion
NaS	Sodium-sulfur
NRMSE	Normalized root-mean-square error
NTU	Nanyang Technological University
PACF	Partial autocorrelation function
PDF	Probability density function
PHEV	Plug-in hybrid electric vehicle
PHS	Pumped-hydroelectric storage
P.U.	Per-unit
PV	Photovoltaic
RES	Renewable energy sources
RMSE	Root-mean-square error
SC	Supercapacitor energy storage
SMES	Superconducting magnetic energy storage
SOC	State-of-Charge
WTG	Wind turbine generator

List of Symbols

φ_a	Weighing factor of the average level component; $0 \leq \varphi_a \leq 1$
ψ_b	Weighing factor of the slope component; $0 \leq \psi_b \leq 1$
γ_ξ	Weighing factor of the seasonal component; $0 \leq \gamma_\xi \leq 1$
$\xi(t)$	Smoothed estimate of the seasonal component determined at time period, t
$\xi(t-1)$	Old smoothed estimate of the seasonal component determined at time period, $t-1$
φ_i	i^{th} parameter of the autoregressive (AR) component
θ_j	j^{th} parameter of the moving average (MA) component
μ	Average level component of the ARMA model
$\mu_{\omega e}$	Mean value of wind speed forecast error
μ_{p_e}	Mean value of wind power forecast error
ω	Wind speed
ω_e	Wind speed forecast error
$\sigma_{\omega e}$	Standard deviation of wind speed forecast error
σ_{p_e}	Standard deviation of wind power forecast error
$\tau_{P,C}$	Charging time of the PHS
$\tau_{P,D}$	Discharging time of the PHS
ΔE	Change in the ESS stored energy level
α	Maximum ramp-up rate of BESS power
β	Maximum ramp-down rate of BESS power
η_P	Cost/day of implementing PHS
AC	Annualized HESS capital cost
$a(t)$	Smoothed estimate of the average level component determined at time period, t
$a(t-1)$	Old smoothed estimate of the average level component determined at time period, $t-1$
$Ah_{B,Ts}$	Total discharge amp-hour throughput
Ah_j	Amp-hour throughput at j^{th} -interval
Ah_r	BESS rated amp-hour

AR_B	Annualized replacement cost for the BESS
AR_S	Annualized replacement cost for the SC
$b(t)$	Smoothed estimate of the slope component determined at time period, t
$b(t-1)$	Old smoothed estimate of the slope component determined at time period, $t-1$
B_P	Remuneration of wind farm operators using PHS
B_W	Remuneration of wind farm operators without using PHS
C	Capacitance
c_1	Cost per MW of the PHS
c_2	Cost per MWh of the PHS
$C_{B,n}$	BESS cycle life at rated conditions
$C_{B,Ts}$	BESS service cycle life
C_{IH}	Higher tiered generation imbalance charge
C_{IL}	Lower tiered generation imbalance charge
C_P	Total energy subjected to imbalance charges
C_{PHS}	Capital cost of PHS
$C_{P,n}$	PHS cycle life at rated conditions
CRF	Capital recovery factor
$C_{S,n}$	SC nominal cycle life at rated conditions
$C_{S,Ts}$	SC service cycle life
$d_{B,max}$	Maximum allowable DOD of BESS
$d_{P,max}$	Maximum allowable DOD of PHS
$d_{S,max}$	Maximum allowable DOD of SC
$E\{\cdot\}$	Expected value of $\{\cdot\}$
$E(t)$	Actual stored energy level in the ESS at time period, t
$E_B(t)$	Energy level of the BESS at time period, t
E_{B_R}	BESS energy capacity
$E_{H,\tau}$	Energy subjected to higher tiered imbalance charge in τ -interval
$E[L_B]$	Expected life of the BESS

$E[L_p]$	Expected life of the PHS
$E[L_s]$	Expected life of the SC
E_{min}	Minimum stored energy level of the ESS
E_{P-R}	PHS energy capacity
E_{PU}	ESS SOC level
E_R	ESS energy capacity
$E_S(t)$	Energy level of the SC at time period, t
$E_{S,k}$	Discharged energy for the SC at k^{th} -interval
E_{S-R}	SC energy capacity
$E_{S,Ts}$	Total discharge energy of the SC
$F'(\bullet)$	First derivative of $F(\bullet)$
f	Performance index of HESS
G	Gain factor
g	Performance index of PHS
I	Interest rate
K	Constant parameter for particular WTG
k_1	Cost per MW of the BESS
k_2	Cost per MWh of the BESS
k_3	Cost per MW of the SC
k_4	Cost per MWh of the SC
N_c	Total PHS full charge/discharge cycles over T_s
$\hat{P}(t+1)$	New forecasted value for next time period (made in present time period, t)
$\hat{P}(t)$	Forecasted value for present time period (made in last time period, $t-1$)
$P(t)$	Actual value in present time period, t
$\left[P(t) - \hat{P}(t) \right]$	Forecasting error for present time period
$P_B(t)$	BESS output power at time period, t
$P_{B,r}(t)$	BESS reference output power at time period, t
$P_{B,R}$	BESS power rating

$P_d(t)$	Constant dispatch power at time period, t
$P_{d,r}(t)$	Reference constant dispatch power at time period, t
$P_E(t)$	ESS output power at time period, t
$P_{E,r}(t)$	ESS reference output power at time period, t
$P_{E,R}$	ESS power rating
$P_{f_L}(t)$	Low frequency components of $P_{W,f}(t)$
$P_{f_LC}(t)$	Low frequency components of $P_{W,fc}(t)$
$P_{f_LL}(t)$	Low frequency components of $P_{W,fl}(t)$
$P_{f_LU}(t)$	Low frequency components of $P_{W,fu}(t)$
$P_{H,o}(t)$	Aggregated HESS output power at time period, t
$P_{H,r}(t)$	Aggregated HESS reference output power at time, t
$P_L(t)$	Low frequency of components of $P_W(t)$
$P_M(t)$	Intermediate frequency of components of $P_W(t)$
$P_p(t)$	PHS output power at time, t
$P_{p,r}(t)$	PHS reference output power at time, t
$P_{P,R}$	PHS power rating
P_r	Rated WTG power
$Prob(\bullet)$	Probability of condition $(\bullet)$ being satisfied
$P_S(t)$	SC output power at time period, t
$P_{S,r}(t)$	SC reference output power at time period, t
$P_{S,R}$	SC power rating
$P_W(t)$	WTG output power at time period, t
$P_{W,f}(t)$	Wind power forecast at time period, t
$P_{W,fc}(t)$	Central band of wind power forecast at time period, t
$P_{W,fl}(t)$	Lower band of wind power forecast at time period, t
$P_{W,fu}(t)$	Upper band of wind power forecast at time period, t
$SOC(t)$	State-of-Charge of ESS at time period, t
$SOC_B(t)$	State-of-Charge of BESS at time period, t
$SOC_P(t)$	State-of-Charge of PHS at time period, t

List of Symbols

$SOC_s(t)$	State-of-Charge of SC at time period, t
TC	Total HESS capital cost
T_s	Study period
T_{WF}	Service life span of the wind farm
V_s	Terminal voltage of the SC
$V_{s,min}$	Minimum voltage across SC terminal
$V_{s,nom}$	Nominal voltage of the SC

Chapter 1: Introduction

1.1 Background and Motivation

Fossil fuels have been considered to be of prime importance for the growth of the modern society since the industrial revolution. However, the extensive burning of fossil fuels produces large amount of carbon dioxide and other greenhouse gases which in turn contribute to global warming [1]. At the same time, with the increase in human population and standard of living, the world consumption of electrical energy is projected to increase by more than 70% from 13, 290 billion kWh in 2005 to 23, 702 billion kWh in 2025 [2]. In order to meet the ever-increasing energy demand coupled with the dwindling availability of the conventional hydrocarbon resources, alternative environmentally-friendly energy sources are to be developed so that a reliable and sustainable energy supply can be attained [3].

Thus with the broad consensus that the world should shift to low-carbon or zero-carbon energy sources so that the ill-effects of climate change can be mitigated, renewable energy sources are increasingly being integrated into electric supply systems. Additionally, governments have established various measures and targets to further encourage the adoption of renewable power generation. For example: there are specific requirements that new housing must incorporate solar collectors for water heating in countries such as Greece and Israel, and the European Union has set a goal that 20% of its total electricity generation will come from renewable energy sources by 2020. Among the various renewable sources, wind power generation is seen to enjoy the most rapid growth, at an average annual cumulative rate of over 25% during the last ten years [4]. On some very windy sites, wind farms are able to produce energy at costs comparable to those of the most economical traditional generators [5]. With the advances in this technology, the largest wind turbine generator (WTG) currently has a rated capacity of 8-MW, an overall tower height of 220 m, and a blade length of about 80 m [6]. Additionally, due to economy of scale from mass production and the accumulated experience, large-scale integration of wind generation into the grid systems can now be found in many parts of the world [7]. Indeed, wind power will

most likely continue to make the greatest contribution to electricity production among the renewable sources over the next decade.

Unfortunately, and similar to most renewable energy sources, wind is stochastic in nature. Wind velocity is highly affected by the weather, climatological conditions, amongst other factors. Wind is therefore generally intermittent and variable. As the power in the wind varies as the cube of the wind speed, variations in the wind speed will appear as fluctuations in the generated wind power. Even though it is possible to rely on the actions of the WTG pitch angle control and the associated power converters to realize a more controllable form of the WTG output power, the control methods would not allow the full harnessing of the energy from the wind. They may also reduce the lifetime of the WTG, as a result of wear and tear from the frequent utilization of the pitch angle control and associated mechanism.

The concern over the unsteady wind power impacting negatively on the reliability and security of the electrical grid remains one major impediment to the large-scale penetration of wind generation into grid systems. Adding to the dilemma of deploying wind, several advanced countries have recently announced the decision to retire nuclear power generation within the next 20 years or so. If the decisions were to eventuate, it is perceived the penetration level of wind generation into the grids would have to increase unless other forms of viable and sustainable energy sources come on stream. Presently, wind power productions are often given dispatch priority over conventional power generation and thus, the wind power generators do not need to participate in modern electricity markets in the manner expected of conventional electrical power producers. However, when the proportion of wind generation in the grid system becomes substantial, it will be more than likely that the wind farm operators will be pressured to provide firm power dispatch in a manner similar to that currently required from the conventional power stations.

In view of the above considerations and to allow a larger penetration of wind generation to be integrated into the electric grids, the shortcomings associated with the variability of the wind power must be overcome. Prior to investigating how this could be achieved, it is necessary to firstly gain some insights into the characteristics of the wind. For this purpose,

the first part of Chapter 2 provides a literature review on wind characteristics as viewed from the time and frequency domains. Furthermore, since the input wind power is time-varying, wind forecasting techniques will need to be used to obtain an estimation of the future wind power production when planning the operation of the wind farm. Unfortunately, as there is no perfectly accurate wind forecasting technique, there shall be the inevitable wind forecasting errors. Hence, the relationship between the prediction error distributions of wind speed and wind power will also be closely examined in this chapter.

Among the different solutions to alleviate the negative impacts of the varying wind power generation, a possible method that has been identified by many researchers is through the use of energy storage system (ESS). However, each type of ESS has its unique characteristic, and the implementation of particular type of ESS depends very much on the intention of the application. Fortunately, various technical constraints on integrating ESS in large-scale utility applications have been steadily circumvented through advances made in energy storage and power electronic technologies. For example, ESS is used as a voltage sag compensator in [8] to improve the quality of the voltage supply while in [9], ESS is considered for the purpose of load leveling. Some other roles in which the ESS have been used with wind renewable are to enhance the low voltage ride through capability of the WTG as described in [10], limit the ramp-rate of the wind power fluctuations [11], support local load demands in an autonomous power system [12], or even decouple the timing of the generation and the delivery of the electrical energy [13]. Besides the above contributions, the use of ESS allows the WTG to meet the electric grid codes requirements which in turn also helps to hasten the adoption of wind renewable energy. Detailed information regarding the various types of ESS, their characteristics and suitability in the various utility applications will be reviewed in the second part of Chapter 2.

As explained afore, wind power producers will need to provide firm power dispatch commitments when higher penetration of this intermittent resource is integrated into an electric grid. When wind power achieves the objective of firm power dispatchability similar to that provided by conventional thermal power stations, the overall power production cost of the grid system can be reduced as the grid will then only need to carry a lower spinning

reserve and the wind farm operators can also expect higher tariff rate from the sale of the dispatchable power by participating in modern electricity market. For wind to achieve firm power dispatchability using ESS, the power and energy storage capacities of the ESS need to be considered judiciously in the planning phase. This is because the effectiveness of the ESS to cater to any mismatch between the wind power generation and the committed power schedule during the later operational planning stage can be directly impacted by the ESS power and energy storage capacities. Herein lies the two aspects to the design of any wind-ESS scheme: planning and operational planning. The main aspect in the wind-ESS planning will be to determine the required ESS power and energy capacities and this is in contrast to that of the operational planning where the ESS capacities are already known or fixed and the concern is on the design of the dispatch scheme. In order for the wind generation to be controllable and schedulable, it is necessary that one must take into account the various essential rules of the prevailing power market in which the wind farm is to operate in during the planning or design stage of the wind-ESS scheme. In this regard, the basic rules pertaining to the general electric power markets shall be briefly discussed in Chapter 3.

For the purpose of wind-ESS planning, three possible schemes will be proposed in this study. The first scheme introduces a basic approach to determine the required capacities of a generic ESS to be integrated within a wind farm. However, recognizing that batteries ESS (BESS) have several distinct advantages over other types of ESS, BESS is used as the primary ESS in the second proposed scheme to harness most of the energy in the wind. With the aims to maximize the harnessing of the wind energy and to prevent the BESS life span from being adversely affected, supercapacitor (SC) energy storage acting as a supplementary short-term ESS is used in conjunction with the BESS to form a hybrid energy storage system (HESS). Recognizing the HESS expected lifetime and the likelihood the wind farm-HESS scheme can meet its power commitment will also be impacted by a poorly designed dispatch strategy, the design of the dispatch strategy is incorporated in the planning technique to determine the required HESS capacities. By doing so, the dispatch strategy is designed while the HESS capacities are still unknown. In this manner, the viability of the wind-HESS scheme is enhanced as the required HESS capacities so

determined would have been evaluated based on the designed dispatch strategy and the same dispatch strategy is also to be used later in the operational planning phase when the wind farm-HESS is in operation. Furthermore, in the design of the HESS, a proposed coordinated power flow control strategy between the BESS and SC is used in conjunction with a developed statistical method. This is with the view to determine the required HESS capacities and to quantify the confidence level the wind farm is capable of meeting its firm power dispatch commitments. Through the minimization of a performance index intended to reduce the cost of the HESS, the optimal HESS capacities are thereby established.

For the likely scenario in which future large-scale wind generation is integrated into an electrical power system within a large geographical area, the third scheme similarly incorporates the design of the dispatch strategy in the planning phase. However, this scheme exploits the inherently larger energy capacity of the pumped-hydroelectric storage (PHS) and its ability to store / supply energy over relatively longer duration. In this scheme and using a newly designed dispatch strategy, not only can the optimal PHS capacities be evaluated, it also enables the PHS to make full use of its store energy capacity during each of the pumping and generating operations. It thus ensures longer PHS life span.

1.2 Major Contributions

The main contributions of this study can be summarized as follows.

- 1. Determination of energy storage system and the significant frequency components of the wind power.** – In power system applications, energy storage systems (ESS) can be deployed in one of the three major functional categories as explained earlier. By analyzing the wind power profiles in the frequency domain as described in Chapter 2 and identifying the significant frequency components in the wind power, the choice of energy storage mediums suitable for wind generation can be made. Besides wind, this approach is applicable to other renewable energy sources.
- 2. Mathematical analysis of wind power prediction error distribution.** – Knowing the mean (μ_{Pe}) and standard deviation (σ_{Pe}) of the wind power forecast error shall allow one to evaluate the confidence level the actual wind power will be within the band $\pm r \cdot \sigma_{Pe}$ from μ_{Pe} . Unfortunately, even if the probability distribution function of the wind speed prediction error is Gaussian, using the wind turbine output power characteristic curve and the predicted wind speed to predict the output wind power does not yield a Gaussian distribution in the error of the predicted wind power. In order to obtain the corresponding mean and standard deviation to quantify the wind power forecast error, an analysis of the wind power prediction error distribution has been made in this work. The details of this contribution will be elaborated in Chapter 2.
- 3. Analysis of a wind generation-ESS scheme to achieve firm power dispatchability.** – A scheme to integrate a generic ESS within a wind farm is proposed in Chapter 3. The purpose of the scheme is so that firm power dispatch commitment can be provided to the grid. The power dispatch problem is examined from two aspects: planning and operational planning. In the planning phase, the required ESS capacities are determined because they have direct impact on both the

economics of the ESS and the effectiveness of the ESS to function as an energy buffer. For operational planning, the design of a short-term power dispatch strategy which takes into account the state-of-charge (SOC) of the ESS is presented. The rationale for designing the strategy is to ensure the capacity of the ESS is efficiently utilized and to minimize the occurrences of the ESS being over-charged and over-discharged.

4. Design of a least-cost battery-supercapacitor energy storage system to realize dispatchable wind power.

– For wind power installation of the scale of a wind farm, battery ESS (BESS) has been a popular choice as it is able to store considerable amount of energy and it is more versatile compared to other long-term ESS. However, the fluctuations in the wind power are such that BESS is unsuitable to be the only ESS medium used to smooth the fluctuating wind farm output power. Therefore, the design in Chapter 4 exploits the technical merits of both the BESS and supercapacitor (SC) energy storage, in terms of the differences in their specific power and energy densities, and their ability to accommodate different rates of change in the charging/discharging powers. The BESS and SC shall form a hybrid ESS (HESS). This is done so as to maximize the harnessing of wind energy and to prevent the BESS life span from being adversely affected. Most of the reported works in this area separate the design of the HESS from the operational planning of the wind farm-HESS, even though both aspects are closely interrelated. In view of this shortcoming, the dispatch strategy is designed while the HESS capacities are still unknown and it is incorporated in the planning technique to determine the required HESS capacities. Furthermore, in the design of the HESS, a new coordinated power flow control scheme between the BESS and SC is used together with an improved statistical planning technique. With the proposed approaches and through the minimization of a performance index, the least-cost HESS capacities are determined.

5. Pumped-hydroelectric storage scheme to achieve power dispatchability of large-scale wind generation.

– For large-scale wind generation which spans across

a large geographical area, pumped-hydroelectric storage (PHS) is a more suitable ESS option due to its larger energy capacity as compared to the BESS. Although the objective is again to enable the integrated wind generation-PHS system to be capable of committing firm power dispatch to the grid at specified confidence level, the approach adopted in this instance is different from that of (3) and (4) above. First, a newly developed dispatch strategy allows the PHS to undergo complete charge-discharge cycle, thereby fully utilizes the PHS energy storage capacity and prevents the PHS lifetime from being adversely affected. Then a statistical approach is applied to the design of the power dispatch strategy for the combined wind generation-PHS system such that the short-term dispatch can be committed at given confidence level. Finally, a computational method which takes into account the expected net benefit and the lifecycle cost of implementing the PHS is developed to evaluate the optimal PHS capacities.

1.3 Organization of the Thesis

This thesis is organized as follows. The motivations and objectives of the studies in the thesis are summarized in Chapter 1.

Chapter 2 begins by describing the characteristics of the wind and its frequency spectrum. Next, the necessity and requirements of wind power prediction is briefly introduced. Subsequently, the relationship between the statistical distributions of the prediction errors of wind speed and wind power will be explained and analyzed. Finally, a brief literature review is included on the different types of ESS, their characteristics and their roles in various utility applications, as well as current research works in integrating ESS with renewable wind power generation.

A proposed scheme to integrate a generic ESS within a wind farm so that firm power dispatch commitment can be provided to the grid is described in Chapter 3. In this scheme, two aspects of the design will be dealt with: that for planning and for operational planning. In order for wind power generation to participate in power dispatch in modern electricity

markets, the typical power market rules are first introduced. Next, the determination of the ESS capacities is considered by taking into account the various operational issues and the accuracy of the wind power prediction. Finally for operational planning, the design of a short-term power dispatch strategy for the wind farm is presented.

In Chapter 4, a battery ESS (BESS) and supercapacitor (SC) energy storage are combined to form a hybrid ESS (HESS) which is then integrated with a wind farm. The purpose of the design is to achieve power dispatchability. In the scheme, the BESS with its inherently larger specific energy density, is applied to harness most of the energy in the wind while the rapid fluctuating power components are diverted to the SC. By doing so, the scheme exploits the desirable attribute of the SC in that it has a much higher cycle life as compared to the BESS. Besides prolonging the BESS life span, this approach concurrently addresses the concern on power dispatch/energy management as well as that on power quality. The BESS is to participate in the energy management function and allows power to be committed several hours or even a day ahead, while the SC is to mitigate shorter-term power quality issues. The HESS allows the maximum harnessing of the wind energy.

The emphasis of Chapter 5 is to use pumped-hydroelectric storage (PHS) with its larger energy capacity to achieve dispatchability for large-scale wind power generation. Specifically, a statistical approach is proposed to determine the required capacity of the PHS in which the PHS is to be integrated into a power system containing a number of wind farms dispersed over a large geographical area. For the design of the dispatch strategy, besides allowing the combined wind generation-PHS to meet power dispatch at specified confidence level, the PHS is also to operate in a cyclic manner thereby fully utilizing the PHS energy storage capacity in each of the pumping and generating operations.

Finally, the conclusions of the thesis and proposed future works are summarized in Chapter 6.

Chapter 2: Grid Integration Issues Pertaining to Wind Power Generation - a Literature Review

Wind power generation is seen to enjoy the most rapid growth among the various renewable energy sources in recent years. Unfortunately, wind is generally unsteady and often intermittent. In order to increase the penetration of wind power generation into the electric power system, the negative impacts of wind on grid systems as explained in Chapter 1 requires much further attention. In view of this, this chapter provides a brief review on several issues pertaining to wind power integration, viz., the characteristics of wind power, advancements made in forecasting wind power, energy storage systems (ESS) as well as the applications of ESS on mitigating the negative effects of this renewable energy resource.

The organization of this chapter will be as follows: Wind characteristics and its frequency spectrum are explained in Section 2.1. Next, a brief introduction to the necessity and requirements of wind power prediction is presented in Section 2.2. Two examples of established linear wind power forecasting methods will also be described. Subsequently, the relationship between the prediction error distributions of wind speed and wind power will be closely examined. Section 2.3 contains a brief review on energy storage systems as well as their applications in power systems. Additionally, some recent works regarding the use of ESS to integrate renewable wind power generation into the grid systems will also be included in this section.

2.1 Wind power variability and spectrum

Wind is a result of differences in atmospheric pressure. When there is a difference in the atmospheric pressure, air moves from a higher to lower pressure region thus resulting in wind. However, owing to factors such as ground roughness, temperatures and rotation of the earth, among others, the speed and direction of the wind vary continuously. Fig. 2-1 shows the spread of daily wind speed averages measured at the author's university for each month of year 2010.

Fig. 2-1 Spread of daily wind speed averages (measurements taken at NTU Block S2 rooftop) for each month of year 2010

From Fig. 2-1, it is seen that even in Singapore where there is no distinct seasons and at a given location, the average wind speed is different from day-to-day. Since wind speed is continuously varying and as the power in the wind varies as the cube of wind speed [7], the variations in the wind speed will appear as larger fluctuations in the generated wind power. This phenomenon is easily seen from Fig. 2-2 which shows the wind speed and wind power captured at the author's university for the month of December 2010.

Fig. 2-2 (a) Wind speed and (b) wind power measured at NTU Block S2 roof-top, Dec. 2010

The seemingly random variations of the wind speed and power warrant close examination, with the view to gain better insights into the phenomenon. Besides representing the fluctuating wind profiles in the time-domain, such as that depicted in Fig. 2-2, it is also

possible to express the variations in the frequency domain. An example of this latter approach, applied to the wind power-time profile of Fig. 2-2(b), is as shown in Fig. 2-3.

Fig. 2-3 Wind power spectrum as derived from the wind power profile of Fig. 2-2(b)

Fig. 2-3 shows the wind power spectrum, obtained from the Fourier transform of the time-domain plot of Fig. 2-2(b), with the magnitude of the wind power plotted against frequency. It can be readily seen from Fig. 2-3 that the low frequency components are of much larger magnitude as compared to those over the higher frequency band. Specifically, the higher frequency turbulences and fluctuations (synoptic variations) are not apparent in this example. From Fig. 2-3, it is seen that the three largest components are the DC, 24 hours/cycle and 12 hours/cycle components. In fact, upon the examination of the various wind power spectra obtained from many sites (Singapore Changi Airport, Washington USA, etc.), it was found that they all share similar characteristics as noted above, i.e. most of the wind energy is contained in the low-frequency power components instead of in the forms of the higher frequency turbulences and fluctuations. These observations were also established by the authors of [14, 15, 16]. Therefore, in view of this characteristic of the wind power, attention should be directed toward the low frequency band of the wind power if the intention is to maximize the harnessing of the wind energy. Pertaining to this aspect, a scheme capitalizing on the low frequency components of the wind power for large-scale wind generation so as to achieve short-term power dispatchability will be the focus of the research in Chapter 5. Specifically, the research focus of the thesis will be on utilizing energy storage systems (ESS) to achieve the wind dispatchability objective. For the

selection of the appropriate type of ESS for particular grid-wind power system application, analyzing the wind power profile in the frequency domain shall be the starting point of this investigation, as shall be explained later in this chapter.

2.2 Wind power forecast

Unlike power produced in conventional power stations, power harnessed from the wind fluctuates with time. Consequently, power system operators need to allocate additional regulating reserves to prevent the unsteady wind power from adversely impacting the reliability and security of the grid systems [17, 18]. To facilitate the integration and to increase the penetration level of wind generation into electric grid systems, accurate prediction of wind power is clearly most desirable. However, currently there is no perfectly accurate wind forecasting technique.

While the present investigation is not into wind power forecasting per se, it is nevertheless important to provide a brief review of the technology in this chapter as such forecasts would be relied on in the schemes to be described in latter chapters. Specific requirements on wind power prediction systems vary considerably and are dependent on the distribution of the wind turbines and the specific market the turbines are operating in. For example, EDF (Electricite de France) requires a-day ahead as well as a-week ahead forecast. On the other hand, the spot market under the British NETA (New Electricity Trading Arrangement) closes only one hour before the time of power delivery, therefore British wind power producers will only require one-hour ahead predictions [7]. Besides the different time-spans the forecasts will cover, different time resolutions (e.g. at every minute, 10-minutes, hourly, 30-minutes mean value, hourly mean value, etc.) may be specified.

Wind prediction tools can be based on either an explicit model to forecast the wind power directly or by firstly, developing a wind speed prediction model and then converting the wind speed forecast into predicted wind power. For example, the authors of [19, 20, 21] rely on the former approach while variations of the latter method are utilized by the authors of [22, 23, 24]. Also, generally one may categorize the prediction tools into one of the two

classes: those based on physical system models and those based on statistical models. The former utilizes considerable physical data such as historical wind power, meteorological information namely local weather conditions, and estimates from numerical weather prediction, among other factors [25, 26]. Conversely, the statistical model mainly uses only historical and current values of wind power and the aim is to quantify the relationship between the historical and future wind power data [24, 27]. Additionally, the statistical models can be further sub-divided into linear and nonlinear systems. A very traditional linear system used in wind prediction is the persistence method where it is assumed that the wind production remains unchanged for all look-ahead times. For nonlinear statistical models, artificial neural networks and support vector machines are some of the commonly used techniques. For example in [28], an interesting nonlinear statistical system has been developed to predict both the wind speed and its direction so that the wind turbine generators (WTG) can be directed toward the oncoming wind to better harness the wind energy. Besides the two major classes of wind prediction tools explained above, hybrid models have also been developed to incorporate the benefits of both the physical and statistical approaches.

For most of the currently available wind power forecasting methods such as that described in [7, 29, 30], the wind power forecast error can be quantified in terms of the Normalized Root-Mean-Square Error (NRMSE) which is obtained by normalizing the RMSE with respect to the wind power generation installed capacity. Typically, NRMSE increases with the time-horizon of the forecast. For example: NRMSE for a single wind farm ranges between 8% for an hour ahead forecast and up to 20% for a day ahead forecast [18]. Due to the so-called spatial smoothing effects described in [7], it is possible to reduce the forecasting errors by a further 30% ~ 50% when wind plants are geographically dispersed over a vast area. Nevertheless, with continuous research in developing improved wind forecasting techniques, it is envisaged that the uncertainty in wind power prediction will be reduced further.

2.2.1 Linear statistical wind power forecasting system

It is explained in Section 2.2 that wind prediction tools based on statistical approach do not require considerable physical data; they only require historical and current values of the wind power. In addition, linear statistical wind power forecasting system is much more computational efficient and straightforward as compared to its nonlinear counterpart that utilizes artificial intelligence techniques [25, 26]. Therefore, in a situation where there is limited historical wind power data and / or for the purpose of initial planning / simulation of wind-grid integration schemes, a situation which is considered in the thesis, the required wind power forecast can be provided by linear statistical methods. This approach was also undertaken by the authors of [25] to simulate the hourly wind speed. The next sub-section serves to present some established linear statistical methods for predicting wind power that were attempted by the author. However, the intention of this study is not to develop any new wind power forecasting technique: rather it is for the completeness of the thesis that wind power forecasting techniques are included. With the stated intention, two methods will be presented and they are namely: Multiplicative Winters' Exponential Smoothing, and Box-Jenkins methods.

2.2.1.1 Multiplicative Winters' Exponential Smoothing [31]

In order to account for linear trend and seasonal (repetitive/cyclic) patterns that are embodied in the original time-series data, *Winters' Exponential Smoothing* is usually the preferred method. This method is able to forecast/estimate the average level component, slope component and seasonal component in the original time-series data. Each of the three components has its own smoothing constant and changes can be made to anyone of the constants without altering the others. In this method, a new forecast can be written as:

$$\hat{P}(t+1) = [a(t) + b(t)] \cdot \xi(t) \quad (2.1)$$

where $\hat{P}(t+1)$ is the new forecast for next time period (made in the present period, t);

$a(t)$ is the smoothed estimate of the average level component determined at t ;

$b(t)$ is the smoothed estimate of the slope component determined at t ;

$\xi(t)$ is the smoothed estimate of the seasonal component determined at t ;

The average level component, $a(t)$, is given by

$$a(t) = \varphi_a \left[\frac{P(t)}{\xi(t-1)} \right] + (1 - \varphi_a) \cdot [a(t-1) + b(t-1)] \quad (2.2)$$

where φ_a is the weighting factor of the average level component ($0 \leq \varphi_a \leq 1$);

$P(t)$ is the actual value for the present period, t ;

$\xi(t-1)$ is the old estimate of the seasonal component determined at the previous period $t-1$;

$a(t-1)$ is the old estimate of the average level component determined at $t-1$;

$b(t-1)$ is the old estimate of the slope component determined at $t-1$;

To compute the slope component, $b(t)$:

$$b(t) = \psi_b [a(t) - a(t-1)] + b(t-1) \cdot [1 - \psi_b] \quad (2.3)$$

where ψ_b is the weighting factor of the slope component ($0 \leq \psi_b \leq 1$);

For the determination of the seasonal component, $\xi(t)$:

$$\xi(t) = \gamma_\xi \left[\frac{P(t)}{a(t)} \right] + (1 - \gamma_\xi) \cdot \xi(t-1) \quad (2.4)$$

where γ_ξ is the weighting factor of the seasonal component ($0 \leq \gamma_\xi \leq 1$);

In demonstrating the explained approach above, the mean daily wind power level for a site in Changi, Singapore will be used. To begin with, the mean daily wind profile from November 2008 to May 2009 is first used to compute the necessary coefficients to build the *Multiplicative Winters' Exponential Smoothing* model. Subsequently, the June 2009 data will be utilized to assess the accuracy of the prediction model. In other words, the wind profile from November 2008 to May 2009 will be used to obtain/train the forecast model. Then the difference between the actual and the forecasted June values will provide a measure of the accuracy of the model. In order to follow the standard practice as used in the time-series analysis literature, the forecasted values obtained during this June period are known as the *predicted* values while the forecasted values for November 2008 to May 2009 are known as the *estimated* values. Fig. 2-4 shows the estimated and the predicted mean daily values for the Changi wind profile using the *Multiplicative Winters' Exponential Smoothing* method.

Fig. 2-4 Actual, estimated and predicted mean daily Changi wind power profile with Multiplicative Winters' Exponential Smoothing model

2.2.1.2 Box-Jenkins methodology [31]

This forecasting method offers a systematic approach to analyze and build a time-series forecast model. However, this method has a main disadvantage, i.e. the calculations of the coefficients for the mathematical equation are cumbersome. Due to the iterative procedure required to derive the coefficients, this method is computationally more intensive as

compared to most other linear statistical forecasting models [31]. When implementing this method, one has to go through several steps, mainly identification, estimation, diagnostic checking and forecasting.

In the identification stage, the behavior of the time-series is examined through the autocorrelation function (ACF) and the partial autocorrelation function (PACF). In constructing the ACF, the autocorrelation coefficients are first computed for different lagged sets of the time-series data. The same reasoning also applies to the derivation of the PACF, i.e. the partial autocorrelation coefficients need to be determined. Next, the tentative Box-Jenkins forecast model of the time-series is identified from the analysis of the ACF and the PACF. The nature of the Box-Jenkins model can be autoregressive (AR), moving average (MA), or autoregressive-moving average (ARMA). For an AR model, it is usually expressed as an AR (p) model where p is the order of the autoregressive part. Alternatively, a MA model is expressed as a MA (q) model where q is the order of the moving average part. As for an ARMA model, the model is expressed as ARMA (p, q) where p and q are the order of the autoregressive and moving average part respectively. Since there is no (q) order of the moving-average part for the case of the AR model and the MA model does not have any (p) order of the autoregressive part, both the AR and MA models are perceived to be subsets of the ARMA model. Mathematically, an ARMA model is expressed as:

$$\hat{P}(t+1) = \sum_{i=1}^p \varphi_i \cdot P(t+1-i) + \sum_{j=1}^q \theta_j \cdot \left(P(t+1-j) - \hat{P}(t+1-j) \right) + \mu \quad (2.5)$$

where $\hat{P}(t+1)$ is the new forecast for next time period (made in the present period, t);

φ_i is the i^{th} -parameter of the autoregressive (AR) component;

$P(t+1-i)$ is the actual wind power in the $(t+1-i)$ period;

θ_j is the j^{th} -parameter of the moving average (MA) component;

$\left(P(t+1-j) - \hat{P}(t+1-j) \right)$ is the forecasting error in the $(t+1-j)$ period;

μ is the average level component;

Even though the appropriate Box-Jenkins model can be identified from the ACF and PACF, it is often necessary and prudent to identify several other tentative forecast models due to the ambiguous interpretation of the ACF and PACF [31].

Once the tentative forecast models have been identified, the estimation for the various parameters (ϕ , θ) and the average level component (μ) for each model such as those shown in (2.5) will need to be computed. This is achieved in the estimation stage numerically. Examples of some commercially available software can be found in [31]. In these software, a combination of search routines and successive approximations are used to obtain the least square estimates of the various ϕ , θ , and μ . The final estimates are those that minimize the sum of squared errors where no other estimates can be found to yield smaller sum of squared errors.

In order to single out the most suitable forecast model, the adequacy of each model as well as their closeness of fit between the *estimated* values and the actual data will need to be assessed. This is accomplished in the diagnostic checking phase. A common diagnostic test can be one of those discussed in Section 2.2 where the Root-Mean-Square error (RMSE) or Normalized RMSE (NRMSE) for each forecast model is computed. An appropriate resulting forecast model should have small RMSE or NRMSE. Another possible diagnostic check is the modified Box-Pierce statistic (which is also known as the Ljung-Box statistic). This test is to examine whether the forecast errors resulting from the forecast model are random and independent up to a certain number of lags. An appropriate model should have forecast errors that are random and independent. Therefore, if a confidence level of β is selected to ascertain that the forecast errors resulting from the model at various lags are random and independent, the computed p -values obtained from the modified Box-Pierce statistic should be much greater than $1 - \beta$ [32]. The results from the modified Box-Pierce statistic are known as the p -values, the “ p ” notation in this context is totally unrelated to the order “ p ” of the AR / ARMA forecasting model explained above. In the case of the AR / ARMA forecasting model, the “ p ” refers to the number of parameters the autoregressive part contains. Once the suitable forecast model has been determined, it is now ready to generate forecasts for future time periods.

To illustrate the abovementioned approach, the same mean daily wind profile captured at a site in Changi, Singapore from November 2008 to May 2009 that was used in the previous sub-section to demonstrate the Multiplicative Winters' Exponential Smoothing method will be used herein to determine the suitable Box-Jenkins model. The procedure begins with the analysis of the autocorrelation function (ACF) and the partial autocorrelation function (PACF) of the mean daily wind profile in the identification stage. The resulting ACF with its autocorrelation coefficients at various lags is shown in Fig. 2-5. Fig. 2-6 illustrates the partial autocorrelation coefficients and the corresponding PACF.

Fig. 2-5 Autocorrelation function (ACF) of the mean daily wind profile (November 2008 ~ May 2009)

Fig. 2-6 Partial autocorrelation function (PACF) of the mean daily wind profile (November 2008 ~ May 2009)

From Figs. 2-5 and 2-6, it is seen that all the autocorrelation and partial autocorrelation coefficients are relatively small. Furthermore, both the ACF and PACF exhibit a damped sinusoidal behaviour.

Hence, it is deduced that an appropriate forecast model will be the ARMA model. As explained afore, it is necessary to also identify several other tentative forecasting models. Consequently, the author decided to include the following possible models: AR (1), AR (2), MA (1), MA (2), ARMA (1, 1), ARMA (1, 2), ARMA (2, 1) and ARMA (2, 2). Generally, no more than two autoregressive parameters or two moving average parameters are required in a forecast model to fit most time-series data [33]. Hence, the order of the autoregressive and moving average parts of the models are limited to a value of 2 in this investigation. Next, the estimation of the various parameters in the tentative forecast models will be performed in the estimation phase using Minitab statistical software [32]. However, in computing the parameters for the various forecasting models, the Minitab software faces convergence difficulty and is unable to obtain the least square point estimates of the parameters for the ARMA (1, 2), ARMA (2, 1) and ARMA (2, 2). In order to select the most suitable forecasting model, the Root-Mean-Square errors (RMSE) of the various forecasting models are next evaluated and they ranged from 185.60W to 200.50W, with ARMA (1, 1) achieving the least RMSE. Subsequently, the modified Box-Pierce statistical tests are performed at various lags of the ARMA (1, 1) model with selected confidence level of 95 % and it was found that all the computed p -values obtained are all greater than 0.05. Thus it is reasonable to select the ARMA (1, 1) model in this context to forecast the mean daily wind profile.

Fig. 2-7 illustrates the estimated and the predicted mean daily values for the Changi wind profile using the ARMA (1, 1) model. The autoregressive coefficient (ϕ_1), moving average coefficient (θ_1), and the average level component (μ) of the ARMA (1, 1) model were determined to be: 0.79, -0.24 , and 47.30 respectively.

Fig. 2-7 Actual, estimated and predicted mean daily Changi wind power profile with a ARMA (1, 1) model

2.2.1.3 Comparison between Multiplicative Winters' Exponential Smoothing, Box-Jenkins, and Persistence forecasting methods

Besides the Multiplicative Winters' Exponential Smoothing and Box-Jenkins forecasting models discussed in Sections 2.2.1.1 and 2.2.1.2, another popular forecasting model is the Persistence model. In the Persistence model, a future forecast equals the value of the current time period. It is regarded as the simplest forecasting model and it is typically used as a standard model to compare the performance among different prediction models. Thus in this sub-section, the two common and useful measures, the Root-Mean-Square error (RMSE) and Normalized RMSE (NRMSE), will be used to assess the accuracy / performance of the Multiplicative Winters' Exponential Smoothing and ARMA (1, 1) methods with those of the Persistence model in forecasting the June 2009 mean daily power level. In this context, the NRMSE is obtained by normalizing the evaluated RMSE with a base value of 1200W where 1200W is the maximum daily mean value obtained from the particular Changi wind profile. Table 2-1 lists the RMSE and NRMSE for the three prediction models.

Table 2-1 RMSE and NRMSE for *Persistence*, *Multiplicative Winters' Exponential Smoothing*, and *ARMA (1, 1)* prediction methods

Prediction Method	RMSE, (W)	NRMSE, (%)
<i>Persistence</i>	197.8	16.5
<i>Multiplicative Winters' Exponential Smoothing</i>	175.1	14.6
<i>ARMA(1, 1)</i>	185.6	15.5

From Table 2-1, it is seen that the improvement in the accuracy of the Multiplicative Winters' Exponential Smoothing method is 1.13 times that of the Persistence model. Even for the ARMA (1, 1) model, its improvement is still 1.06 times that of the Persistence method. Nevertheless, forecasting is not the focus of this thesis and the present study only provides an example of the applications of two current forecasting techniques. Examples of some advanced forecasting methods can be found in [22 – 24].

2.2.2 Relationship between the prediction error distributions of wind speed and power

From [7], it is established that wind power is proportional to the cube power of wind speed. Hence wind power forecast could be obtained from predicted wind speed, once the wind turbine output power characteristic curve is known. From [25, 30, 34], it was established that wind speed prediction error distributions are Gaussian. However in [30, 34], it was reported that when the predicted wind speed is used to predict output wind power of a typical wind turbine, the resultant distribution in the predicted wind power error is non-Gaussian. The reason for this shall be explained in this section. Firstly, consider Fig. 2-8 which shows a rather idealized relationship between wind speed and the wind turbine generator (WTG) electrical output power [35].

Fig. 2-8 Idealized WTG output power characteristic curve [35]

The relationship between the wind speed ω and that of the WTG output power P can be described by [7]

$$P = \begin{cases} 0, & 0 < \omega \leq \omega_i \text{ and } \omega > \omega_o \\ K \cdot (\omega^3 - \omega_i^3), & \omega_i < \omega < \omega_r \\ P_r, & \omega_r \leq \omega \leq \omega_o \end{cases} \quad (2.6)$$

where K is a constant parameter for particular WTG;

ω_i is the turbine cut-in speed;

ω_r is the turbine rated speed;

ω_o is the turbine cut-out speed;

P_r is the rated turbine power

With reference to Fig. 2-8, the WTG will not generate any electrical power below the cut-in wind speed, ω_i . As wind speed increases above ω_i , the generator output power tends to increase as the cube of the wind speed. For wind speed above the rated wind speed ω_r to cut-out wind speed, ω_o , the generator is delivering its rated (nameplate) power P_r . Finally, when the wind speed reaches ω_o and beyond, there is the attendance risk of damaging the wind turbine and the turbine is shut down. Therefore beyond ω_o , the generator output power is zero.

Fig. 2-9 Wind power error distributions from three Gaussian wind speed error curves (each with a wind speed error standard deviation of 1m/s) [30]

The three Gaussian curves plotted along the abscissa in Fig. 2-9 describe the three possible distributions in the wind speed error. Suppose each distribution has a standard deviation of 1 m/s, and they are superimposed onto the particular WTG output power characteristic curve. The three resultant wind power error curves are shown on the y-axis of the figure. From Fig. 2-9, it is clear that each of the resultant wind power error distributions cannot be described by a Gaussian distribution, especially at regions around the turbine cut-in speed and beyond the turbine rated speed. The reason is the turbine power-wind speed curve is non-linear.

Fig. 2-10 shows another wind speed error curve which is wider than that shown in Fig. 2-9. It can be seen from the figure that again, the resultant wind power error distribution is non-Gaussian and is highly unsymmetrical. Thus in general, given Gaussian wind speed error distribution but with different mean and/or standard deviation, the resultant wind power error distribution is unlikely to be Gaussian.

Fig. 2-10 A wider Gaussian wind speed error curve than that shown in Fig. 2-9 superimposed onto the same WTG output power characteristic curve to produce the resultant wind power error curve

2.2.2.1 Analysis on wind power prediction error distribution

It has been shown in the previous sub-section that even though the wind speed prediction error distributions are Gaussian in nature, the resultant distributions in the predicted wind power error are non-Gaussian due to the non-linear turbine power-wind speed curve. Thus Section 2.2.2 serves to provide a qualitative insight into the error distribution of the predicted wind power, based on the wind speed forecast. If the resultant wind power error distributions cannot be described by a Gaussian distribution, how does one determine the wind power error distribution in a quantitative manner? In this section, a quantitative approach which aims to extend the works of [30, 34] will be undertaken to derive the wind power error distribution. Once the wind power error distribution is determined, one will then be able to compute the mean and standard deviation from the probability distribution of the wind power error. It will be shown later in this sub-section how the knowledge of these useful parameters shall allow one to evaluate the confidence level of the wind power to be within a certain range. In additional, it will be shown in Chapter 5 that the knowledge of the mean and standard deviation of the predicted wind power error can allow the output power of a combined wind-energy storage power station to be committed to meet the power dispatch at specified confidence level.

In this work, it is necessary to mathematically relate the random variables: wind speed error, ω_e , and the wind power error, P_e , via the wind turbine power characteristic curve. The wind speed error, ω_e , is obtained by subtracting the forecasted wind speed from the actual wind speed whereas the difference between the actual wind power and the forecasted wind power yields the wind power error, P_e . From the generic WTG output power-wind speed characteristic described by (2.6), it can be seen that the wind power error P_e can lie within any one of the three sections: Section I, $P_e = 0$, for $0 < \omega_e \leq \omega_i$ and $\omega_e > \omega_o$; Section II, $P_e = K(\omega_e^3 - \omega_i^3)$, for $\omega_i < \omega_e < \omega_r$; and Section III, $P_e = P_r$, for $\omega_r \leq \omega_e \leq \omega_o$.

Denote in this context the probability density function (pdf) of wind power error P_e as $f_{P_e}(p_e)$. This notation follows the standard practice for designating pdf as used in the literature: “ P_e ” in the subscript of the pdf function signifies the wind power error random variable while “ p_e ” in the parenthesis is the value the random variable P_e can assume. Similar naming practice applies to the pdf of the wind speed error ω_e which is written as $f_{\omega_e}(\omega_e)$. Obviously, with regard to the pdf of P_e such as that shown on Fig. 2-10(c), $f_{P_e}(p_e)$ is of a mixed type distribution, i.e. the distribution of P_e is discretely concentrated at $P_e = 0$ and $P_e = P_r$, but continuously distributed over the interval $0 < P_e < P_r$. In order to determine $f_{P_e}(p_e)$, one will need to evaluate $f_{\omega_e}(\omega_e)$ over each of the three respective sections of the wind turbine power characteristic curve defined earlier and then combine the results.

In view of the above and to derive the desired wind power error probability density function, $f_{P_e}(p_e)$, one starts by expressing the Gaussian pdf of the wind speed error random variable ω_e , i.e. $f_{\omega_e}(\omega_e)$ as:

$$f_{\omega_e}(\omega_e) = \frac{1}{\sqrt{2\pi\sigma_{\omega_e}^2}} \cdot e^{-\frac{(\omega_e - \mu_{\omega_e})^2}{2\sigma_{\omega_e}^2}} \quad (2.7)$$

where μ_{ω_e} and σ_{ω_e} are the mean and standard deviation of the wind speed error, ω_e , respectively.

Next, let the pdf of P_e in Section I be denoted as $f^1_{Pe}(p_e)$ and it is evaluated as

$$\begin{aligned}
 f^1_{Pe}(p_e) &= \int_0^{\omega_i} f_{\omega_e}(\omega_e) \cdot d\omega_e + \int_{\omega_o}^{\infty} f_{\omega_e}(\omega_e) \cdot d\omega_e, & 0 < \omega_e \leq \omega_i, \text{ and } \omega_e > \omega_o \\
 &= \frac{1 + \text{Erf}\left[\frac{\mu_{\omega_e}}{\sqrt{2} \cdot \sigma_{\omega_e}}\right] + \text{Erf}\left[\frac{\mu_{\omega_e} - \omega_o}{\sqrt{2} \cdot \sigma_{\omega_e}}\right] - \text{Erf}\left[\frac{\mu_{\omega_e} - \omega_i}{\sqrt{2} \cdot \sigma_{\omega_e}}\right]}{2}, & p_e = 0 \\
 &= \text{Prob}(P_e = 0)
 \end{aligned} \tag{2.8}$$

In (2.8), $\text{Erf}[\cdot]$ is the error function and it is defined as: $\text{Erf}[\cdot] = \frac{2}{\sqrt{\pi}} \int_0^{\cdot} e^{-x^2} dx$.

$\text{Prob}(\cdot)$ in (2.8) denotes the probability the condition $(\cdot)$ is being satisfied, i.e. in this case, the wind power error $P_e = 0$. As explained before, the distribution of P_e ($f^1_{Pe}(p_e)$) is discretely concentrated at $P_e = 0$. Hence $f^1_{Pe}(p_e)$ is also the probability when $P_e = 0$.

Next, denote the pdf of P_e over Section II as $f^2_{Pe}(p_e)$. To obtain $f^2_{Pe}(p_e)$, one starts with the cumulative probability function (cdf) of P_e over the interval $0 < P_e < P_r$, viz.

$$F^2_{Pe}(p_e) = \text{Prob}(0 < P_e \leq p_e) \tag{2.9}$$

where $F^2_{Pe}(p_e)$ represents the cumulative probability function (cdf) of P_e over the interval $0 < P_e < P_r$.

With the wind power error P_e and the wind speed error ω_e governed by the relationship $P_e = K \cdot (\omega_e^3 - \omega_i^3)$ in Section II of the WTG output power-speed characteristic curve, one can express (2.9) in terms of the cdf of ω_e , viz.

$$\begin{aligned} Prob(0 < P_e \leq p_e) &= Prob\left(0 < K(\omega_e^3 - \omega_i^3) \leq p_e\right) = Prob\left(\omega_i < \omega_e \leq \left(\frac{p_e}{K} + \omega_i^3\right)^{\frac{1}{3}}\right) \\ &= F_{\omega_e}\left(\sqrt[3]{\frac{p_e}{K} + \omega_i^3}\right) - F_{\omega_e}(\omega_i) \end{aligned} \quad (2.10)$$

where $F_{\omega_e}(\cdot)$ represents the cdf of the wind speed error. Differentiate $F_{\omega_e}(\cdot)$ in (2.10) with respect to p_e and one obtains $f^2_{Pe}(p_e)$, i.e.

$$F'_{\omega_e}\left(\sqrt[3]{\frac{p_e}{K} + \omega_i^3}\right) - F'_{\omega_e}(\omega_i) = f^2_{Pe}(p_e) = \frac{1}{3 \cdot K} \cdot \left(\frac{p_e}{K} + \omega_i^3\right)^{-\frac{2}{3}} \cdot f_{\omega_e}\left(\sqrt[3]{\frac{p_e}{K} + \omega_i^3}\right) \quad (2.11)$$

where $F'_{\omega_e}(\cdot)$ denotes the first derivative of $F_{\omega_e}(\cdot)$. With (2.7), $f^2_{Pe}(p_e)$ is then expressed as

$$f^2_{Pe}(p_e) = \frac{1}{3 \cdot K \cdot \sqrt{2\pi\sigma_{\omega_e}^2}} \cdot \left(\frac{p_e}{K} + \omega_i^3\right)^{-\frac{2}{3}} \cdot e^{-\frac{\left(\sqrt[3]{\frac{p_e}{K} + \omega_i^3} - \mu_{\omega_e}\right)^2}{2\sigma_{\omega_e}^2}}, \quad 0 < p_e < K \cdot (\omega_r^3 - \omega_i^3) \quad (2.12)$$

Finally, denote the pdf of P_e in Section III as $f^3_{Pe}(p_e)$. $f^3_{Pe}(p_e)$ is computed in similar manner as $f^1_{Pe}(p_e)$ but the integration limits are from ω_r to ω_o , viz.

$$\begin{aligned} f^3_{Pe}(p_e) &= \int_{\omega_r}^{\omega_o} f_{\omega_e}(\omega_e) \cdot d\omega_e, & \omega_r \leq \omega_e \leq \omega_o \\ &= \frac{Erf\left[\frac{\mu_{\omega_e} - \omega_r}{\sqrt{2} \cdot \sigma_{\omega_e}}\right] - Erf\left[\frac{\mu_{\omega_e} - \omega_o}{\sqrt{2} \cdot \sigma_{\omega_e}}\right]}{2}, & p_e = P_r \\ &= Prob(P_e = P_r) \end{aligned} \quad (2.13)$$

Again, as the distribution of P_e ($f^3_{Pe}(p_e)$) is discretely concentrated at $P_e = P_r$, hence $f^3_{Pe}(p_e)$ is the probability of $P_e = P_r$.

The resultant pdf of the wind power error P_e ($f_{Pe}(p_e)$) is obtained by combining $f^1_{Pe}(p_e)$, $f^2_{Pe}(p_e)$, and $f^3_{Pe}(p_e)$, i.e.

$$f_{Pe}(p_e) = \begin{cases} \frac{1 + \text{Erf}\left[\frac{\mu_{\omega e}}{\sqrt{2} \cdot \sigma_{\omega e}}\right] + \text{Erf}\left[\frac{\mu_{\omega e} - \omega_o}{\sqrt{2} \cdot \sigma_{\omega e}}\right] - \text{Erf}\left[\frac{\mu_{\omega e} - \omega_i}{\sqrt{2} \cdot \sigma_{\omega e}}\right]}{2}, & p_e = 0 \\ \frac{1}{3 \cdot K \cdot \sqrt{2\pi\sigma_{\omega e}^2}} \cdot \left(\frac{P_e}{K} + \omega_i^3\right)^{-\frac{2}{3}} \cdot e^{-\frac{\left(\sqrt[3]{\frac{P_e}{K} + \omega_i^3} - \mu_{\omega e}\right)^2}{2\sigma_{\omega e}^2}}, & 0 < p_e < K \cdot (\omega_r^3 - \omega_i^3) \\ \frac{\text{Erf}\left[\frac{\mu_{\omega e} - \omega_r}{\sqrt{2} \cdot \sigma_{\omega e}}\right] - \text{Erf}\left[\frac{\mu_{\omega e} - \omega_o}{\sqrt{2} \cdot \sigma_{\omega e}}\right]}{2}, & p_e = P_r \end{cases} \quad (2.14)$$

Let the mean and standard deviation of P_e be represented as μ_{Pe} and σ_{Pe} respectively. Whence μ_{Pe} and σ_{Pe} can be expressed as

$$\mu_{Pe} = E\{P_e\} = \left(0 \cdot f^1_{Pe}(p_e)\right) + \int_0^{K(\omega_r^3 - \omega_i^3)} p_e \cdot f^2_{Pe}(p_e) \cdot dp_e + \left(P_r \cdot f^3_{Pe}(p_e)\right) \quad (2.15)$$

$$\sigma_{Pe} = \sqrt{E\{P_e^2\} - (E\{P_e\})^2} = \sqrt{\int_0^{K(\omega_r^3 - \omega_i^3)} p_e^2 \cdot f^2_{Pe}(p_e) \cdot dp_e + (P_r^2 \cdot f^3_{Pe}(p_e)) - (\mu_{Pe})^2} \quad (2.16)$$

In (2.15) and (2.16), $E\{\cdot\}$ denotes the expected value of $\{\cdot\}$.

As stated in the beginning of this sub-section, the difference between the actual and the forecasted wind power yields the wind power error. Thus, by making use of (2.14) - (2.16), one can then evaluate the confidence level by which the actual wind power $P_W(t)$ in a future

time period will be within $\pm r \cdot \sigma_{Pe}$ from μ_{Pe} . For example when $r = 1$, the boundary of the actual wind power which lies within $\pm 1 \sigma_{Pe}$ from the power error mean (μ_{Pe}) can be expressed as

$$P_W(t) = P_{W,f}(t) + \mu_{Pe} \pm 1 \sigma_{Pe} \quad (2.17)$$

In (2.17), $P_{W,f}(t)$ denotes the forecasted wind power.

The above derivation is useful. For example, using (2.14) – (2.16), the confidence level the wind power error is predicted to be within $\pm 1 \sigma_{Pe}$ from μ_{Pe} for (say) $K = 1$, $\omega_i = 3$ m/s, $\omega_r = 14$ m/s, $\omega_o = 18$ m/s, $\mu_{\omega e} = 9$ m/s and $\sigma_{\omega e} = 1.5$ m/s is

$$Prob\{\mu_{Pe} - \sigma_{Pe} \leq P_e \leq \mu_{Pe} + \sigma_{Pe}\} = \int_{\mu_{Pe} - \sigma_{Pe}}^{\mu_{Pe} + \sigma_{Pe}} f_{Pe}(p_e) \cdot dp_e = 0.705 \quad (2.18)$$

Thus the confidence level that the actual wind power in a future time, t , as expressed by (2.17) is within $\pm 1 \sigma_{Pe}$ from μ_{Pe} is 70.5%.

Fig. 2-11 illustrates the pdf of P_e using (2.14) for this particular example. Table 2-2 compares the probability of the error in the predicted wind power for a range of values of $\mu_{\omega e}$ and $\sigma_{\omega e}$ and the probability of the error in the predicted wind speed. From (2.14), the range of the wind power error P_e is between 0 to P_r . Therefore, if the lower band of the P_e evaluated at $-r \cdot \sigma_{Pe}$ from μ_{Pe} assumes a negative value, the lower band of P_e is set to zero. Conversely, when the upper band of P_e at $+r \cdot \sigma_{Pe}$ from μ_{Pe} is computed to exceed P_r , the upper band of P_e will be set equal to P_r .

Fig. 2-11 Pdf of wind power error ($f_{Pe}(p_e)$) with $K = 1$, $\omega_i = 3$ m/s, $\omega_r = 14$ m/s, $\omega_o = 18$ m/s, $\mu_{\omega e} = 9$ m/s and $\sigma_{\omega e} = 1.5$ m/s

Table 2-2 Comparison between the probability of the error in the predicted wind power for ranges of $\mu_{\omega e}$ and $\sigma_{\omega e}$ (Rows 6 – 8) and the probability of the error in the predicted wind speed (Rows 3 – 5)

$\mu_{\omega e}$	7		9	
$\sigma_{\omega e}$	0.5	1.5	0.5	1.5
$Prob\{\mu_{\omega e} - \sigma_{\omega e} \leq \omega_e \leq \mu_{\omega e} + \sigma_{\omega e}\}$	0.682			
$Prob\{\mu_{\omega e} - 2\sigma_{\omega e} \leq \omega_e \leq \mu_{\omega e} + 2\sigma_{\omega e}\}$	0.954			
$Prob\{\mu_{\omega e} - 3\sigma_{\omega e} \leq \omega_e \leq \mu_{\omega e} + 3\sigma_{\omega e}\}$	0.997			
$Prob\{\mu_{Pe} - \sigma_{Pe} \leq P_e \leq \mu_{Pe} + \sigma_{Pe}\}$	0.687	0.723	0.685	0.705
$Prob\{\mu_{Pe} - 2\sigma_{Pe} \leq P_e \leq \mu_{Pe} + 2\sigma_{Pe}\}$	0.957	0.952	0.956	0.958
$Prob\{\mu_{Pe} - 3\sigma_{Pe} \leq P_e \leq \mu_{Pe} + 3\sigma_{Pe}\}$	0.995	0.984	0.996	0.990

It is observed from Fig. 2-11 that the pdf of P_e is not symmetrical about its mean μ_{Pe} which is unlike that of a Gaussian distribution. Furthermore, it is seen from (2.18) and Row 6 of Table 2-2 that the probability of the wind power error at one standard deviation in the case of the non-Gaussian distribution is greater than 68.2% when compared to the case of the Gaussian wind speed error (Row 3 of Table 2-2). In addition, the wind power error probabilities at three standard deviations (Row 8) are lower than the 99.7% of the wind speed error probability shown in Row 5. This is due to the non-Gaussian wind power forecast error distribution has a longer tail (see Fig. 2-11) as compared to the case of a Gaussian distribution. Thus based on the above findings, it is seen that regardless of different wind speed error mean μ_{ω_e} and wind speed error standard deviation σ_{ω_e} , the confidence level of the Gaussian wind speed error at particular $\pm r \cdot \sigma_{\omega_e}$ from μ_{ω_e} remains the same but this is not true for that of the non-Gaussian wind power error at particular $\pm r \cdot \sigma_{Pe}$ from μ_{Pe} .

With reference to Table 2-2, the next task is to provide some examples to illustrate the observation that for the same wind speed error mean (μ_{ω_e}) but with different wind speed error standard deviation (σ_{ω_e}), the resultant probabilities of the wind power error even at the same $\pm r \cdot \sigma_{Pe}$ from μ_{Pe} will be different. Take for example the cases of $\mu_{\omega_e} = 9$ m/s but with $\sigma_{\omega_e} = 0.5$ m/s and $\sigma_{\omega_e} = 1.5$ m/s. First, consider how the confidence level of the wind power error at $\pm 1 \sigma_{Pe}$ from μ_{Pe} for $\mu_{\omega_e} = 9$ m/s and $\sigma_{\omega_e} = 0.5$ m/s is derived. At $(\mu_{Pe} - 1 \sigma_{Pe}) \leq P_e \leq (\mu_{Pe} + 1 \sigma_{Pe})$, the lower and upper boundary of P_e are determined using (2.15) and

(2.16) to be 0.587 kW and 0.831 kW respectively. With the relationship of $\omega_e = \sqrt[3]{\frac{P_e}{K} + \omega_i^3}$,

the lower and upper P_e values are computed to correspond to $(\mu_{\omega_e} - 1 \sigma_{\omega_e})$ and $(\mu_{\omega_e} + 1.01 \sigma_{\omega_e})$. By evaluating the cdf of the Gaussian wind speed error between the interval $(-1 \sigma_{\omega_e} + \mu_{\omega_e}) \leq \omega_e \leq (+1.01 \sigma_{\omega_e} + \mu_{\omega_e})$, the confidence level of the wind power error at $\pm 1 \cdot \sigma_{Pe}$ from μ_{Pe} for $\mu_{\omega_e} = 9$ m/s, $\sigma_{\omega_e} = 0.5$ m/s is found to be 68.5%. Next, repeating the above procedure for $\mu_{\omega_e} = 9$ m/s, $\sigma_{\omega_e} = 1.5$ m/s and with (2.15), (2.16) plus the relationship of ω_e and P_e , it was found that $(\mu_{Pe} - 1 \sigma_{Pe}) \leq P_e \leq (\mu_{Pe} + 1 \sigma_{Pe})$ actually corresponds to $(\mu_{\omega_e} - 1.06 \sigma_{\omega_e}) \leq \omega_e \leq (\mu_{\omega_e} + 1.03 \sigma_{\omega_e})$. Due to the slightly larger integration limits when evaluating the cdf of ω_e as compared to the former case of $\sigma_{\omega_e} = 0.5$ m/s, the probability

for $\sigma_{\omega_e} = 1.5$ m/s yields a higher probability at 70.5%. Consider the examples of the confidence level of P_e at $\pm 3 \sigma_{P_e}$ from μ_{P_e} for $\mu_{\omega_e} = 9$ m/s and $\sigma_{\omega_e} = 0.5$ m/s versus $\sigma_{\omega_e} = 1.5$ m/s. For $\mu_{\omega_e} = 9$ m/s, $\sigma_{\omega_e} = 0.5$ m/s, $(\mu_{P_e} - 3 \sigma_{P_e}) \leq P_e \leq (\mu_{P_e} + 3 \sigma_{P_e})$ corresponds to $(\mu_{\omega_e} - 3.65 \sigma_{\omega_e}) \leq \omega_e \leq (\mu_{\omega_e} + 2.66 \sigma_{\omega_e})$ and the resulting probability is 99.6%. On the latter case of $\mu_{\omega_e} = 9$ m/s, $\sigma_{\omega_e} = 1.5$ m/s, the lower and upper P_e at $\pm 3 \cdot \sigma_{P_e}$ from μ_{P_e} are -0.39 kW and 1.91 kW respectively. However as explained above, the wind power error P_e will be set to zero when P_e is negative, the above $(\mu_{P_e} \pm 3 \sigma_{P_e})$ corresponds $(\mu_{\omega_e} - 4 \sigma_{\omega_e}) \leq \omega_e \leq (\mu_{\omega_e} + 2.32 \sigma_{\omega_e})$. Since the probability of the Gaussian wind speed error at $(\omega_e < \mu_{\omega_e} - 3 \sigma_{\omega_e})$ can be assumed negligible, the much larger lower integration limit between this latter case and that of the former (for $\mu_{\omega_e} = 9$ m/s, $\sigma_{\omega_e} = 0.5$ m/s) will not have as much impact as the upper integration limit. At a smaller upper integration limit of $2.32 \sigma_{\omega_e}$, this is the reason for the lower confidence level of P_e at $\pm 3 \cdot \sigma_{P_e}$ from μ_{P_e} for $\mu_{\omega_e} = 9$ m/s, $\sigma_{\omega_e} = 1.5$ m/s.

With the above reasoning and using the appropriate relationship of ω_e and P_e (which depends on the determined values of the $\pm r \cdot \sigma_{P_e}$ from μ_{P_e} at the respective section of the wind turbine power characteristic curve), an insight can be gained to understand the different confidence levels resulting from the various cases of μ_{ω_e} and σ_{ω_e} . Thus using the procedure explained in this section, one shall be able to derive the mean and standard deviation of the predicted wind power error from that of the predicted wind speed error. Subsequently, by adding $\mu_{P_e} \pm r \cdot \sigma_{P_e}$ of the predicted wind power error to the forecasted wind power, the upper and lower limits of the forecasted wind power are obtained. Consequently, the confidence level by which the actual wind power will be within these limits can then be evaluated for any future time period. In addition, it will be shown in Chapter 5 how the knowledge of the mean and standard deviation of the predicted wind power error can allow the output power of a combined wind-energy storage power station to be committed to meet the power dispatch at specified confidence level.

2.3 Energy storage systems and their applications in power system

As the penetration level of the renewable energy sources (RES) into grid system rises, there is increasing concern on the reliability and security of the grids due to the unsteady power harnessed from the RES. One possible solution to the problem is to incorporate energy storage systems (ESS) with the renewable generators. It is even claimed that the lifetime of conventional thermal stations can be extended due to the fewer occurrences of startups, shutdowns and part-load operations, thereby leading to higher reliability for the power system [7].

As stated in Chapter 1, in power system applications, ESS are deployed in one of the three major functional area: power quality, bridging power and energy management. In power quality applications, fast-responding ESS is used for seconds or less intervals and respond almost instantaneously to compensate for voltage sags and/or swells to maintain voltage. Bridging power functionality involves the operation of the ESS for durations of minutes to tens of minutes to satisfy power demands from large industrial loads during, for example the loads' start-ups (peak-shaving) or to continuously support critical loads during momentary power system disruptions. ESS for energy management purposes must be able to store/supply uninterruptible power supply from a couple of hours up to a couple of days [9]. The use of such ESS can delay or even dispense with the need to start up conventional fossil fuel-based generators. Thus, they are capable of eliminating the uncertainty and intermittent nature of renewable energy sources. Another important application of ESS designed under this category is that the ESS can be charged when the energy cost is low and discharged as needed or when prices on the electricity spot market reach a threshold. Consequently, the timing of the production and consumption of the electrical energy is effectively decoupled. Unfortunately, none of the present-day ESS is economical or suitable to fulfill all the three functions. Examples of ESS applications in power systems are listed in Table 2-3.

Table 2-3 Examples of ESS applications in electric power system [38]

Grid application	Discharge duration	Power rating	Benefit (\$/kW)
Transmission support	10 s	100 MW	50 ~ 150
Area regulation	30 min.	40 MW	700 ~ 1500
Spinning reserve	15 min.	40 MW	700 ~ 1500
Load following	4 h.	1 MW	120 ~ 240
Electric energy time shift	8 h.	100 MW	120 ~ 250
Renewable energy management	1 ~ 10 h.	100 MW	1000 ~ 1500

From Table 2-3, it can be seen that the required power rating of ESS in practical utility applications typically ranges from few MW to about a hundred MW. Furthermore, by comparing the median benefit of the ESS among the various grid applications, using ESS for managing renewable energy will bring in most benefit. Therefore in accordance with this observation, it is indeed logical that the attention of this thesis shall be focused on the incorporation of ESS with renewable power generation such as that harnessed from the wind.

2.3.1 Types of ESS

Several types of energy storage technologies have been under active development over the last few decades. The basic operating principles for some of these technologies that have found successful applications in electric power systems will be briefly explained in this section.

2.3.1.1 Supercapacitor energy storage

Supercapacitor energy storage (SC) has characteristics similar to that of the conventional capacitor except that its physical size is about a hundred times smaller and its cycle life is two times longer [39, 40]. The efficiency of the SC is very high at about 95%. Similar to

the flywheel energy storage (FES) and superconducting magnetic energy storage (SMES), supercapacitor is useful in high power, short duration applications such as for power quality enhancement. The disadvantages of SC are its relatively high cost and its voltage is less than 3-volt. For typical grid storage application, it will require a large number of series connected SC. Consequently, many voltage balancing circuits would be needed which adds complexity and cost to the design. An example of supercapacitor energy storage is described in [8] where it can provide 2 MW, 2-s ride through during momentary power system disturbances.

2.3.1.2 Battery energy storage

A battery stores electricity in the form of chemical energy and it is available in a variety of chemistry materials. For example: lead acid, sodium-sulfur, nickel cadmium, vanadium redox, lithium, are some of the different types of battery energy storage system (BESS) implemented on a large-scale and are used in utility-scale applications such as in frequency regulation, un-interruptible power supply and for integrating renewable energy resources [8, 41]. Depending on battery chemistries, the energy efficiency of BESS ranges between 60 to 90%. As a long-term ESS, BESS is considered to be more versatile as compared to pumped hydroelectric storage (PHS) plant and compressed air energy storage (CAES). The energy capacity for BESS can be sized to fit particular applications. Therefore its design is modular. Additionally, BESS is less restricted by location / terrain constraints and it has much shorter construction time compared to PHS and CAES. Currently, the nickel cadmium BESS installation located in Alaska, USA, has the capability to discharge 46 MW for five-minute and it is considered to be the most powerful BESS by Guinness world records.

2.3.1.3 Pumped Hydroelectric Storage

Pumped Hydroelectric Storage (PHS) plant is typically deployed for energy management applications as it can store the largest amount of electrical energy and the period of storage is among the longest [42]. Consequently, PHS is one of the most widely implemented energy management ESS and is regarded as the most effective option among all large-scale

energy storage technologies. Depending on the energy capacity of the reservoir, large amount of energy can be stored / produced by the PHS for a few hours and up to a couple of days. The generator units also serve as motor units but apart from that, they operate along the same principles of a hydroelectric power plant. Generally, the energy efficiency of PHS is between 70% to 80%: Factors affecting the efficiency include the capacity of the plant, diameter of the penstock, types of hydro-turbines used, and the height between the upper and lower reservoirs [43]. The major disadvantages of the PHS are the long construction time (up to about 8 to 10 years), significant capital outlay of about \$1000/kW and limited available sites as the upper and lower reservoirs required large land area with suitable topography. Currently, the nameplate capacity of the largest operating PHS facility is 3 003 MW and it is located at Bath County, Virginia, USA [44].

2.3.1.4 Compressed air energy storage

Compressed air energy storage (CAES) is another large-scale ESS suitable for energy management applications. A CAES plant uses two-third less fuel compared to a conventional generation unit and this leads to a two-third reduction in the environmental pollution compared to that caused by the conventional combustion process of turbines. CAES stores energy by using off peak electrical power generated from base load plants or renewable energy sources to compress air into an underground reservoir such as in a rock or salt cavern [45]. Then during times of high electrical demand, the compressed air is combined with one of the variety of fuels to drive a turbine-generator set. The efficiency of CAES is about 70% [46]. The disadvantages of CAES are that the air storage reservoir needs to be air-tight and very large in order to operate for an extensive period of time. Although CAES is a mature storage technology, there are only two existing projects in the world currently.

2.3.1.5 Flywheel

Flywheel energy storage (FES) stores energy in the angular momentum of a spinning mass. During charging, an accelerating torque is created by a motor to store energy in the flywheel while the same motor acts as a generator slows down the flywheel and produces

electricity when discharging. The energy capacity of a flywheel is dependent on the physical dimensions and speed of its rotor while the power rating is governed by its motor-generator rating [47]. Consequently, recent developments improve the flywheel energy capacity by utilizing composite materials instead of making the wheel out of homogeneous metals, while the standard bearing is replaced with levitated magnetic bearing. These are done so as to increase the speed but reduce the physical size and weight of the flywheel. The efficiency of the flywheel is a function of its output power and it is usually higher than 80% for power in the range of 10 to 100% of its rated power [41]. A utility-scale FES is the ten-flywheel installation totaling 5 MW, 0.5 MWh in Ontario, Canada where it is used to balance real and reactive power flows from a 20 MW wind farm [47].

2.3.1.6 Superconducting magnetic energy storage

Superconducting magnetic energy storage (SMES) is able to store electricity as direct current passing through a circular inductor made from superconducting material so that the current will circulate indefinitely with almost zero losses. Although SMES has relatively small energy density, it has a rapid response and is capable of withstanding high voltage and current, thus making it suitable for high power but short duration applications [48]. SMES has very high energy storage efficiency of greater than 90% [41]. The disadvantages of this type of ESS are the high cost, environmental as well as the safety issues associated with large magnetic field [41]. Presently, only several demonstration projects have been deployed.

2.3.2 Comparison between ESS

The Ragone plots of Fig. 2-12 provide a useful comparison between the usage regimes of various ESS. It is seen that the supercapacitor has much higher power density as compared to that of the battery. Additionally, as the energy density of the fuel cell can be higher than that of the battery, it is deemed that fuel cell is suitable for use in long duration energy management applications. The types of ESS suitable for the three major functional categories of grid storage applications are illustrated in Fig. 2-13. It shows that for short

duration applications such as for power quality enhancement, one could utilize supercapacitors, SMES or FES [50]. Conversely, PHS, CAES, flow batteries such as vanadium redox (VRB) and advanced lead-acid battery will be suitable for energy management function as this application requires the ESS to be able to sustain discharge for hours. For bridging power purposes which involve discharging time in terms of minutes, it is seen that the main ESS candidate is the electrochemical batteries [50].

Fig. 2-12 Ragone plots of various energy storage devices [49]

Fig. 2-13 Suitable ESS for deploying in the three major functional categories of grid storage applications [50]

The essential parameters for some of the energy storage devices described in this section are listed in Table 2-4. As shown in the table, the typical capacity, efficiency, capital cost

and lifetime of the storage system are compared. It is seen that both the PHS and CAES can be used for very large-scale energy management applications as they have very large power ratings. Additionally, both ESS have very extensive lifetime but the capital cost of the PHS is higher than that of the CAES. Although both the supercapacitor and flywheel energy storage have similar characteristics in terms of power rating and efficiency, it is seen that the cost / MWh for the SC can be about 3 times lower than that of the FES. Even though lead-acid battery has a much lower lifetime as compared to all the ESS listed, it still provides a good compromise in many applications as it is based on a much matured technology [8, 50].

Table 2-4 Key parameters for the different energy storage technologies [42]

Technology	Typical size range (MW)	Round-trip electrical efficiency (%)	Typical lifetime	Capital cost (2006)	
				\$ / MW	\$ / MWh
Pumped hydroelectric storage (PHS)	100~1000	70 ~ 80	> 30 years	600,000 ~ 1000,000	10,000 ~ 350,000
Compressed air energy storage (CAES)	50~300	70	20 ~ 40 years	500,000 ~ 900,000	10,000 ~ 50,000
Lead-acid battery	0.5~100	75 ~ 90	300 ~ 500 charge / discharge cycle	100,000 ~ 200,000	150,000 ~ 300,000
Flywheel Energy Storage (FES)	1~10	80 ~ 90	≈ 20 years	200,000 ~ 500,000	1000,000 ~ 5000,000
Supercapacitor energy storage (SC)	≤ 2	85 ~ 98	≥ 50000 charge / discharge cycle	100,000 ~ 300,000	300,000 ~ 2000,000

2.3.3 Energy storage medium selection

It is explained in Section 2.1 that analyzing wind power profile in frequency domain can be a logical starting point in selecting a suitable type of ESS for particular grid-wind power application. From the wind power spectrum obtained at NTU as well as other published works, it is established that most of the wind energy is contributed by the low-frequency power components instead of that in the higher frequency power components. As the focus of this thesis is on achieving power dispatchability of wind generation by the incorporation of ESS, therefore those ESS which are intended for short duration applications such as the

supercapacitor, flywheel and the superconducting magnetic energy storage will be unsuitable for the power dispatching purpose. Conversely, suitable ESS contenders can be BESS, PHS and CAES as they have high specific energy density and the capability to be fully charged / discharged over long periods. For a typical wind farm capacity which is up to a hundred MW, BESS is deemed more appropriate as compared to the PHS and CAES. This is because as described in Section 2.3.1.2, the BESS does not require significant land area and unique geographic terrain. However in the event of many such wind farms distributed geographically over a vast area, PHS will be the preferred ESS for fulfilling the energy management function. PHS is selected over CAES as PHS is based on a much more matured technology and it is also regarded as the most effective option among all large-scale energy storage devices [35, 41].

2.3.4 Literature reviews on various wind-ESS schemes

The importance of the flexibility that energy storage technologies can provide to electric power system is widely anticipated and recognized. With wind power experiencing rapid growth, this situation has stimulated much research activities on various schemes such as that of [12, 14, 51 – 75]. The aims of these schemes are to exploit the advantages offered by ESS so as to successfully integrate the intermittent wind resource into the grid systems and also to enhance the value of wind power.

In the use of ESS to mitigate the negative impacts of renewable wind resource, most literatures categorize the design of the wind-ESS scheme into planning and operational planning. For the former, the tasks can be to select the suitable type of ESS and determine both the power and energy capacities of the ESS. Operational planning is pertaining to the design of control strategies for the short-term operation of the wind power station where the ESS power and energy capacities are already known. In most literatures, the planning and operational planning of the wind-ESS schemes are often separated.

On the main objective in planning to determine the capacities of the ESS, several planning tools have been developed in [12, 51 – 58]. However, the tools developed in these

references are intended for autonomous power systems only and not for grid-connected wind farms. For the scheme in [53], a low-pass filter with a variable time constant is utilized to determine the optimal BESS capacities. One drawback of this method, as well as that proposed by the authors of [54, 55], are the BESS capacities are determined for the worst case scenario. Unfortunately, this would lead to exceedingly large and thus uneconomical ESS. Alternatively in [56], the optimal BESS ratings are established as the minimum BESS capacities selected from among four different control strategies. However, the method only considers the capital costs of the BESS but neglects the benefit that can be derived from the use of the BESS. A probabilistic approach to evaluate the required ESS capacities and also takes into consideration the uncertainty in the input wind power is proposed in [57]. The method proposed there requires the ESS power and energy capacities to be treated as independent design variables. Hence in determining the power capacity, the authors assume the ESS energy capacity is unbounded and vice versa. This shortcoming is also seen in the approach of [58].

The works in [59 – 69] are related to operational planning where the objective is to develop control strategies to operate the combined wind power-energy storage system. A simulation study is undertaken in [59] to investigate the effect of using ESS to enhance the grid system power quality in which there is high penetration of wind power generation in the grid. The study analyses whether the output fluctuations of wind power will be smoothed more effectively if single ESS unit is installed within each individual WTG in a distributed manner or as an aggregated ESS which is then connected at the collection bus of the wind farm. The simulation results show that with lesser power losses, the aggregated ESS is more effective in smoothing the wind power variability. Nevertheless, the study of [59] as well as that of [60] are in contrast to the main objective of this thesis which is on energy management where economic benefit can be obtained from wind power trading as the wind power becomes dispatchable. In [61], a probabilistic method is used to estimate the percentage of the time the ESS is in fully charged and discharged states. However, the method is applicable only for a standalone power system but the need to meet firm power dispatch has been ignored. In a similar manner, model predictive control method is used in [62] to develop a BESS controller to meet local load requirements in an isolated power

system containing wind and solar renewable generations. The disadvantages of this scheme are that the energies from both the wind and the sun are not maximally harnessed and the energy storage capacity of the BESS is not utilized efficiently. In the event when the total power generation from both wind and solar is greater than the load, the excess energy is curtailed instead of charging the battery. In [63], the performance of a demonstration project consisting of a BESS and hybrid PV/wind power system which is installed on the rooftop of an educational institution is reported. However, the hybrid PV/wind system is operated in a manner similar to the present situation in which utilities are often obliged to give priority to renewable energy resources. In the event that there is insufficient energy from the PV-wind resource and the BESS has discharged to its minimum storage capacity, the local load will be served by the grid. Conversely, when the BESS is charged to its maximum storage capacity and there is still excess PV-wind energy, the excess energy is then fed into the grid. Although this method prevents the load and the excess energy from the PV-wind resource from being curtailed, there are no preventive measures or control schemes to ensure that the occurrences of the maximum and minimum state-of-charge of the BESS will be kept to a minimum. Thus, the advantages of deploying the BESS are severely defeated.

To this end, a method which draws on the state-of-charge of the ESS will be presented in Chapter 3 and it is capable of mitigating the abovementioned shortcomings. An interesting fact brought out by the author of [63] is that although it is possible to utilize the wind and/or solar irradiance data from a nearby site when on-site historical data is unavailable, the energy harnessed at the actual site can be reduced significantly as a result of uncorrelated or little correlation between the two sites. The studies of [64, 65] are intended to realize short-term wind power dispatch similar to that achieved by most conventional thermal stations. However, a shortcoming of these schemes is that they can only compute the dispatch level for the next hour whereas longer duration of power dispatch commitments is usually required from the network operators. A main finding from [64, 65] concludes that if the finite power and energy capacities of the ESS are not appropriately selected, the effectiveness of the ESS will be compromised even with aptly designed dispatch strategies. In [66], a method based on optimization search procedure is proposed so that profit from

the trading of the wind power can be maximized. PHS is assumed as the form of the ESS. However, the scheme unrealistically assumes that the power generated from wind will be constant at hourly interval in order to facilitate computation. The authors of [66] claim that it is possible to use finer resolution of wind power data, but if this practice were to be adopted, the PHS will need to undergo frequent changes between pumping and generating operations. Clearly, this scheme is undesirable as the expected lifetime of the PHS or any ESS can be adversely affected by the excessive number of such pumping-generating mode changes.

As explained in Sections 2.3.1 – 2.3.3, different storage technologies have their own advantages and disadvantages. Therefore, instead of using just a particular type of ESS, the works of [67 – 69] have evaluated schemes involving hybrid energy storage system (HESS). HESS is formed from a combination of two or more different storage mediums. This is done to exploit the technical merits of the short-term ESS with its fast responding attribute and the large energy storage capacity of the long-term ESS. An important consideration when using the HESS is on how to coordinate the power flows between the long and short-term ESS. In [67], a simple ruled-based method has been proposed in which the charging/discharging of the short-term ESS is placed at higher priority than the long-term ESS. The authors assume the short-term ESS has higher round trip efficiency as compared to the long-term ESS. However, in the event when both the short and long-term ESS have to operate together, the authors have not suggested how the two ESS are to coordinate their actions. In both [68], [69], supercapacitor is selected to be the short-term ESS while battery ESS is chosen as the long-term ESS. A moving average filter is used in [68] to charge/discharge the BESS and the remaining fluctuant power will be handled by the SC. The aim of the study in [69] is to assess the practicality of a control algorithm to smoothen the wind power fluctuations by coupling the HESS with a wind turbine generator. Two filters are utilized for the purpose of establishing the reference powers of the BESS and SC. However by doing so, the proposed control algorithm results in heavier computational burden as compared to that of [68] where only a filter is used. Furthermore, since the usage of ESS with wind in [69] is only intended for power quality enhancement,

it is deemed that the approaches applied by [70, 71] will be more advantageous as the need to integrate the long-term ESS is eliminated.

For the output power from a wind-ESS scheme to be made dispatchable similar to conventional thermal generators during operational planning, it is realized that wind prediction tools are required to obtain an estimation of the future wind power production, based on the random input wind power. Furthermore, the wind farm needs to operate in a manner in compliance to the various prevailing power market rules. Hence, in view of the above and coupled with the main findings from [64, 65], the effectiveness of the ESS can be enhanced if the planning tool to determine the ESS capacities is developed with consideration to various pertinent operational issues such as the inevitable wind power prediction errors and the prevailing power market rules. A possible approach could be to design the dispatch strategy when the ESS capacities are unknown, such as during the planning stage of the ESS. The planning tool is to be developed in conjunction with the designed dispatch strategy to determine the optimal ESS capacities. In this manner, the planning study shall be carried out with the planned operational strategy of the wind-ESS scheme in mind. The viability of the wind-ESS scheme is achieved as a result that the committed firm power dispatch schedules are met. Similar approaches have also been utilized by the authors of [14, 72 – 75].

In [72, 73], short-term power dispatch schemes using BESS which are in compliance with the prevailing power market rules are proposed. However, the scheme in [72] utilizes two pairs of BESS-converters, with one handling the charging process while at the same time, the other is in the discharging mode. Compared to the use of single pair of BESS-converter in [73], the proposed approach of [72] may not be economically viable. Although the work reported in [73] only utilizes single unit of BESS, the developed technique only allows the BESS energy capacity to be determined but not its power capacity. This is an incomplete planning method as the cost of the ESS also depends on its power capacity. The planning technique developed in [74] is intended to determine the capacities of the BESS so that the wind farm-BESS scheme can provide firm power dispatch commitments similar to that of conventional thermal stations and also maintain the voltage level across the DC-link within

an allowable preset limits as the wind power fluctuates. As explained above, the design of the ESS/BESS does depend very much on the dispatch strategy and it is also important to consider the inevitable errors in the wind power prediction. However, the approaches in [74] as well as that of [73, 75] use actual wind data. In [75], the planning method is extended to determine the capacities of the HESS where the SC and BESS are the short-term and long-term ESS respectively. Unfortunately, this scheme and also that of [74] compute the required ESS capacities that are meant for the worst-case scenario. Moreover, the committed firm power schedules determined from the designed dispatch strategy in both schemes can only assume a constant value instead of according to the predicted wind conditions. Clearly, the designed dispatch strategies in both schemes are inflexible. The coupling of HESS with a wind farm is proposed in [14]. Although the HESS and the wind farm are connected to the main grid in the scheme, the output power of the wind farm-HESS is used mainly to satisfy a local load. In the event of insufficient wind power generation, the HESS will be discharged to meet the load demand. Conversely, the HESS will be charged with the excess wind power when there is a congested transmission line situation. When given a combined HESS power reference, a low-pass filter is first utilized to derive the preliminary power references for the two individual storage devices. Subsequently, to maintain the state-of-charge of both the short-term and long-term ESS at half of their rated energy storage capacities so that there will be sufficient energy margin for the HESS to absorb (discharge) the surplus (deficit) in wind power, the preliminary power references are modified by artificial neural network based controllers to obtain the final power references. One major disadvantage of this scheme is that instead of charging the HESS with the excess wind power during uncongested transmission line conditions and then using the surplus energy to derive economic benefits in periods of high energy price, the scheme simply exported the excess energy to the grid. In doing so, the large energy capacity of the long-term ESS is not being exploited to decouple the timing of the production and consumption of electric energy. Furthermore as a result of the exported wind power is still highly fluctuating, additional provision of regulating reserves becomes necessary.

Beside the above reported works on coupling ESS with wind power generation, another active topic of research is on the use of ESS in smart grids. ESS is often deployed in a smart grid to provide grid support functions such as peak shaving and to assist in alleviating the ill effects brought about by intermittent renewable energy sources. For example: the study in [76] focuses on using stochastic optimization method to handle distributed renewable generations in a smart grid so that the expected electricity cost for residential customers is minimized. Conversely the objectives in [77] are for smoothing the fluctuations in wind power and also to reduce the operating cost of a power system by considering smart charging patterns for plug-in hybrid electric vehicles (PHEV) using stochastic unit commitment method.

Although some literatures such as that of [78 – 80] have reported that for the purpose of enhancing the grid system power quality, it is sufficient to rely on the operation of the wind turbine generators (WTG) alone without the need of any ESS. For example: The authors of [78] state that kinetic energy can be stored in the rotating masses of the WTG which in turn can be used to provide power system frequency regulation. Nevertheless, given the relatively low inertia constant of the mechanical part of the WTG, the proposed method may be unable to provide sufficient energy required to support frequency regulation. It is suggested in [79, 80] that with the associated power converters and the actions of the WTG pitch angle control, a power margin can be made available to the WTG. With this power margin, the WTG can either generate additional or further reduce its output power to aid frequency regulation. However, the main drawbacks of this strategy are the energy from the wind is not maximally harnessed and the reduced lifetime of the WTG as a result of wear and tear from frequent utilization of the pitch angle mechanism.

2.4 Conclusions

This chapter provides an introduction to the characteristic of wind and illustrates that variations in the wind speed induce fluctuations in the generated wind power as wind power varies as the cube power of the speed. From the analysis of the wind power in the frequency domain, the wind power spectrum provides an insight to the selection of ESS for particular grid application. As the most significant proportion of the wind energy is concentrated over the low-frequency band of the wind power, attention should be directed at the low-frequency wind power components when selecting the appropriate ESS for the purpose of maximizing the harness of the wind energy. As the input wind power is random, it is necessary to use forecasting tools to estimate the future wind power production.

With regard to wind power forecasting techniques, linear statistical wind forecasting techniques are less demanding to implement. As a result of the non-linear wind turbine output power characteristic curve, the analysis shown in this chapter explains why the statistical distribution of wind power prediction error is non-Gaussian, even though the wind speed prediction error distribution can be Gaussian.

To mitigate the unsteady wind power, a technique can be to use energy storage systems (ESS) as energy buffer. In this approach, the requirements of the ESS for different grid applications are discussed. Comparison among the different types of ESS in terms of their electrical efficiencies, typical capacity ranges, costs, power and energy densities, have also been shown.

In the next chapter, a statistical method will be proposed to determine the capacities of the ESS so that the output power of a wind farm can achieve controllable and dispatchable behavior similar to that of a conventional power station. For operational planning of the wind farm-ESS scheme, a dispatch strategy which takes into account the state-of-charge (SOC) of the ESS will be presented. This is done so as to minimize the occurrences of the ESS being over-charged or over-discharged and also to utilize the ESS in a more efficient manner.

Chapter 3: Wind Turbine Generator – Energy Storage Scheme to Achieve Power Dispatchability

As alluded to in Chapter 2 while wind-powered electricity generation technology is quite mature, unfortunately wind itself is an unsteady energy source. Consequently, power system operators need to allocate additional regulating reserves to mitigate the negative impacts brought about by the fluctuating wind generation [17]. Fortunately, the extents of the power fluctuations at the output of a wind farm are impacted by the number of wind turbine generators (WTG) which are dispersed at different locations in the farm. For a farm with N units of WTG, the fluctuation in the aggregated wind farm power is expected to reduce by a factor of $N^{-1/2}$ when compared to that of a single WTG. This is because all the N units of WTG do not encounter the same turbulence intensity of the wind concurrently as there will be time delays for the wind to traverse the distances separating the various WTG. This is the notion of the so-called spatial smoothing effect described in [7, 81].

Two commonly used strategies pertaining to grid-connected wind generators as described in [79, 82], either lead to the maximum harnessing of the wind energy or result in more constant (less fluctuant) power dispatch. The shortcoming based on the former strategy is that the intensity of the WTG output power fluctuations could be so high as to degrade power quality to an unacceptable level, especially in weak grids [82]. Conversely, the power strategy that results in less power fluctuations utilizes the control actions of power conditioning converters coupled to the WTG, complemented by pitch angle control [79]. However as explained in Section 2.3.4, the drawback of this latter scheme is energy from the wind is not maximally harnessed. Furthermore, even taking advantage of the abovementioned spatial smoothing effect, the application of the two strategies would not readily allow wind farm to commit its output power several hours or a day ahead. Such short-term power dispatchability is an advantage enjoyed by most conventional thermal stations and it would be most desirable if wind farms could also exhibit the same level of dispatchability.

In this connection, one technique to help achieve short-term dispatchability of wind power generation can be through the incorporation of energy storage system (ESS) in wind farms. Indeed and as described by the literature reviews in Section 2.3.4, integrating ESS in wind farms to realize short-term wind power dispatch has attracted the attention of various researchers. In view of the above, the objective in this chapter will be to design a scheme to integrate an ESS within a wind farm which will in turn allow it to provide firm power dispatch commitment to the grid. In this scheme, two aspects of the design will be dealt with: that for planning and for operational planning. In the planning phase, the task is to determine the required ESS power and energy capacities. A statistical approach will be adopted to deal with this design issue. Operational planning is pertaining to the design of a short-term dispatch scheme where it has been assumed the ESS power and energy capacities are known. As such, a method will be developed to determine the schedule of the wind farm output power to meet the prevailing power market rules, even when it is subjected to the condition of varying and uncertain wind power. With this method, wind farm operators will have the opportunity to participate in power dispatch under a modern power market environment.

Having explained the advantages of achieving wind power dispatchability in Chapter 2 and the rationale of the design objective above, Section 3.1 will present an overview of the structure of the adopted wind-ESS scheme. Next, pertinent design consideration such as the prevailing power market rules shall be described in Section 3.2. In Section 3.3, the determination of the ESS capacities is considered in the planning phase, by taking into account the various operational issues and the accuracy of the wind power prediction. For operational planning, the design of a short-term power dispatch strategy for the wind farm is presented in Section 3.4. The new dispatch strategy takes into account the state-of-charge (SOC) of the ESS. A numerical example is included in Section 3.5 to demonstrate the feasibility of the proposed scheme in achieving firm power dispatch.

Some of the materials contained in this chapter also appear in the author's publication [83].

3.1 Structure of dispatchable wind power – ESS scheme

Fig. 3-1 Wind farm incorporating an ESS interconnected to the grid

Fig. 3-1 shows the real power flows within a generic grid-connected wind farm-ESS scheme where the directions of the arrows represent the assumed positive direction of the power flows. It shows a wind farm (represented by an equivalent WTG) operating in parallel with an ESS and dispatching power $P_d(t)$ into the grid. Power conversion devices between the wind farm, ESS and the grid have been omitted from the power flows consideration as losses in these devices tend to be relatively small. These devices include the electronic switches used in the converters for the WTG, for charging / discharging the ESS as well as those utilized in the inverter to interface the wind-ESS scheme to the grid. $P_W(t)$ in Fig. 3-1 denotes the wind generator output power. $P_d(t)$ represents the constant dispatch power that the wind farm can commit to the grid. With the ESS acting as an energy buffer, the fluctuating power components from the wind will be regulated by the ESS, i.e. any power deviations between $P_d(t)$ and $P_W(t)$ will be compensated by $P_E(t)$. Hence from Fig. 3-1, $P_d(t)$, $P_W(t)$ and $P_E(t)$ are governed by the relationship

$$P_d(t) = P_W(t) - P_E(t) \quad (3.1)$$

The ESS power $P_E(t)$ in Fig. 3-1 should ideally be represented by a bidirectional arrow as it is possible for power to flow both to / from the ESS. However, to illustrate the relationship between $P_d(t)$, $P_W(t)$ and $P_E(t)$ as described by (3.1), it is decided to represent

the positive direction (charging) of the power flows for $P_E(t)$ by a unidirectional arrow in Fig. 3-1. The advantage of the single ESS unit considered in Fig. 3-1 obviates the need of the rather complicated BESS switch-over scheme described in [72].

3.2 Short-term power market rulings

In the present context, the planning phase of the scheme is only concerned with determining the required capacities of the ESS for a fixed wind farm size. However, planning and operational planning of the wind-ESS scheme are closely interrelated. Various operational issues such as complying with the prevailing power market rules and the inevitable wind power prediction errors should be taken into consideration when devising the planning tool. As alluded to in Chapter 2, operating wind generation in a grid requires the forecasting of wind power in order to plan for the allocation of the regulating reserves to be carried by the grid or for determining the constant dispatch power $P_d(t)$. How to determine $P_d(t)$ will be dealt with in the next section. From Chapter 2, it is seen that wind power forecast is prone to error and this contributes to power mismatch between the power production and the load demand. The role of the ESS, as described in Section 3.1, is to act as an energy buffer to compensate for any power deviations between $P_d(t)$ and $P_w(t)$, and hence, the errors in the predicted wind power must be considered. This is as explained in Section 2.3.4 and from the finding of [64, 65] that by considering the inevitable wind power prediction errors, one of the pertinent operational issues in the development of the planning tool to determine the ESS capacities, the effectiveness of the ESS can be enhanced. Therefore, the approach herein is in contrast to those described in [73, 75] which use the actual wind data.

Fig. 3-2 shows a typical example of the various types of electricity market. For short-term firm power dispatching purpose, only the day-ahead market and the intraday market will need to be considered. Generally, the firm dispatch schedule will be allowed to vary from one constant level to another after an interval of τ hours, where τ is typically 0.5 or 1 or even longer: the exact duration shall depend on the prevailing dispatch policy of the power market. Additionally, most intraday market rule requires the power plant operators to adhere to their pre-determined bids on the power dispatch commitment of the immediate

m hours or face financial penalty. Typically m ranges from 1 to 3 [18, 85]. To meet this objective, the wind farm operators will have to rely on the forecasted wind power when planning the power dispatch commitment and the exact method to do so shall be explained in the next Section.

Fig. 3-2 Types of electricity market [84]

The error in the wind power forecast increases with longer prediction horizon and this aspect has been explained in Chapter 2 as well as in [22, 84]. Consequently, operational planning for a day-ahead market as compared to an intraday market will pose greater challenges for both the determination of the ESS rating requirements and the design of the short-term dispatch.

3.3 Determination of ESS capacities: a planning task

A new planning method is now proposed which considers the operational constraints of the intraday power market and the errors in the wind power forecast.

3.3.1 Determination of dispatch power reference

When designing the ESS for a wind farm, it is reasonable to assume sufficient historical data on $P_W(t)$ is available. For the ESS design problem in hand, it is necessary to firstly consider how the wind farm-ESS shall operate in order to meet the short-term dispatch commitments $P_d(t)$. Unlike a conventional power station, the input wind power $P_W(t)$ is random and therefore, in planning $P_d(t)$, the wind farm operator will need to forecast $P_W(t)$. To emulate a possible short-term dispatch planning procedure undertaken by the operator,

a portion of $P_w(t)$, $0 \leq t \leq T_1$, is used to provide the wind power forecast $P_{w,f}(t)$ for the following period T , which is typically of several hours. An example of $P_w(t)$, and of $P_{w,f}(t)$ are shown in Fig. 3-3. The exact method of obtaining $P_{w,f}(t)$ is not the focus of this thesis; rather it is assumed any one of the currently available forecasting methods such as that described in Section 2.2 has been used. The forecasted short-term wind power for the period T ($T_1 < t \leq T_2$), can, therefore, be generated.

Fig. 3-3 $P_w(t)$ from WTG and $P_{d,r}(t)$ obtained from the forecasted $P_{w,f}(t)$: detailed plot showing ESS charging (C) and discharging (D) intervals

The short-term dispatch power $P_d(t)$ is then derived from the forecasted wind power $P_{w,f}(t)$ for $T_1 < t \leq T_2$. As explained in Section 3.2, $P_d(t)$ is intended to remain constant at every τ hourly duration. The constant dispatch level is denoted as $P_{d,r}(t)$, the reference quantity for $P_d(t)$ for the interval τ , is shown in Fig. 3-3. Within each τ , $P_{d,r}(t)$ shall be determined from $P_{w,f}(t)$ by ensuring that there is no net change in the ESS stored energy level, in accordance to the forecasted $P_{w,f}(t)$, i.e.,

$$\int_0^{\tau} (P_{w,f}(t) - P_{d,r}(t)) \cdot dt = 0 \quad (3.2)$$

The main intention is to devise useful preliminary planning tools for various wind-ESS schemes to achieve firm power dispatchability from wind resource. Thus (3.2) as well as the studies in latter chapters do not consider the losses in the ESS for ease of computation. Next, the dispatch power $P_d(t)$ is set equal to its reference level $P_{d,r}(t)$: $P_{d,r}(t)$ becomes the wind farm committed dispatch power. However as explained afore, long prediction horizon leads to larger wind power forecast errors. Therefore to improve accuracy and to obtain a more precise dispatch $P_{d,r}(t)$, those $P_{d,r}(t)$ beyond the immediate m hours ahead will be revised at every τ -interval using (3.2) in accordance to the latest wind power forecast $P_{W,f}(t)$. As under normal power market rule, revision of $P_{d,r}(t)$ can be affected at every τ -interval. Thus, the approach explained above is deemed reasonable.

3.3.2 A statistical method to determine ESS power and energy capacities

Even with the approach of revising the dispatch commitment at every τ -interval, it is expected that $P_{W,f}(t)$ would not be identical to the actual wind power $P_W(t)$, $T_1 \leq t \leq T_2$, due to the inevitable forecasting error. By setting $P_d(t) = P_{d,r}(t)$ into (3.1), one can then rewrite (3.1) as

$$P_{E,r}(t) = P_W(t) - P_{d,r}(t) \quad (3.3)$$

$P_{E,r}(t)$ in (3.3) denotes the reference mismatched power between $P_W(t)$ and $P_{d,r}(t)$ which also represents the power to be compensated by the ESS. Note that with spatial smoothing effect as explained in [7, 81], the level of power fluctuation in $P_W(t)$ and $P_{E,r}(t)$ can be reduced correspondingly as the number of WTG increases. Fig. 3-3 shows that within any particular interval τ , the areas labeled as C correspond to instances when $P_W(t)$ is larger than $P_{d,r}(t)$. Hence, the ESS is being charged by the WTG over these instances, i.e. $P_{E,r}(t) > 0$. Conversely, areas D signify instances when the ESS is discharging. Hence $P_{E,r}(t) < 0$.

Using (3.3), $P_{E,r}(t)$ over a given study period T_s can be determined. As $P_W(t)$ is a random variable, it is expected that $P_{E,r}(t)$ would be random too. It is therefore proposed that the probability density function (pdf) and cumulative probability function (cdf) of $P_{E,r}(t)$ be

computed. An example of the pdf and cdf of $P_{E,r}(t)$, denoted by the functions $f(P_{E,r}(t))$ and $g(P_{E,r}(t))$ are shown in Figs. 3-4 and 3-5 respectively. Note that $f(P_{E,r}(t))$ may not be symmetric and hence, the maximum charging power level X is not equal to the maximum discharging power level Y .

Fig. 3-4 Probability density function of $P_{E,r}(t)$

Fig. 3-5 Cumulative probability function of $P_{E,r}(t)$

The result shown on Fig. 3-5 is very useful. Depending on the confidence level that the wind farm operator wishes to commit power reliably into the grid, the ESS power rating $P_{E,R}$ can be readily determined using the cdf. Using Fig. 3-5 as an example, suppose $X > Y$ and it was decided that the power rating of the ESS is to be X p.u. MW, this means that the ESS is capable of delivering/absorbing a maximum power of X p.u. MW. With this rating, a confidence level of 100% in terms of successful power dispatch can be expected in view of Fig. 3-5. Therefore, this statistical method can be used to determine the ESS power capacity in which the capacity can be related to the confidence level in successful power dispatch.

Next, in order to determine the ESS energy capacity, the mismatched ESS power is first integrated with respect to time to obtain the change in the stored energy level ($\Delta E(t)$) in the ESS. The initial $\Delta E(0)$ in the ESS is 0-MWh. Suppose if the maximum change in the stored value of the ESS when absorbing the surplus energy from the wind is ΔE_+ (a positive value) and the maximum change in the stored energy when supplying its energy to the grid is ΔE_- (a negative value). Then $(\Delta E_+ - \Delta E_-)$ will represent the minimum energy capacity of the ESS in order to commit power reliably into the grid within the study period T_s . In most ESS, there is a finite range of its stored energy level in which the ESS is allowed to operate in. Consequently, both the minimum and maximum storage energy limits of the ESS should not be violated to prevent reduction in the ESS lifetime. For example, the useful stored energy level of electrochemical batteries designed for renewable energy applications typically ranged from 50% to 90% [8]. Denote the useful range, minimum and maximum energy storage level of the ESS as $d_{E,max}$, E_{min} , and E_{max} respectively where $d_{E,max}$ has the unit of percentage while E_{min} , and E_{max} are expressed in p.u. MWh. Thus E_{min} can be expressed in terms of $d_{E,max}$ and the above $(\Delta E_+ - \Delta E_-)$, viz.

$$E_{min} = \frac{(1 - d_{E,max}) \cdot (\Delta E_+ - \Delta E_-)}{d_{E,max}} \quad (3.4a)$$

where both ΔE_+ and ΔE_- have the unit of p.u. MWh.

And the maximum energy storage limit of the ESS E_{max} which should not be exceeded is determined as

$$E_{max} = E_{min} + (\Delta E_+ - \Delta E_-) \quad (3.4b)$$

E_{max} , as determined in (3.4b), shall be the minimum energy capacity (nameplate) rating (E_R) of the ESS required to commit power reliably into the grid within the study period T_s at 100% confidence level. An example of E_R is shown in Fig. 3-6(b). With the ESS rated

energy capacity E_R so defined, the actual stored energy in the ESS at any given time t is given by

$$E(t) = E_{min} - \Delta E_- + \Delta E(t) \quad (3.4c)$$

where both $E(t)$ and $\Delta E(t)$ have the unit of p.u. MWh.

With all values of $E(t)$ so determined over T_s , its pdf and cdf can then be computed. An example of $\Delta E(t)$ is shown in Fig. 3-6(a) while Fig. 3-6(b) shows $E(t)$ and also the minimum stored energy level E_{min} .

Fig. 3-6(a) Change in the stored energy level of the ESS; and (b) actual energy level in the ESS

3.4 Operational planning: short-term power dispatch scheme

Once the power and energy capacities of the ESS have been determined, the next focus is on how to achieve firm power dispatch from the wind farm for operational planning purpose. A short-term power dispatch scheme is hereby proposed.

Although the dispatch $P_{d,r}(t)$ can be determined using the wind power forecast explained in Section 3.3.1, it is intended in operational planning that the ESS be utilized more efficiently and to avoid the situation where the ESS is empty or full by taking into account

the current amount of stored energy in the ESS when planning for future power dispatch bids. Denote the amount of stored energy in the ESS by its State-of-Charge (SOC). Hence the premise of the proposed design is to set a higher dispatch power bid than the original $P_{d,r}(t)$ when the ESS SOC is above a pre-determined level, and vice versa. To achieve this, the original dispatch bid $P_{d,r}(t)$ is modified by the inclusion of a correction factor denoted as the gain factor G . The gain factor G can be of the form shown in Fig. 3-7: the gain-factor is shown to vary with respect to the available ESS SOC level E_{PU} (in p.u. of ESS rated energy capacity) in a piece-wise linear manner.

Fig. 3-7 Gain-factor for determining new dispatch bid based on ESS SOC

Fig. 3-8 Short-term power dispatch control scheme

Fig. 3-8 shows the computational procedure for the short-term power dispatch control scheme. Suppose $P_{d,r}(t)$ is to be committed for the j^{th} -hour and beyond. The dispatch bids will need to be submitted latest at the i^{th} -hour where $i = j - m$. This is so because $P_{d,r}(t)$ for the immediate m hours after the i^{th} -hour cannot be altered from those values which have been committed earlier according to the power market rule described in Section 3.2. Therefore, the original dispatch power bid $P_{d,r}(t)$ will first be derived using (3.2) for $t \geq j$. Subsequently, by taking into consideration the ESS SOC level $E_{PU}(i)$ at the end of the i^{th} hour which is known through on-line measurement, the gain-factor G will be determined by the “Gain factor G : look-up table” block. However, as explained in Section 3.3.1, those $P_{d,r}(t)$ beyond the immediate m hours ahead will be revised at every τ -interval using (3.2) in accordance to the latest wind power forecast so that a more precise dispatch $P_{d,r}(t)$ will be obtained; only the original $P_{d,r}(t)$ which is within the interval $j \leq t < j + \tau$ will need to be modified by the proposed operational planning method. Note that the modification of $P_{d,r}(t)$ needs to be within $j \leq t < j + \tau$ as $P_{d,r}(t)$ must remain constant within the τ interval. Consequently, the new dispatch power value $P'_{d,r}(t)$ will be revised, viz.

$$P'_{d,r}(t) = P_{d,r}(t) + (G \times P_{d,r}(t)), \quad \text{for } j \leq t < (j + \tau) \quad (3.5)$$

With the new dispatch power value $P'_{d,r}(t)$ so determined, the reference power to be compensated by the ESS $P_{E,r}(t)$ in (3.3) now becomes

$$P_{E,r}(t) = P_w(t) - P'_{d,r}(t) \quad (3.6)$$

3.5 Numerical example

In this section, the feasibility of achieving firm power dispatch into the grid using the methodologies described in Sections 3.3 to 3.4 will be demonstrated using a numerical example. The case study is for a 30-MW wind farm operating in parallel with an ESS. In this investigation, the duration τ in which $P_{d,r}(t)$ is to remain constant is taken to be 1-hour.

Recalled that the power dispatch commitment of the immediate m hours cannot be altered and $m = 2$ herein.

To begin the ESS design process, $P_{E,r}(t)$ must first be determined. This in turn requires the knowledge of $P_{d,r}(t)$ which is derived from the forecasted wind power $P_{W,f}(t)$. As the exact method of obtaining $P_{W,f}(t)$ was not the focus of this investigation, it was assumed that the error in the forecast $P_{W,f}(t)$ follows Beta distribution similar to that adopted by [36]. The error in the wind power forecast was generated and added to $P_W(t)$ to form $P_{W,f}(t)$. The root-mean-square of the error was assumed to be 15%, a level typical in wind power forecast [22]. Fig. 3-9 shows an example of $P_{E,r}(t)$ obtained over the one-year study period.

Fig. 3-9 An example of $P_{E,r}(t)$ obtained over the one-year study period

3.5.1 Determining ESS power rating and energy capacity

The proposed planning scheme highlighted in Section 3.3 will be used to determine the ESS power and energy capacities. The actual wind power given in [87] for Iowa, USA from January 2009 to December 2009 will be used, and from it, the forecasted wind power $P_{W,f}(t)$ and committed power dispatch $P_{d,r}(t)$ are determined. Next, the ESS power $P_{E,r}(t)$ and the energy level in the ESS $E(t)$ over T_s are computed. The pdf and cdf of $P_{E,r}(t)$ are shown in Figs. 3-10 and 3-11 respectively.

Fig. 3-10 Pdf of $P_{E,r}(t)$ for the 30-MW wind farm

Fig. 3-11 Cdf of $P_{E,r}(t)$ for the 30-MW wind farm

From the cdf of $P_{E,r}(t)$ shown in Fig. 3-11, it was decided that the power rating of the ESS will be 11 MW. In Fig. 3-11, the probability of $P_{E,r}(t)$ of less than -11 MW is evaluated to be 0.5% while for that of $P_{E,r}(t) \leq 11$ MW is about 99.5%. Consequently, the rating of 11 MW will provide a confidence level of 99%. Hence, this means that for 99% of the time, the ESS is able to handle the mismatch power between $P_W(t)$ and $P_{d,r}(t)$ without $P_{E,r}(t)$ exceeding the ESS power rating.

Fig. 3-12 illustrates the example of the change in the ESS stored energy level $\Delta E(t)$ in a year while Fig. 3-13 shows that of the actual stored energy $E(t)$ in the ESS.

Fig. 3-12 A yearly example of $\Delta E(t)$

Fig. 3-13 A yearly example of $E(t)$

From Fig. 3-12, it can be seen that the maximum increase in the ESS stored energy change ΔE_+ is about 4 MWh while ΔE_- is about -5 MWh. Thus the minimum energy capacity of the ESS ($\Delta E_+ - \Delta E_-$) requires to commit power reliably into the grid within the study period T_s is 9 MWh. In Fig. 3-13, the minimum storage energy level of the ESS E_{min} is shown to be 2.25 MWh. This is evaluated using (3.4a) by assuming $d_{E,max} = 0.8$. Subsequently, the maximum energy storage limit of the ESS E_{max} which should not be exceeded is determined using (3.4b) and it is 11.25 MWh.

Next, similar statistical approach used to determine the ESS power capacity will be applied to determine the ESS energy capacity. Firstly, using the actual ESS stored energy $E(t)$ determined over the study period T_s which is as shown in Fig. 3-13, the pdf and cdf of ESS

stored energy level were computed and they are shown in Figs. 3-14 and 3-15 respectively. As the minimum energy storage level of the ESS $E_{min} = 2.25$ MWh for $d_{E,max} = 0.8$ in this study, therefore, both the pdf and cdf of the ESS energy $E(t)$, i.e. $f(E(t))$ and $g(E(t))$ are zero for $E(t) < 2.25$ MWh. Suppose it is intended to achieve a confidence level of 98.5%, then from Fig. 3-15, this will require the rated ESS energy capacity E_R to be 10-MWh.

Fig. 3-14 ESS energy pdf

Fig. 3-15 ESS energy cdf

3.5.2 Short-term power dispatch

A 1-month duration of the actual wind power for the same Iowa wind turbine site in [87] for January 2010 will be used in this example. With the forecasted wind power $P_{w,f}(t)$, the original dispatch bid $P_{d,r}(t)$ will first be determined using (3.2). The purpose in this section is to have the wind farm operates in parallel with the 11-MW, 10-MWh ESS determined from the previous section and then to design the short-term dispatch for the January period.

The simulation results from this case study will provide a good test of the adequacy for the determined ESS ratings and also the proposed dispatch scheme.

The gain of the piece-wise linear gain factor curve shown in Fig. 3-7 was chosen in a manner to maximize the energy exported from the wind-ESS scheme over T_s , i.e.

$$\text{Max.} \int_{t \in T_s} P'_{d,r}(t) \cdot dt \cdot$$

The optimal gain factors were searched between the range of -1 to 1 at the corresponding ESS SOC of 0.2, 0.5 and 1.0 of the selected E_R of 10-MWh. Subsequently, the “Gain factor G : look-up table” block shown in Fig. 3-8 was constructed by linearly interpolating the gain factors determined. The optimal gain factors were determined to be -0.28, 0 and 1.0 at the ESS SOC of 0.2, 0.5 and 1 respectively. Fig. 3-16 depicts the determined piece-wise linear gain factor G curve used in this study.

Fig. 3-16 Determined gain factor G curve

The initial SOC of the ESS for this part of the study is assumed to be 0.5 p.u. From the simulation results obtained, it is seen that despite the varying wind power $P_W(t)$, the proposed WTG-ESS scheme is able to maintain its output power $P_d(t)$ in a constant manner at hourly interval: an ability which is not possible for a wind power station without energy storage facility. Hence, the objective of firm power dispatch has been attained. A sample plot of $P_W(t)$, $P_d(t)$ and $P_E(t)$ over a 24-hour period is shown in Fig. 3-17(a) – (c) while Fig. 3-18 shows the ESS SOC level over a period of one month.

Fig. 3-17 Daily power plots of (a) $P_W(t)$; (b) $P_d(t)$; and (c) $P_E(t)$

Fig. 3-18 ESS SOC level

From Fig. 3-17, it is seen that the power absorbed/discharged by the ESS is kept within the limit of 11 MW. In addition, the export power $P_d(t)$ is equal to the difference between $P_W(t)$ and $P_E(t)$ in every instance. Hence, the specified confidence level of being able to commit power reliably into the electric grid can be achieved by the proper selection of the required ESS ratings. However, as the confidence level is less than 100%, there will still be instances whereby $P_E(t)$ reaches its limit and $P_d(t)$ cannot be maintained at the set level.

Fortunately, over the studied interval, no such events have been observed from the simulation results.

Furthermore, with the usable range of the ESS stored energy level $d_{E,max}$ set to be 0.8, it is seen from Fig. 3-18 that the SOC level of the ESS is kept between its stipulated limit of 0.2 and 1.0 pu of its rated energy capacity. From the simulation results, it is promising to note that this short-term dispatch scheme does indeed provide a viable option for firm power dispatch from the wind farm.

3.6 Conclusions

An energy storage system (ESS) has been considered in this chapter which allows the unsteady power harnessed from the wind to be stabilized. To achieve the hourly constant power dispatch objective, the power dispatch problem has been examined from two aspects: planning and operational planning. The planning problem is pertaining to the determination of the ESS power and energy capacities. The operational planning aspect is to deal with the short-term dispatch of the wind farm. The two aspects are interrelated and it is imperative to take into account the various operational requirements when determining the appropriate ESS capacities. Simulation results obtained so far show that the proposed approach to the planning and dispatch strategy of the wind farm-ESS scheme is promising. With the wind farm being capable of scheduling its output power in a manner similar to conventional thermal station, power system operators will need to allocate less regulating reserves for the grid. In this manner, it thus reduces the overall power production cost for the grid.

In this chapter, a generic ESS is proposed to be incorporated with a wind farm. For a typical wind farm and as alluded to Sections 2.3.1.2 and 2.3.3, batteries ESS (BESS) can be a feasible ESS medium because it is more versatile as long-term ESS as compared to the PHS and CAES. However, due to the relatively high cost of the BESS when deployed for energy management purpose and most BESS tend to have shorter lifetime when compared to the service life of the wind farm, it becomes highly desirable to maximize the operational

life of the BESS. In view of the above reasons, a statistical approach to the design of a hybrid battery-supercapacitor energy storage system for a wind farm will be described in the next chapter. The intent is to prevent the expected lifetime of the BESS from being adversely reduced by the perturbing wind farm output power.

Chapter 4: Least-Cost Battery-Supercapacitor Energy Storage System for Wind Power Dispatching

In the previous chapter, a scheme is proposed to integrate a generic energy storage system (ESS) within a wind farm so that the integrated wind farm-ESS output power can be controlled in a manner similar to that of a conventional thermal station. In the scheme, a statistical approach has been utilized to determine the ESS capacities, and the capacities are related to the confidence level in successfully meeting the committed power dispatch. However, the method requires the ESS power and energy capacities to be treated as independent design variables. Hence, in determining the ESS energy capacities, the ESS power capacity is assumed unconstrained. Similar approach has also been utilized in the works of [57, 58, 88]. Furthermore, the previous scheme has yet to address issues with regard to unserved power commitments and suitable ESS options to be incorporated with a wind farm.

For the purpose of achieving firm power dispatch objective for a single wind farm such as that described previously as well as in the present chapter, batteries ESS (BESS) can be a feasible ESS medium. For the consideration of power dispatchability from a single wind farm which typically has a capacity of up to a hundred MW, BESS is appropriate in terms of its power and energy capacities. PHS and CAES are intended for applications which require much higher energy storage capacity [41, 89]. However, if the BESS were to be the only ESS media used to smooth the fluctuating wind farm output power such as the technique adopted by [64, 73], the number of BESS charging/discharging cycles could be so high that it can reduce the useful life span of the BESS to an unacceptable level [14, 68]. A possible solution to this design dilemma is to add a supplementary short-term ESS to the BESS and form a hybrid ESS (HESS). From the Sections 2.3.1.1, 2.3.1.5 – 2.3.1.6, possible short-term ESS can be in the form of superconducting magnetic energy storage (SMES), flywheel energy storage (FES), and supercapacitor energy storage (SC). However, due to the high cost and environmental issues associated with strong magnetic field, SMES is unlikely to be suitable. The SC is deemed more suitable as its cost/kWh is about 3 times

lower than that of the FES [41]. Hence in this chapter, the SC shall be used in conjunction with the BESS to form a battery-supercapacitor HESS.

Specifically, an alternative method of designing the HESS shall be proposed herein to address the shortcomings of [57, 58, 88] and that undertaken in the previous chapter. In the proposed method to be described shortly, the HESS power and energy capacities shall be determined, without the need to assume the HESS power and energy capacities are independent design variables and to address the issue of unserved power commitments. Furthermore, the proposed method in this chapter differs from most of the reported works on wind-ESS schemes and that of Chapter 3 which separates the design of the ESS from the operational planning of the wind farm-ESS. As planning and operational planning are closely interrelated, hence in this investigation, it is decided to design the dispatch strategy while the HESS capacities are still unknown and then incorporate the dispatch strategy into the planning technique to determine the HESS capacities. Thus, the dispatch strategy becomes a part in the design of the ESS. By doing so, the viability of the wind-HESS scheme is enhanced as the required HESS capacities so determined have been evaluated based on the designed dispatch strategy and the same dispatch strategy is also used later in the operational planning phase of the wind farm-HESS.

The design of the HESS is intended to exploit the technical merits of the BESS and SC, in terms of the differences in their specific power and energy densities, and their ability to accommodate different rates of change in the charging/discharging powers. In this manner, the designed HESS shall be able to concurrently address the concern on power dispatch/energy management as well as that on power quality, which is unlike the approaches of the previous chapter and [57, 58, 73]. The BESS is to participate in the energy management function and allows power to be committed several hours or even a day ahead, while the SC is to mitigate the shorter-term power quality issues. Although the authors of [81] propose to rely on the actions of the WTG pitch angle control and the associated power converters to reduce the level of wind farm output power fluctuations, their technique unfortunately cannot extract the maximum energy from the wind. As the

SC in the HESS is designed to handle such short-term power quality issues, the WTG shall be able to operate in a manner to harness the maximum amount of wind power possible.

Summarizing the above, the objective in this chapter is thus to devise a suitable coordinated power flow control strategy between the BESS and SC, and for the designed HESS to be economically viable in order to achieve wind power dispatchability while ensuring maximum extraction of wind energy from a wind farm. Therefore, having specified the motive of this chapter, Section 4.1 will present an overview of the wind farm-HESS scheme and the pertinent design/operational considerations with regard to the BESS and SC. The proposed power flow control strategy for the two energy storage media is described in Section 4.2. Section 4.3 shows the method to determine the optimal HESS design, from which the combined wind farm-HESS power station is able to dispatch power at a given confidence level. The computational procedure to determine the most economical HESS design is developed in Section 4.4. Finally, a case study is given in Section 4.5 to demonstrate the proposed design methodology.

Some of the materials contained in this chapter also appear in the author's publication [90].

4.1 Wind farm with hybrid energy storage

4.1.1 Schematic

Fig. 4-1 Schematic diagram showing real power flows of the grid-connected wind farm-HESS

Fig. 4-1 shows the real power flows within a generic grid-connected wind farm-HESS scheme. The WTG in the wind farm are aggregated to form the equivalent WTG and produces the total output power $P_W(t)$. Power conversion devices between the WTG, BESS, and SC have been omitted from the power flow consideration as losses in these devices tend to be small. The arrows indicate the assumed positive direction of the power flows. $P_S(t)$ and $P_B(t)$ are the respective SC and BESS output powers while $P_{H,o}(t)$ is the aggregated power of the HESS. The role of the HESS is to buffer the grid from the fluctuating $P_W(t)$ and exercises control on the dispatch power $P_d(t)$. In this scheme, it is assumed that the power plant can only export power to the grid. From Fig. 4-1, $P_d(t)$, $P_W(t)$, and $P_{H,o}(t)$ are governed by the relationship

$$P_d(t) = P_W(t) - P_{H,o}(t) \quad (4.1)$$

The aggregated power of the HESS $P_{H,o}(t)$ in Fig. 4-1 should ideally be represented by a bidirectional arrow as it is possible for the HESS to be charged as well as discharged. However, to illustrate the relationship between $P_d(t)$, $P_W(t)$ and $P_{H,o}(t)$ as described by (4.1), the arrow in Fig. 4-1 represents the positive direction (charging) of the power flows for $P_{H,o}(t)$. Similar assumed direction also applies to the power flows of the SC $P_S(t)$ and BESS $P_B(t)$. Both $P_S(t)$ and $P_B(t)$ are represented by unidirectional arrows to show that their sum is equaled to $P_{H,o}(t)$.

4.1.2 BESS and SC service lifetimes

A typical wind farm is expected to have a service life of some 20 - 25 years whereas, depending on battery chemistry and application, most electro-chemical BESS tend to have shorter lifetime ranging from less than 10 years to about 15 years [8, 91, 92]. Thus any method which could lead to an increase in the operational life of the BESS is highly desirable. Improved battery design is one way to prolong BESS life but the manner by which the BESS are used can also affect battery life span significantly. These usage factors include the depth of discharge (DOD) and the rate of change of the charging/discharging power (ramp-rate) [8, 91].

DOD has a direct impact on the number of charge-discharge cycles (cycle life) the BESS can undertake over its useful lifetime. Too deep a discharge should be avoided as it leads to permanent physical damage to the BESS and an exceedingly low cycle life [93]. For renewable energy applications, batteries designed for deep-cycle applications with high cycle life are usually preferred. Typical DOD of such batteries ranged from 50% to 90% [8]. Such high DOD is necessary so that a higher amount of energy can be handled by the BESS over its lifetime.

Even when the battery operates below its rated power level, the rate of change in the charging/discharging power should be controlled. This is due to the limitation imposed by the chemical processes inside the battery. Subjecting the battery to charge/discharge ramp-rate faster than the chemicals can react causes local overcharge/over-discharge conditions inside the battery. These include polarization, overheating as well as undesirable chemical reactions near to the electrodes, which potentially can be damaging to the battery [91]. The maximum allowable rate of change of charging / discharging power depends on battery chemistry, and type of application the battery is designed for, among other factors. For the stationary, utility-scale BESS application considered in this investigation, hence one main consideration shown in latter sections is to include into the HESS design the optimum maximum rate of change of the BESS charging/discharging power, measured in terms of certain performance index.

The life span of a SC is affected by its operating temperature and voltage [94]. Generally, when the operating temperature of the SC is raised by 10°C, the life span of the SC will decrease by a factor of two. If the SC is operated above its rated voltage, the life of the SC can be shortened considerably as gas generated by the electrochemical reactions inside the SC may cause it to leak or rupture [94]. Since the SC included in the wind farm-HESS scheme is likely to be housed in an environment where temperature control can be expected, and the interposing power conversion equipment between the SC and grid would actively exercise voltage control, thus the effects of both the operating temperature and voltage of the SC on the SC lifetime have been omitted in this study.

4.2 Coordinated BESS-SC power flows control scheme

When designing the HESS for a wind farm, it is required to consider how the wind farm-HESS shall operate in order to meet the short-term dispatch commitments since the input wind power $P_W(t)$ is random. To emulate a possible short-term dispatch planning procedure, i.e. to obtain the short-term dispatch power $P_{d,r}(t)$ from the wind power forecast $P_{W,f}(t)$, procedures described in Section 3.3.1 will be used. Then based on the committed dispatch $P_{d,r}(t)$ and the known $P_W(t)$, a new coordinated power flow control scheme is now developed.

Set $P_d(t)$ in (4.1) as $P_{d,r}(t)$ and (4.1) can be rewritten as

$$P_{H,r}(t) = P_W(t) - P_{d,r}(t) \quad (4.2)$$

$P_{H,r}(t)$ in (4.2) denotes the reference mismatched power between the actual wind power $P_W(t)$ and the committed dispatch $P_{d,r}(t)$. $P_{H,r}(t)$ is the reference for $P_{H,o}(t)$ and in instances when $P_{H,r}(t) > 0$, the HESS is being charged by the excess wind power as $P_W(t)$ is larger than $P_{d,r}(t)$. Conversely, $P_{H,r}(t) < 0$ corresponds to those instances when the HESS is discharging. Furthermore, $P_{H,r}(t)$ now includes both the reference powers for the BESS, denoted as $P_{B,r}(t)$, and that of the SC, denoted as $P_{S,r}(t)$, viz.

$$P_{H,r}(t) = P_{B,r}(t) + P_{S,r}(t) \quad (4.3)$$

where $P_{B,r}(t)$ and $P_{S,r}(t)$ in (4.3) follows similar notation of $P_{H,r}(t)$, i.e. when the BESS and the SC are being charged, $P_{B,r}(t) > 0$ and $P_{S,r}(t) > 0$ respectively. On the other hand, $P_{B,r}(t) < 0$ and $P_{S,r}(t) < 0$ will represent that the BESS and the SC are discharging. Unlike the approach described in [14], the newly proposed power flows coordination method begins by first considering the BESS lifetime. Section 4.1.2 explains that the BESS useful lifetime can be significantly affected by the rate of change of the charging/discharging power of the battery. Suppose $P_{H,r}(t)$ is increasing and to achieve a reasonable BESS lifetime, the

maximum ramp-up rate of the BESS power is set at α p.u. MW/s. Hence, the BESS shall meet the power demand on the HESS on its own if the ramp-up rate of change of $P_{H,r}(t)$ is lower than α . Then in (4.3), $P_{B,r}(t)$ shall then be set equal to $P_{H,r}(t)$ while $P_{S,r}(t) = 0$. However, should the rate of change of $P_{H,r}(t)$ exceed α , both the BESS and SC shall share in meeting $P_{H,r}(t)$: the BESS shall operate at the maximum ramp-up rate while the SC shall take the balance between $P_{H,r}(t)$ and $P_{B,r}(t)$. Hence by adopting this strategy, the BESS will only cater for a change in $P_{H,r}(t)$ at a rate not exceeding α .

Fig. 4-2 Examples illustrating the coordination of power flows between the BESS and SC.

A more detailed analysis of the above proposed strategy is shown in Fig. 4-2 where $P_{H,r}(t)$ is seen to increase linearly over a sufficiently small time step Δt . From Fig. 4-2(a), the HESS is shown being charged by the WTG and between the interval t_{i-1} to t_ϵ , $P_{B,r}(t)$ is to increase at the maximum rate of α and the SC is tasked to handle the difference between $P_{H,r}(t)$ and $P_{B,r}(t)$. Thus, $P_{B,r}(t)$ and $P_{S,r}(t)$ are set as follows:

$$\left. \begin{aligned} P_{B,r}(t) &= P_{B,r}(t_{i-1}) + \alpha \cdot (t - t_{i-1}) \\ P_{S,r}(t) &= P_{H,r}(t) - P_{B,r}(t) \end{aligned} \right\} \text{ as } P_{B,r}(t_{i-1}) + \alpha \cdot (t - t_{i-1}) < P_{H,r}(t) \quad (4.4)$$

For the interval $t_\varepsilon < t \leq t_i$, the rate of change in $P_{H,r}(t)$ is less than the maximum BESS ramp-up rate α . Hence

$$\left. \begin{aligned} P_{B,r}(t) &= P_{H,r}(t) \\ P_{S,r}(t) &= 0 \end{aligned} \right\} \text{ as } P_{B,r}(t_{i-1}) + \alpha \cdot (t - t_{i-1}) \geq P_{H,r}(t) \quad (4.5)$$

Conversely, suppose the BESS has the maximum ramp-down rate of β p.u. MW/s. Consider Fig. 4-2(b) when the HESS happens to be discharging; in the interval $t_{j-1} < t \leq t_\zeta$, the BESS discharging power is set to decrease at the maximum rate of β and SC is tasked to take up the difference between $P_{H,r}(t)$ and $P_{B,r}(t)$. Thus

$$\left. \begin{aligned} P_{B,r}(t) &= P_{B,r}(t_{j-1}) + \beta \cdot (t - t_{j-1}) \\ P_{S,r}(t) &= P_{H,r}(t) - P_{B,r}(t) \end{aligned} \right\} \text{ as } P_{B,r}(t_{j-1}) + \beta \cdot (t - t_{j-1}) > P_{H,r}(t) \quad (4.6)$$

In the interval $t_\zeta < t \leq t_j$, $P_{B,r}(t) = P_{H,r}(t)$ as ramp-down rate of $P_{H,r}(t)$ is less than β . Hence, $P_{B,r}(t)$ and $P_{S,r}(t)$ are:

$$\left. \begin{aligned} P_{B,r}(t) &= P_{H,r}(t) \\ P_{S,r}(t) &= 0 \end{aligned} \right\} \text{ as } P_{B,r}(t_{j-1}) + \beta \cdot (t - t_{j-1}) \leq P_{H,r}(t) \quad (4.7)$$

Let the BESS and SC power ratings be denoted as $P_{B,R}$ and $P_{S,R}$ respectively. Then in (4.4) – (4.7), clearly it is necessary $|P_{B,r}(t)| \leq P_{B,R}$ and $|P_{S,r}(t)| \leq P_{S,R}$. However, both $P_{B,R}$ and $P_{S,R}$ are unknown at this stage and the procedure to determine them shall be described in Section 4.3.1. Furthermore, the BESS state of charge is directly dependent of $P_{B,r}(t)$ and the BESS energy capacity. Denote the BESS state of charge and its energy capacity as $SOC_B(t)$ and E_{B-R} respectively. Thus, $SOC_B(t)$ is given by

$$SOC_B(t) = SOC_B(0) + \int_0^t P_{B,r}(\tau) \cdot d\tau / E_{B-R} \quad (4.8)$$

where $SOC_B(0)$ is the BESS initial state of charge. As stated in Section 4.1.2, the BESS should not operate beyond a certain depth of discharge (DOD). Hence, the BESS maximum allowable DOD is denoted in this context as $d_{B,max}$, then $P_{B,r}(t)$ in (4.4) – (4.7) must ensure $SOC_B(t)$ at any instance must lie within the range $(1 - d_{B,max}, 1)$.

Similar reasoning also applies to the SC. In this investigation, the respective SC state of charge and its energy capacity are denoted as $SOC_S(t)$ and E_{S_R} . Thus $SOC_S(t)$ is given by

$$SoC_S(t) = SoC_S(0) + \int_0^t P_{S,r}(\tau_i) \cdot d\tau_i / E_{S_R} \quad (4.9)$$

where $SOC_S(0)$ is the SC initial state of charge. Let the SC maximum allowable DOD be $d_{S,max}$, then the SC power $P_{S,r}(t)$ in (4.4) – (4.7) must ensure that $SOC_S(t)$ must lie within the range $(1 - d_{S,max}, 1)$. Note that both E_{B_R} and E_{S_R} are also unknown at this design stage and the procedure to determine them shall be described in Section 4.3.2.

Apart from the scenarios shown in Fig. 4-2, (4.4) and (4.5) will also apply to cases when the HESS is ramping up as it is discharging while (4.6) and (4.7) will be equally applicable when the HESS is ramping down as it is being charged. Thus the proposed power flow coordination scheme constrains the respective BESS power ramp-up and ramp-down rates within every Δt to be no more than α and β p.u. MW/s. The more rapid fluctuating power components are to be dealt with by the SC. This proposed method is capable of addressing the shortcoming of [64, 73] where the limit on the ramp-rate of the BESS output power may be exceeded during the charging and discharging processes. By judiciously selecting the values of α and β , and the method to do so shall be described in Section 4.4.4, it is intended that the larger proportion of the energy contained in $P_{H,r}(t)$ shall be dealt with by the BESS, as compared to that handled by the SC, although the SC shall have to undergo a larger number of charge/discharge cycles. In this manner, the proposed scheme is to exploit the desirable attribute of the SC in that it has a much higher cycle life as compared to the BESS. By diverting the rapid fluctuating power components to the SC therefore prolongs the life span of the BESS, while the BESS, with its inherently larger specific energy density, handles the larger proportion of the charging/discharging energy in $P_{H,r}(t)$.

Another important consideration is the value selection for Δt . There are two pertinent factors concerning the selection of Δt and these are the dynamic response characteristics of the WTG and the wind speed at the wind farm. For the case of the variable speed WTG, the power converter allows the rotor generator speed to be varied and in the event of wind gusts, the WTG can better compensate the fast variations in the wind power [7]. Hence, it would be several seconds before one could expect any appreciable change in $P_w(t)$ and for the need of $P_{H,r}(t)$ to be recomputed using (4.2). However, in the case of fixed speed pitch angle-regulated WTG, due to the relatively slower response of the pitch mechanism to avoid the power fluctuations in the wind gusts [7, 95], a shorter duration of Δt would be required. In selecting the appropriate Δt , one could refer to [14] and [64]: the sampling interval Δt for $P_w(t)$ is stated as 0.2s in [14] when the authors investigate the adequacy of a control strategy for a HESS whereas Δt is set as 1s in [64] for the design of a dispatch scheme using BESS. Computer simulation study could be conducted using the wind speed data collected at the wind farm. With the inclusion of suitable WTG model and by a process of iterative searching, appropriate Δt can be obtained to produce a suitable HESS scheme. In the present work, Δt of 4s has been found to be satisfactory.

4.3 Method to determine HESS power and stored energy capacities

The next task is to determine the HESS power and stored energy capacities based on the proposed power flows coordination strategy. Unlike [57, 58, 88] and the previous scheme, the method shown below does not assume the HESS power and energy capacities are independent design variables.

4.3.1 BESS and SC power capacities

For determining the power capacities of the BESS and SC, similar statistical approach as described in the previous chapter can be adopted. By following the procedures described in Section 3.3.1, $P_{d,r}(t)$ is determined and then using (4.2), the HESS power reference $P_{H,r}(t)$ is evaluated. Based on the power coordination strategy described in Section 4.2, suppose $P_{S,r}(t)$ and $P_{B,r}(t)$ are determined using (4.4) – (4.7) over the complete study period of (say) T_s days.

Next, start by statistically quantifying $P_{B,r}(t)$. The absolute values of $P_{B,r}(t)$ is first obtained. Subsequently, the probability density function (pdf) and cumulative probability function (cdf) of $|P_{B,r}(t)|$ are computed. From the cdf of $|P_{B,r}(t)|$, the battery rated power capacity $P_{B,R}$ could be chosen to be the value of $|P_{B,r}(t)|$ which corresponds to the cdf of 1 so that the BESS can meet all the possible charging/discharging power requirements. $P_{B,R}$ so determined is to meet the worst case scenario, an approach which is utilized by the authors of [54, 55]. Unfortunately, the $P_{B,R}$ obtained may be unacceptably large and uneconomical. To overcome this dilemma, $P_{B,R}$ can be limited to a lower value which has the corresponding cdf of p_l : i.e. the BESS can be expected to successfully meet the power demand on it with the probability of p_l . With this BESS power rating, $P_{d,r}(t)$ can no longer be met at those instances when $P_{B,r}(t)$ exceeds $P_{B,R}$ unless the SC power capacity $P_{S,R}$ is made sufficiently large. Unfortunately, it is also prudent to limit $P_{S,R}$ in order for the HESS scheme to be viable. Hence the extent of successful power dispatch would depend on the selection of both power ratings $P_{B,R}$ and $P_{S,R}$. Accordingly, let B , S and A denote three sets of events: when $|P_{B,r}(t)| \leq P_{B,R}$, when $|P_{S,r}(t)| \leq P_{S,R}$, and when power dispatch is successful respectively. Mathematically, the above are expressed as

$$\left. \begin{aligned} B &= |P_{B,r}(t)| \leq P_{B,R}, \\ S &= |P_{S,r}(t)| \leq P_{S,R}, \\ A &= (|P_{B,r}(t)| \leq P_{B,R}) \cap (|P_{S,r}(t)| \leq P_{S,R}) \end{aligned} \right\} \quad (4.10)$$

Hence as already explained, successful power dispatch can only be achieved when $|P_{B,r}(t)|$ does not exceed $P_{B,R}$ and $|P_{S,r}(t)|$ is less than $P_{S,R}$, i.e. events B and S are both satisfied. Consequently, the probability of successful power dispatch $Prob\{A\}$ can be written as

$$Prob\{A\} = Prob\{B \cap S\} \quad (4.11)$$

where $Prob\{\cdot\}$ denotes the probability of condition $\{\cdot\}$ being met.

As can be seen from (4.2) and (4.3), the determination of $P_{S,r}(t)$ is dependent on the value of $P_{B,r}(t)$. Thus, the two events B and S are dependent and $Prob\{A\}$ can be rewritten either as

$$Prob\{A\} = Prob\{B/S\} \times Prob\{S\} \quad (4.11a)$$

Or

$$Prob\{A\} = Prob\{S/B\} \times Prob\{B\} \quad (4.11b)$$

In (4.11a), $Prob\{B/S\}$ denotes the conditional probability of B is successful subject to S being successful. Conversely in (4.11b), $Prob\{S/B\}$ is the conditional probability of S is successful given B being successful. Given either (4.11a) or (4.11b), the order of the BESS and SC power ratings selection will be governed by the unconditional probability: e.g. in (4.11a), $P_{S,R}$ will be selected prior to that of $P_{B,R}$. Equation (4.11b) will be used instead in the present investigation because the primary motive of using the HESS is to exploit the inherently larger specific energy density of the BESS whereas the SC plays the role of prolonging the life span of the BESS by handling the less energy-intensive but rapid microcycles during the charge-discharge process. Hence the power capacity of the BESS will be selected before that of the SC.

The process to determine $P_{B,R}$ and $P_{S,R}$ and the corresponding probability of successful power dispatch $Prob\{A\}$ will now be described. Firstly the cdf of $|P_{B,r}(t)|$ is used to set the BESS power rating $P_{B,R}$. This means that over T_s , the probability of event B being successful is p_1 , i.e.

$$Prob\{B\} = p_1 \quad (4.12)$$

Then, in each of the time-steps Δt such as that shown in Fig. 4-2, only those intervals when event B is satisfied will be considered, i.e. $|P_{B,r}(t)| \leq P_{B,R}$. Using the i^{th} time-step in Fig 4-3(a) as an example, the corresponding $P_{S,r}(t)$ is calculated using (4.3) and because event B is satisfied over the whole time-step, $P_{S,r}(t)$ over this Δt is to be included in the evaluation of $Prob\{S/B\}$. In Fig. 4-3(b) however, event B is only satisfied between $t_{i-1} \leq t \leq t_\varepsilon$ because beyond t_ε , $P_{B,r}(t) > P_{B,R}$ and the BESS shall be overloaded. Thus in computing $Prob\{A\}$ using (4-11b), only the corresponding $P_{S,r}(t)$ between the interval $t_{i-1} \leq t \leq t_\varepsilon$ needs be considered.

Fig. 4-3 Tracking of $P_{S,r}(t)$: (a) over complete time-step Δt ; and (b) between $t_{i-1} \leq t \leq t_\varepsilon$

This tracking procedure of $P_{S,r}(t)$ is repeated for all Δt in T_S but only during those instances when condition B i.e. $|P_{B,r}(t)| \leq P_{B,R}$ is satisfied. From the tracked $P_{S,r}(t)$, construct the pdf and cdf of $|P_{S,r}(t)|$, much in the same manner as for those of $|P_{B,r}(t)|$. Note that the obtained pdf and cdf of $|P_{S,r}(t)|$ is only applicable for the selected BESS power rating $P_{B,R}$. Again similar in the manner in selecting $P_{B,R}$, the SC power rating $P_{S,R}$ is decided based on the confidence level one wishes to achieve with respect to the final successful power dispatch $Prob\{A\}$. So from the cdf of $|P_{S,r}(t)|$, suppose one selects a SC power rating of $P_{S,R}$ and it corresponds to a confidence level of p_2 , i.e.,

$$Prob\{S/B\} = p_2 \quad (4.13)$$

Based on (4.11b), therefore, the probability of successfully meeting the committed dispatch power with the HESS is

$$Prob\{A\} = p_2 \times p_1 \quad (4.14)$$

Thus in summary, the above statistical method determines the BESS and SC power capacities to yield the successful power dispatch probability given by (4.14). In other words, the committed dispatch power can be met with the capacities of the HESS so determined, with the probability $p_2 \times p_1$. Note that the above method also extends the work in the previous chapter by quantifying the probability of how successful the committed dispatch power can be met. The proposed method does not assume the BESS and SC power capacities are independent design variables when determining the BESS and SC energy capacities, as will be explained in the next sub-section.

4.3.2 BESS and SC stored energy capacities

To ensure the HESS so determined is capable of accommodating the amount of energy it has to store, the HESS energy capacity needs to be evaluated. With regard to the BESS energy capacity and with respect to an arbitrary reference time $t = 0$, at time γ , the BESS stored energy is changed by the amount

$$\Delta E_B(\gamma) = \int_0^\gamma P_{B,r}(t) \cdot dt \quad (4.15)$$

In the event when $P_{B,r}(t) > P_{B,R}$, $P_{B,r}(t) = P_{B,R}$. Suppose over T_s , the range of $\Delta E_B(t)$ is between a maximum value of ΔE_{B+} and a minimum value of ΔE_{B-} . Then $(\Delta E_{B+} - \Delta E_{B-})$ will represent the minimum BESS energy capacity required to meet the committed power dispatch based on the BESS power rating $P_{B,R}$. However, as stated in Sections 4.1.2 and 4.2, the BESS should not operate beyond the depth of discharge $d_{B,max}$. Therefore the rated BESS stored energy capacity is then determined as

$$E_{B-R} = \frac{(\Delta E_{B+} - \Delta E_{B-})}{d_{B,max}} \quad (4.16)$$

Fig. 4-4 Profiles of BESS stored energy and depth-of discharge

Fig. 4-4 shows instances whereby the energy level in the BESS is increasing: these correspond to the intervals C when the BESS is being charged. Conversely, those instances when the BESS is discharging power are labeled as D. The portion of energy level labeled as $\{(1 - d_{B,max})/d_{B,max}\} \times [\Delta E_{B+} - \Delta E_{B-}]$ corresponds to the minimum energy level that must be retained by the BESS to avoid damage.

Similar treatment can be applied to determine the minimum energy capacity of the SC. The energy stored in the SC at any time t is given by

$$E_s(t) = \frac{1}{2} \times C \times V_s(t)^2 \quad (4.17)$$

where C and V_s are the capacitance and terminal voltage of the SC respectively. Although it is possible to completely discharge the SC ($V_s = 0$) without much adverse effects, in practice it is necessary to maintain a minimum voltage ($V_{s,min}$) across the SC terminal as the device is connected to the grid system. Therefore, with the nominal voltage of the SC denoted as $V_{s,nom}$ and using (4.17), it can be readily shown that the maximum allowable DOD of the SC, denoted as $d_{s,max}$ can be expressed in terms of $V_{s,min}$ and $V_{s,nom}$ as

$$d_{s,max} = 1 - \left(\frac{V_{s,min}}{V_{s,nom}} \right)^2 \quad (4.18)$$

Also, from the known profile of $P_{s,r}(t)$ and in similar manner as described above for the BESS, calculate the maximum (ΔE_{s+}) and minimum (ΔE_{s-}) changes in the stored energy in the SC over T_s . The rated energy capacity ($E_{s,R}$) of the SC, with the power rating $P_{s,R}$ is therefore

$$E_{s,R} = \frac{(\Delta E_{s+} - \Delta E_{s-})}{d_{s,max}} \quad (4.19)$$

4.4 Determination of BESS power ramp-rates

The proposed method described in Section 4.3 allows one to determine the BESS and SC power and energy capacities to yield the successful power dispatch probability $p_2 \times p_1$. The capacities are determined from $P_{B,r}(t)$ and $P_{s,r}(t)$, based on the BESS power ramp-up and ramp-down rates α and β . This section describes how to determine (α, β) to achieve the

most economical HESS design, measured in terms of the annualized life cycle cost of the HESS and the expected penalty cost for failing to meet the power dispatch obligations.

4.4.1 Expected lifetimes of the BESS and SC

Generally, manufacturers express BESS cycle life in terms of the number of charge-discharge cycles the BESS can undertake before the BESS has to be replaced. Typically the cycle life is obtained by discharging the BESS to a specified DOD level and re-charging it to its full capacity at rated current. The process is repeated until the BESS is unable to be so discharged and re-charged. Unfortunately, the charging-discharging cycles are irregular in the present scheme due to the unsteady input wind power. Hence, the number of life cycles the BESS has undergone at any given time cannot be so readily determined.

One possible way to circumvent the abovementioned problem is to evaluate the BESS ampere-hour (Ah) throughput measure and use it to estimate the lifetime of the BESS. This approach has also been adopted in [92] to estimate battery expected lifetime in a PV application. In the present investigation, consider only those instances when the BESS is discharging. This is reasonable as the charging and discharging Ah throughputs of the BESS will be the same if the study period T_s is sufficiently long. Suppose the terminal voltage of the BESS does not vary greatly from its rated value, then from $P_{B,r}(t)$, the discharge current $I_{B,r}(t)$ can be readily calculated. By integrating $I_{B,r}(t)$ with respect to the j^{th} discharge interval between $t = t_{j-1}$ and $t = t_j$, it yields the amp-hour throughput Ah_j

$$Ah_j = \int_{t_{j-1}}^{t_j} I_{B,r}(t) \cdot dt \quad (4.20)$$

And by summing all the discharging Ah_j obtained over T_s , the total discharge amp-hour throughput of the BESS, denoted as $Ah_{B,Ts}$, can be obtained:

$$Ah_{B,Ts} = \sum_{j \in Ts} Ah_j \quad (4.21)$$

Next, Ah_{B,T_s} will be divided by the BESS rated Ah, denoted as Ah_r and the so-called BESS equivalent service cycle life (C_{B,T_s}) over T_s is obtained, viz.:

$$C_{B,T_s} = \frac{Ah_{B,T_s}}{Ah_r} \quad (4.22)$$

Since the BESS cycle life at rated conditions ($C_{B,n}$) is provided by the manufacturer, the expected life $E[L_B]$ of the BESS can be calculated as

$$E[L_B] = \left(\frac{C_{B,n}}{C_{B,T_s}} \right) \times T_s \quad (4.23)$$

where $E[L_B]$ has the unit of time. SC manufacturers also specified cycle life for the SC in terms of the number of charge-discharge cycles the SC can undertake before it needs to be replaced. In each cycle the SC is charged to its rated energy capacity by a constant current source and it is then discharged completely by a constant current load [96]. It is only necessary for the current level used in this cycling test not to exceed the rated SC current: the level will only affect how fast the SC discharges or charges up. Furthermore, SC can be fully cycled or micro-cycled (irregularly cycled) without affecting its cycle life [97]. Thus, the SC discharged energy throughput is suitable for use in estimating the lifetime of the SC.

Accordingly and similar to the case of the BESS, only consider those intervals when the SC is discharging. The discharged energy from the SC, denoted as $E_{S,k}$ for the k^{th} discharge interval, is obtained by integrating $P_{S,r}(t)$ with respect to the discharge time between t_{k-1} and t_k

$$E_{S,k} = \int_{t_{k-1}}^{t_k} P_{S,r}(t) \cdot dt \quad (4.24)$$

Next, all the discharging energies $E_{S,k}$ obtained over T_S are summed to yield the total discharged energy (E_{S,T_S}) of the SC

$$E_{S,T_S} = \sum_{k \in T_S} E_{S,k} \quad (4.25)$$

E_{S,T_S} is then divided by the SC rated energy capacity E_{S_R} to yield the equivalent service lifecycle (C_{S,T_S}) over the period T_S

$$C_{S,T_S} = \frac{E_{S,T_S}}{E_{S_R}} \quad (4.26)$$

Using the SC cycle life ($C_{S,n}$) provided by the manufacturer, the expected life $E[L_S]$ of the SC is given as

$$E[L_S] = \left(\frac{C_{S,n}}{C_{S,T_S}} \right) \times T_S \quad (4.27)$$

Again $E[L_S]$ has the unit of time.

4.4.2 Annualized cycle cost of the HESS

The life cycle cost of the HESS is now considered. The capital cost of the BESS includes both its power converter and the battery. Hence, the BESS capital cost can be expressed as $(k_1 \times P_{B,R} + k_2 \times E_{B_R})$ where $P_{B,R}$ and E_{B_R} are the respective BESS power and energy capacities determined in Section 4.3. k_1 and k_2 are expressed in terms of the cost per MW and cost per MWh respectively, and they can be obtained from the manufacturers or literatures [39, 41, 98]. Similar reasoning applies to the SC. The SC capital cost becomes $(k_3 \times P_{S,R} + k_4 \times E_{S_R})$ where k_3 and k_4 are the cost per MW and cost per MWh respectively for the SC, given the SC power rating of $P_{S,R}$ and energy capacity of E_{S_R} . Thus the total HESS capital cost (TC) is expressed as

$$TC = (k_1 \times P_{B,R} + k_2 \times E_{B,R}) + (k_3 \times P_{S,R} + k_4 \times E_{S,R}) \quad (4.28)$$

Let I to be the interest rate and T_{WF} denotes the service life span of the wind farm, the annualized HESS capital cost (AC) can be calculated through the determination of the capital recovery factor (CRF) where

$$CRF = \frac{I \cdot (1 + I)^{T_{WF}}}{(1 + I)^{T_{WF}} - 1} \quad (4.29)$$

Thus, the annualized HESS capital cost AC is expressed as

$$AC = TC \times CRF \quad (4.30)$$

The annualized replacement cost for the BESS AR_B is

$$AR_B = (k_2 \times E_{B,R}) \cdot \left[(1 + I)^{-(E[L_B])} + (1 + I)^{-2(E[L_B])} + \dots \right] \times CRF \quad (4.31)$$

where $E[L_B]$ is the expected life of the BESS obtained from (4.23). The number of times the BESS will need replacement during the service life of the wind farm will be equal to the number of terms in the square bracket of (4.31). The same reasoning applies to the SC: the annualized replacement cost for the SC AR_S is determined as

$$AR_S = (k_4 \times E_{S,R}) \cdot \left[(1 + I)^{-(E[L_S])} + (1 + I)^{-2(E[L_S])} + \dots \right] \times CRF \quad (4.32)$$

where $E[L_S]$ is the SC expected life obtained from (4.27).

4.4.3 Cost for failing to meet dispatch obligations

A tiered approach has been used to penalize a generator that fails to meet its dispatch obligation so as to ensure good scheduling practices by power generators. For example, the regulatory rule contained in [99] subjects the generator to a lower tier penalty of a certain fixed generation imbalance cost if its generation deviates within the band of $\pm 1.5\% \sim \pm 7.5\%$ from the hourly scheduled energy; a higher tier penalty shall be imposed if the deviations exceed $\pm 7.5\%$.

With the HESS in place, the wind farm-HESS is designed to dispatch power much like a conventional power station. Suppose the probability of successful dispatch $Prob\{A\} = p_2 \times p_1$ is selected to be less than 1. By selecting this dispatch probability level, which in turn determines the HESS capacities, the incurred penalty cost in which the committed dispatch power $P_{d,r}(t)$ cannot be successfully met is evaluated in the following way. Adopting a similar practice as [99], let C_{IH} and C_{IL} (expressed in \$/p.u. MWh) denote the higher and lower tiered fix generation imbalance charge respectively. Suppose the penalty bands are set at $\pm l \sim \pm h$ percent. Since $P_{d,r}(t)$ is to remain constant over interval τ , therefore the amount of energy subjected to the higher tiered imbalance charge C_{IH} in τ is

$$E_{H,\tau} = \left| \int_{t \in \tau} (P_W(t) - P_{B,r}(t) - P_{S,r}(t) - P_{d,r}(t)) \cdot dt \right|, \quad (4.33)$$

$$\text{if } \left| \int_{t \in \tau} (P_W(t) - P_{B,r}(t) - P_{S,r}(t) - P_{d,r}(t)) \cdot dt \right| > \left| h \cdot \int_{t \in \tau} P_{d,r}(t) \cdot dt \right|$$

Similarly, the amount of energy subjected to the lower tiered imbalance charge in τ is

$$E_{L,\tau} = \left| \int_{t \in \tau} (P_W(t) - P_{B,r}(t) - P_{S,r}(t) - P_{d,r}(t)) \cdot dt \right|, \quad (4.34)$$

$$\text{if } \left| h \cdot \int_{t \in \tau} P_{d,r}(t) \cdot dt \right| \geq \left| \int_{t \in \tau} (P_W(t) - P_{B,r}(t) - P_{S,r}(t) - P_{d,r}(t)) \cdot dt \right| \geq \left| l \cdot \int_{t \in \tau} P_{d,r}(t) \cdot dt \right|$$

The total amount of energy which is subjected to the higher and lower tiered imbalance charges is the summation of all $E_{H,\tau}$ and $E_{L,\tau}$ in T_s . If the period of the study T_s is one year, then the total annual penalty cost (C_p) incurred due to the un-met power dispatch is

$$C_p = \left[(C_{IH} \times \sum_{\tau \in T_s} E_{H,\tau}) + (C_{IL} \times \sum_{\tau \in T_s} E_{L,\tau}) \right] \quad (4.35)$$

4.4.4 Procedure to determine the optimum BESS ramp-rates

Sections 4.2 to 4.4.3 have been devoted to developing the techniques and procedures to determine the BESS and SC power and energy capacities so that the committed power dispatch can be met with probability $p_2 \times p_1$. The capacities are seen to be dependent on the selected BESS power ramp rate limits (α, β). It is proposed herewith that the selection of the most suitable (α, β) shall be based on the minimization of the following performance index f , viz.

$$\min f = AC + AR_B + AR_S + C_p \quad (4.36)$$

The index f in (4.36) takes into consideration the HESS annualized life cycle cost, which includes both its annualized capital cost, the BESS and SC replacement costs, plus the expected penalty cost shown in Sections 4.4.2 and 4.4.3. Thus index f represents the total cost/year due to the inclusion of the HESS in the wind farm and the expected cost the committed power schedule $P_{d,r}(t)$ cannot be met. Consequently, the index f takes into consideration some of the essential issues pertaining to the objective of achieving wind dispatchability using ESS but have not been addressed by the proposed method described in Chapter 3.

A computational procedure is needed to search for (α, β) so that f is minimized. From the optimal (α, β), one can then determine the power and energy capacities of the BESS and SC. A linear search method is utilized in this research to achieve this design objective. In this method, (4.36) shall be the objective function and the variables to be searched for are

the BESS charge/discharge power ramp rates (α , β). Fig. 4-5 provides the detailed search procedure for obtaining the optimum (α , β). Starting with the calculated $P_{H,r}(t)$, the search begins with an initial set of (α , β). The procedure described in Section 4.2 is then used to obtain the corresponding $P_{B,r}(t)$ and $P_{S,r}(t)$. Note that in Section 4.2, although there are explicit power and energy limits placed on both the BESS and SC, these limits are unknown at this stage. Therefore, the only constraint is the rates of change in the BESS power $P_{B,r}(t)$ in (4.4) – (4.7) must not exceed the ramp-up and ramp-down rates (α , β).

Fig. 4-5 Linear search method to obtain the optimum BESS ramp-rates

Then with the procedures described in Section 4.3, the cdf of $|P_{B,r}(t)|$ is first established and the BESS power capacity $P_{B,R}$ is determined for a selected confidence level p_1 . Next, the corresponding $E_{B,R}$ is obtained. Following which the conditional cdf of $|P_{S,r}(t)|$ is established and determine $P_{S,R}$ for the confidence level p_2 and the corresponding $E_{S,R}$. Subsequently, the expected lives of the BESS and SC, and the HESS annualized life cycle cost are evaluated using the results of Sections 4.4.1 and 4.4.2 respectively. Subsequently, the expected annual penalty cost is evaluated using (4.35) to account for the cost of not meeting the dispatch obligations. Finally, calculate the index f using (4.36). Increment α by a small value ($\Delta\alpha$) and β by a small value ($\Delta\beta$) so as to revise the current set of (α, β) . Repeat the above procedure for different sets of (α, β) and search until the minimum f is obtained. The corresponding set of (α, β) provides the least-cost HESS design in meeting the committed dispatch with probability $p_2 \times p_1$. Note that the above proposed method differs from that of Chapter 3 and most of the other wind-ESS schemes reported in literatures because in this study, the dispatch strategy is designed while the HESS capacities are still unknown and the dispatch strategy has been incorporated into the planning stage when determining the HESS capacities.

4.5 Numerical example

In this section, the proposed HESS design methodology will be demonstrated. A one-year wind power data (May 2009 - April 2010) sampled at 4-s interval from a WTG installed on Nanyang Technological University (NTU) S2 rooftop is first expressed in per-unit. The nameplate capacity of the WTG is 2.4kW and it is used as the base value. Next, a new base value of 5MW is then used to scale the per-unit wind power data so that the new wind power data resembles that originating from 5MW WTG units as described in [100]. In order to simulate the spatial smoothing effects resulting from the dispersed distribution of the WTGs in a wind farm, the method proposed by the authors in [81] will be utilized. In the method, it is assumed that the aggregated wind power from N units of WTGs in a wind farm is characterized by the time delays it takes the wind at average velocity to traverse the distances separating the WTGs.

In this investigation, N is taken to be 20 to simulate a hypothetical 100-MW rated wind farm. The time delay is computed to be 60-seconds. It is determined by dividing the optimum spacing between two consecutive WTGs as recommended in [35] by the average wind velocity. The average wind velocity is taken to be the speed at half the power of the 5-MW WTG [100]. Using the approach explained above, the wind power obtained from two consecutive WTGs will always be delayed by 60-seconds. Finally, $P_W(t)$ is obtained by summing all the power harnessed from the twenty WTGs.

To begin the HESS design process, $P_{H,r}(t)$ must first be determined. This in turn requires the knowledge of $P_{d,r}(t)$ which is derived from the forecasted wind power $P_{W,f}(t)$. As was stated in Chapter 3, the exact method of obtaining $P_{W,f}(t)$ was not the focus of this study. Instead, it is again assumed herewith that the error in the forecast $P_{W,f}(t)$ follows Beta distribution similar to that adopted by [36]. The error was generated and added to $P_W(t)$ to form $P_{W,f}(t)$. The root-mean-square of the error was assumed to be 15%, a level typical in wind power forecast [22]. Using the method from Section 3.3.1, $P_{d,r}(t)$ was then obtained from $P_{W,f}(t)$ to yield constant hourly dispatch. A sample plot of $P_W(t)$, $P_{W,f}(t)$ and $P_{d,r}(t)$ over a 24-hour period is shown in Fig. 4-6.

Fig. 4-6 Daily power plots from the hypothetical 100-MW rated wind farm: (a) $P_W(t)$, (b) $P_{W,f}(t)$ and (c) $P_{d,r}(t)$

Fig. 4-6 shows that even though the input wind power is random, the dispatch power has indeed been scheduled to constant level within every hour. It is also interesting to note that the average power over the day is some 20MW or 20 % of the wind farm rated capacity: this plant factor is quite typical for a wind power generating station.

4.5.1 Optimal BESS ramp-rates

From $P_W(t)$, $P_{W,f}(t)$ and $P_{d,r}(t)$, calculate $P_{H,r}(t)$ using (4.2). The linear search procedure described in Section 4.4.4 can be used to determine the optimal (α, β) to yield the least-cost BESS-SC design. In this example, assume $\beta = -\alpha$ and the following results were obtained to meet the probability $p_1 = p_2 = 95\%$. Fig. 4-7 shows the required BESS and SC power and energy ratings at the various power ramp rate α . At $\alpha = 0$ MW/s which corresponds to BESS not in service, all the HESS power flows are those to/from the SC. However, as α increases, the BESS handles an increasingly larger proportion of $P_{H,r}(t)$ while that dealt with by the SC is correspondingly reduced. Hence, the required SC power rating (also the SC energy capacity) reduces with the increase in α while the BESS power rating (also its energy capacity) increases. The SC appears to play an insignificant role in the power flow control beyond α of about 1.2-MW/s and the BESS appears to be the only ESS required to handle the wind power perturbations.

Fig. 4-7 Required BESS and SC power and energy ratings at various BESS power ramp-rates:
 $p_1 = p_2 = 95\%$

Fig. 4-8 shows the expected life of the BESS decreases as α increases while the opposite trend is observed for the SC. This is due to the increase in the BESS usage. The BESS expected life ranges from 554 to 1130 days while that of the SC is from 1456 to 2743 days.

Fig. 4-8 Expected life of BESS and SC at various BESS power ramp-rates: $p_1 = p_2 = 95\%$

Fig. 4-9 shows the total un-served energy over the 1-year period. For comparison purpose, cases for $p_1 = p_2 = 95\%$ and $p_1 = p_2 = 98\%$ are shown, corresponding to the penalty bands set at $l = 1.5$ and $h = 7.5$. As the tiered imbalance charge rates C_{IL} and C_{IH} are not specified in [99], C_{IL} and C_{IH} (in US\$/MWh) are assumed to be 500 and 1000 respectively in this example.

Fig. 4-9 $\sum E_{L,\tau}$ and $\sum E_{H,\tau}$ for $l = 1.5$ and $h = 7.5$ at $p_1 = p_2 = 95\%$ and $p_1 = p_2 = 98\%$: plotted against various BESS power ramp-rates

It is seen from Fig. 4-9 that the un-served energy remains relatively constant for a given dispatch confidence level despite the difference in α . And as expected, the un-served energy reduces with the increase in the probability of successful dispatch $Prob\{A\}$.

Fig. 4-10 Performance index f at the various BESS power ramp-rates and $k_1 - k_4$ values: $p_1 = p_2 = 95\%$.

The total cost/year index (f) expressed as (4.36) for various α is shown in Fig. 4-10. It shows the sensitivity of f with α which leads to the ranges of HESS capacities, annualized life cycle cost and the expected penalty cost shown in Figs. 4-7 – 4-9. The interest rate and compounding periods for determining (4.29) were taken from [39] at $I = 8.5\%$ and T_{WF} of 20 years. The nominal BESS and SC cycle life values ($C_{B,n}$, $C_{S,n}$), and the possible ranges of cost per MW (k_1 , k_3) in US\$/MW and cost per MWh (k_2 , k_4) in US\$/MWh were taken from [41, 98]: $C_{B,n} = 500$ cycles and $C_{S,n} = 50,000$ cycles, $125 \times 10^3 \leq k_1 \leq 175 \times 10^3$, $150 \times 10^3 \leq k_2 \leq 235 \times 10^3$, $200 \times 10^3 \leq k_3 \leq 400 \times 10^3$ and $1500 \times 10^3 \leq k_4 \leq 2000 \times 10^3$.

The HESS cost/year index f is impacted by the uncertainty in the cost parameters $k_1 - k_4$ of the HESS. Fig. 4-10 illustrates this sensitivity through the inclusion of three sets of the cost parameters. From Fig. 4-10, it is seen that f is much larger at $\alpha = 0$ MW/s as compared to those of other BESS power ramp-rates. This reinforces the fact that SC is not viable as a long-term storage device, as reported in the preceding chapter on ESS. It is also seen that the impact of α on f is not significant for $\alpha \geq 0.8$ MW/s for $k_1 = 125 \times 10^3$, $k_2 = 150 \times 10^3$, when k_3 varies from $200 \times 10^3 - 400 \times 10^3$ and k_4 varies from $1500 \times 10^3 - 2000 \times 10^3$. This is due to the much larger power and energy capacities of the BESS over that of the SC when evaluating the annualized HESS capital and replacement costs in (4.36). It is

observed from Fig. 4-10 that f is a convex function with respect to α : there exists a minimum cost/year point close to $\alpha = 1.0$ MW/s. Other studies for various ranges of $k_1 - k_4$, p_1 and p_2 also lead to the same conclusion. Thus, it is reasonable to select $\alpha = -\beta = 1.0$ MW/s. With the identification of the optimum α and β through the search for the minimum f , the least-cost HESS design is thus obtained. The corresponding BESS and SC power and energy capacities can be readily inferred from Fig. 4-7 at $\alpha = 1.0$ MW/s. The design meets the committed dispatch power at the confident level of $p_2 \times p_1$.

Fig. 4-11 shows a sample hourly profiles of $P_{B,r}(t)$ and $P_{S,r}(t)$ for $\alpha = |\beta| = 1.0$ MW/s. The respective numbers of discharge cycles that the BESS and SC have undergone for a day were also computed using (4.22) and (4.26). The BESS is seen to have undergone the equivalent of 0.71 cycles while that of the SC is 22.54 cycles. Hence, the results indicate that the proposed HESS power coordination method has indeed exploited the much larger cycle life of the SC. In the process, the SC has prolonged the BESS lifetime.

Fig. 4-11 Hourly plots of the resulting $P_{B,r}(t)$ and $P_{S,r}(t)$ using BESS ramp-rate of 1.0 MW/s.

4.5.2 HESS power and energy capacities

Fig. 4-12 shows the BESS and SC power cdf for $\alpha = 1.0$ MW/s and $p_1 = p_2 = 0.95$. It is seen that the required BESS power capacity $P_{B,R}$ is 11 MW and that of the SC is 530 kW. The corresponding energy capacities are $E_{B,R} = 48$ MWh while $E_{S,R} = 500$ kWh. Hence, the probability of successful power dispatch $Prob\{A\}$ is 0.95×0.95 or 0.9025.

Fig. 4-12 Cdf of $|P_{B,r}(t)|$ and $|P_{S,r}(t)|$; $\alpha = 1.0$ MW/s, $p_1 = 0.95$.

Although not shown here, the case of $\alpha = 1.0$ MW/s, $p_1 = p_2 = 0.98$ have also been evaluated. The corresponding BESS power and energy capacities are 12.5 MW, 49.5 MWh and that of the SC are 1000 kW, 1.5 MWh. At the expense of higher HESS capacities and cost/year index (f), $Prob\{A\}$ is improved to 0.98×0.98 or 0.9604.

4.5.3 Energy production cost increase due to the HESS

It will be interesting to assess the increase in the cost of energy production due to the addition of the HESS. In this example, from the $P_w(t)$ obtained over the one-year study period, the total yearly captured wind energy for $p_1 = p_2 = 100\%$ was determined to be some 170,820 MWh. Assuming $k_1 = 125 \times 10^3$, $k_2 = 150 \times 10^3$, $k_3 = 200 \times 10^3$ and $k_4 = 1500 \times 10^3$, the cost/year (f) was determined to be US\$5,487,300 for $p_1 = p_2 = 95\%$. Dividing f by the net yearly dispatched wind energy which is the difference between the total yearly harnessed and the un-served energies, the increase in cost due to the HESS installation is about US\$0.033/kWh for $p_1 = p_2 = 95\%$ or $Prob\{A\} = 0.9025$. Increasing the certainty of successful power dispatch to $p_1 = p_2 = 98\%$ or 0.9604 increases the cost to US\$0.034/kWh.

On the other hand, for absolute certainty of power dispatch, i.e. $p_1 = p_2 = 100\%$, there would be an increase of f to US\$5,502,000. However, in this case all the harnessed wind energy of 170,820 MWh would be dispatched and the resulting cost/kWh energy production is slightly lower at US\$0.032/kWh.

As a comparison, present-day average electricity production cost of large central thermal power stations is between US\$0.05/kWh – US\$0.10/kWh while that of onshore wind farms is about US\$0.06/kWh – US\$0.15/kWh [35]. Hence, the electricity production cost from the example wind farm-HESS is between US\$0.092 – US\$0.184/kWh for various confidence levels of successful dispatch. While the energy production cost of the wind farm-HESS power station is seen to be about 2 times that of the thermal power stations, the combined wind farm-HESS scheme results in much less environmental damage and hence attracts no environmental costs, e.g. carbon-tax. Also with continuing advances being made in energy storage technology, the cost of the HESS is expected to reduce in the future. Therefore it is very hopeful the proposed wind farm-HESS scheme can be an attractive alternative form of reliable power generation, especially in locations where the wind resource is bountiful.

4.6 Conclusions

A hybrid energy storage system comprising of battery and supercapacitor has been proposed for use in a wind farm to achieve firm power dispatch objective, while maximizing the wind energy capture. In this scheme, a power-flows coordination strategy between the BESS and SC has been proposed where the BESS power ramp-up and ramp-down rates are constrained so as to achieve an acceptable BESS life span. The more rapid fluctuating wind power components are dealt with by the SC. Furthermore, due to the random input wind power, a statistical approach is used to design the HESS so that the wind farm power dispatch can be achieved at specified confidence level. The method allows the HESS power and energy capacities as well as the BESS power ramp-rates to be determined. This is done through minimizing the sum of the annualized capital and replacement costs of the HESS, and the expected penalty cost for not meeting the dispatch

obligations. Through the use of elaborate cost analysis of the HESS and a tiered penalty method to deal with unserved power commitments, some essential issues of the wind farm-HESS scheme have been taken into account which also serves to extend the work in the previous chapter. Additionally, the proposed method incorporates the design of the dispatch strategy into the planning technique to determine the HESS capacities and this method does not require the capacities to be treated as independent design variables.

From the evaluation of the cost/year index (f) of the HESS, it is confirmed that SC is not viable as a long-term storage device. Furthermore, numerical examples show that the capacities of the HESS increases with the confidence level needed to achieve firm power dispatch. Hence the proposed statistical approach is a useful tool in the design of the HESS for it balances the objective of meeting the firm power dispatch against the cost of the HESS.

With the drive towards renewable generation continuing for the foreseeable future, an even higher penetration level of wind power into the electrical grid systems is expected. On the topic of using ESS to achieve wind dispatchability such as in the likely scenario of future large-scale wind generation which spans across a large geographical area, the pumped-hydroelectric storage (PHS) will be a more suitable ESS option. This is because PHS has inherently much larger energy capacity and it is able to store / supply energy over relatively longer duration as compared to the BESS, as alluded in Sections 2.3.1.3 and 2.3.2. The possibility of using PHS for large-scale wind power integration shall be examined in the next chapter.

Chapter 5: A Statistical Approach to Determine the Power Dispatch and Pumped-Hydroelectric Storage Capacity for Large-scale Wind Generation

Present trend worldwide is to establish various measures and targets to further encourage the adoption of renewable power generations. As wind generation has the most significant growth among the various renewable sources, large-scale wind generations are now found in many parts of the world [7, 101] and is likely to continue. In an investigation carried out on large-scale wind power generation into the control areas of Electric Reliability Council of Texas (ERCOT), the authors in [102] have established that more than 20% of the ERCOT peak load demand can be served by wind power. Nevertheless, [102] concludes that the negative impacts of the variable wind power on system security still needs to be surmounted with well-designed ancillary service. Additionally, their analysis assumes the utilities are obliged to give priority to wind power productions and the ratio of conventional dispatchable portfolio mix of generators to the total generation capacity in the ERCOT system will remain constant even as the wind power capacity grows. To predict how generation mix would evolve in a power system is an extremely challenging task. Adding to the dilemma of deploying wind, several advanced countries have recently announced the decision to retire nuclear power generation within the next 20 years or so. If the decision is to eventuate, the penetration level of wind power would be expected to increase in these countries. When this occurs, it will be more than likely wind farm operators will be pressured to provide firm power dispatch, in a manner similar to that provided by conventional power stations.

Despite leveraging on the notion of spatial smoothing effect, it remains a challenging task to firmly commit the wind output power several hours or a day ahead. In Chapter 4, BESS is proposed to be used for the energy management of wind power generation. Unfortunately, supporting a number of wind farms sited over a vast area with a BESS is neither practical nor economical. For this purpose, pumped-hydroelectric storage (PHS) is a more suitable ESS option due to its larger energy capacity and it is able to store/supply energy for hours

or longer, as alluded to in Sections 2.3.1.3 and 2.3.2. Thus the emphasis of this present investigation will be to develop a useful planning technique for the design of the PHS system which is to operate in conjunction with large-scale wind power generation. Specifically, a statistical approach is proposed to determine the required capacities of the PHS and the PHS is to be integrated into a power system containing a number of wind farms dispersed over a large geographical area.

In the proposed scheme, both the PHS power and energy capacities are again determined and similar to the previous approach in Chapter 4, the scheme herein incorporates the design of the dispatch strategy in the planning phase. Thus, the dispatch strategy becomes a part in the design of the ESS, which is not the case in Chapter 3. Again, the scheme does not need to assume the capacities are independent design variables. By utilizing the known distribution of the error in the predicted wind power, a statistical approach will be used to determine the capacities of the PHS and also to design the dispatch strategy for the combined wind generation-PHS system to meet power dispatch at specified confidence level. Nevertheless, the approach adopted in this study is different from that of Chapters 3 and 4. In the dispatch strategy utilized in Chapter 4, it is seen that the BESS does not undergo complete charge-discharge cycle. Consequently, the BESS energy storage capacity is often not fully utilized. Furthermore, due to the irregular charge-discharge cycles of the BESS, an approximate method needs to be applied to assess the lifetime of the BESS which consequently leads to uncertainties in the economic performance evaluation of the wind-BESS system. In this chapter, it will be shown that the designed dispatch strategy shall result in the PHS undergoing motoring (pumping) action until the stored energy of the PHS reaches a set maximum level, following which the PHS will go into generating mode until its stored energy arrives at a set minimum level. The pumping-generating cycle is then repeated. By doing so, not only is the PHS energy storage capacity fully utilized, it is also possible to know the number of cycles the PHS has undergone at any given time. Hence, this approach will allow the determination of the PHS expected lifetime more accurately as compared to that using the BESS energy throughput, as proposed in Chapter 4. In addition, this designed mode of operation will have distinct advantage over that described in [66]. In [66], besides not fully utilizing the PHS energy

storage capacity, the PHS is subjected to series of pumping/generating cycles. As a result of the more frequent transition between the pumping/generating modes, the lifetime of the PHS will be adversely reduced.

Thus Section 5.1 provides an overview of the large-scale wind generation-PHS scheme. A proposed methodology to determine the short-term power dispatch schedule is then given in Section 5.2. Section 5.3 develops a statistical method to determine the PHS capacities so that the output power of the combined wind generation-PHS system can be successfully dispatched at specified confidence level. Additionally, it will be shown how the confidence level shall be affected by the accuracy of the wind power forecast and the PHS capacities. While achieving such firm power dispatch is highly desirable, this advantage must be weighed against the cost of the PHS. Thus, Section 5.4 describes a method to derive the expected benefit in utilizing the PHS and to determine the optimal PHS capacities to achieve firm dispatch at given confidence level. The presented method shall also serve to address the inadequacy of the study in Chapter 4 where only the BESS lifecycle cost is considered. Section 5.5 presents a case study to demonstrate the proposed design methodology.

5.1 Large-scale wind generation-PHS scheme

Fig. 5-1 shows a schematic diagram of a large-scale wind power generation scheme incorporated with PHS. Recall the purpose of this study is to determine the required capacities of the PHS so as to achieve dispatchability in the output power $P_d(t)$ of the combined wind generation-PHS system. Hence, the manner by which the harnessed wind power is controlled and transmitted is not considered in the study. The aggregated output power from the farms is denoted herein as $P_w(t)$. From the finding established in [14, 15] and as seen in Section 2.1, most of the wind energy is contained in the low frequency band of $P_w(t)$. Hence, this study will only focus on the energy intensive low-frequency components of $P_w(t)$. To prevent the faster components in $P_w(t)$ from affecting the grid power quality, additional regulating reserves can be procured from the ancillary services market or supplementary short-term ESS such as that utilized in Chapter 4 can be installed

within the individual wind farms. This aspect of the design to deal with the faster components in $P_W(t)$ is not included in this chapter.

Fig. 5-1 Schematic diagram of the PHS and grid-connected wind farms distributed over a large geographical area

Let $P_L(t)$ in Fig. 5-1 represents the low frequency components of $P_W(t)$ and $P_P(t)$ denote the PHS output power. The arrows indicate the assumed positive direction of active power flows. From Fig. 5-1, the relationship between $P_d(t)$, $P_L(t)$ and $P_P(t)$ is

$$P_d(t) = P_L(t) - P_P(t) \quad (5.1)$$

The power of the PHS $P_P(t)$ in Fig. 5-1 should ideally be represented by a bidirectional arrow as the PHS can be charged as well as discharged. However, to illustrate the relationship between $P_d(t)$, $P_L(t)$ and $P_P(t)$ as described by (5.1), a unidirectional arrow is assigned to represent the positive direction (charging) of the power flows for $P_P(t)$ in Fig. 5-1.

5.2 Determination of power dispatch

Recall that the design of the wind generation-PHS scheme will need to comply with the prevailing market rules such as that described in Section 3.2. For example: Dispatch $P_d(t)$ will need to remain constant within each τ -interval and the committed dispatch of the immediate m hours cannot differ from their pre-determined bids. Therefore, the planning study begins with similar procedure as described in Section 3.3.1, i.e. to emulate a possible short-term dispatch planning procedure. First, based on the historical data on $P_w(t)$, $0 \leq t \leq T_1$, the wind power forecast $P_{w,f}(t)$ for the following period T , $T_1 \leq t \leq T_2$, which can be up to a day ahead is generated. Then with the known $P_w(t)$, the corresponding low frequency components $P_L(t)$ can be obtained using a low-pass filter, an approach which has also been adopted in [15]. Similarly, from the wind power forecast $P_{w,f}(t)$ for $T_1 \leq t < T_2$, its low frequency components $P_{f,L}(t)$ can also be derived. $P_{f,L}(t)$ forms the basis on which the short-term dispatch $P_d(t)$ for day-ahead planning is derived, subject to the prevailing power market constraints described above.

As explained afore, most of the energy in $P_w(t)$ shall be in $P_L(t)$ whereas most of the energy in the forecasted wind power $P_{w,f}(t)$ shall be contained within $P_{f,L}(t)$. To illustrate this observation, a 400-hour wind power data measured at NTU S2 was scaled to reflect the spatial smoothing effect of the many WTGs dispersed over a control region. For this purpose, the method that was utilized to scale the wind power data in Section 4.5 will be applied herein. Specifically, in the numerical example to be described in a latter section, the per-unit wind power data obtained from the author's campus is assumed to have a base value of 5 MW to mimic the output power of a 5 MW WTG. Let the total number of WTGs in the control region (N) herein be 200 and they are cited in a linear configuration. Subsequently, the wind power data from any two adjacent WTGs are assumed identical except the wind power data from one of the WTGs would be delayed from the other by 60-seconds. Finally, $P_w(t)$ is obtained by summing all the power from the N WTGs. As the exact method of obtaining the forecasted wind power $P_{w,f}(t)$ is not the focus of this study, it was assumed that the error in the forecast $P_{w,f}(t)$ had zero-mean and was normally distributed. It is reasonable to assume error in $P_{w,f}(t)$ to be normally distributed and this

aspect shall be justified later. Based on an investigation carried out in [29], it was found that the aggregated wind power forecast error can be between 3% ~ 8% of the total rated wind power capacity in the control region. Thus, the root-mean-square of the wind power forecast error in this investigation was taken to be 5%. The error in the wind power forecast was generated and added to $P_W(t)$ to form $P_{W,f}(t)$. Using a low-pass filter of cutoff frequency of 0.093×10^{-3} Hz, a value selected from [15], $P_L(t)$ and $P_{f,L}(t)$ were derived. The energy contents in $P_W(t)$, $P_L(t)$, $P_{W,f}(t)$ and $P_{f,L}(t)$ over the 400-hours were determined and compared. It is seen that the difference between $P_W(t)$ and $P_L(t)$ is approximately 2% of the total harnessed wind energy. Similar percentage difference between $P_{W,f}(t)$ and $P_{f,L}(t)$ was also observed. These observations clearly verify that the largest energy content in $P_W(t)$ and $P_{W,f}(t)$ are within their low frequency band.

5.2.1 Principle of determining the dispatch

In this context, let the rated PHS energy capacity be denoted as $E_{P,R}$. In practice, stored energy level in the PHS depends on the water level in the PHS (upper) reservoir [103]: for example, the maximum designed water storage height establishes the PHS energy capacity $E_{P,R}$ and this maximum height should not be exceeded as overtopping of the PHS may lead to catastrophic consequences [43]. In addition, when the water level drops below its minimum designed height, the PHS will not generate any power. Hence, the water level between the minimum and maximum designed heights dictates the effective usable range of the PHS stored energy [103]. This range can be considered to be the maximum allowable depth of discharge ($d_{P,max}$) of the PHS. Thus one can describe the amount of PHS stored energy by the term state of charge (SOC_P). SOC_P could be inferred from the knowledge of the water level in the reservoir.

Let the PHS charging and discharging times in this context be denoted as $\tau_{P,C}$ and $\tau_{P,D}$ respectively. $\tau_{P,D}$ is defined as the PHS discharging time when the PHS p.u. energy level changes from the fully charged state $SOC_P = 1$ to the maximum allowable discharged state $SOC_P = 1 - d_{P,max}$. Conversely, $\tau_{P,C}$ is the PHS charging time when SOC_P changes from $1 - d_{P,max}$ to 1.

In the designed scheme to be described shortly, it is intended that the PHS be charged/discharged in a cyclic manner. Thus, the duration $\tau_{P,C} + \tau_{P,D}$ represents one full charge-discharge time of the PHS. Several advantages can be brought about by operating the PHS in such a cyclic manner: Firstly, with the PHS going through full charge-discharge cycle, the energy storage potential of the PHS is thus maximized. Secondly unlike the scheme in [66], the life span of the PHS will not be adversely affected because the PHS is not subjected to frequent motoring/generating transitions [17, 104]. Moreover, the PHS lifetime can be expressed in terms of the number of charge-discharge cycles the PHS can undertake before it fails to function properly. Therefore, with the knowledge of the number of cycles the PHS has undergone at any given time, it will allow one to predict the PHS expected lifetime much more accurately as compared to the use of the energy throughput in Chapter 4.

Fig. 5-2 Determination of $P_{d,r}(t)$ for PHS discharging operation at $t \geq j^{th}$ -hour

A new method will now be proposed to design the dispatch strategy. Let the reference quantity of the dispatch $P_d(t)$ be denoted as $P_{d,r}(t)$ where $P_{d,r}(t)$ will be the committed output power of the combined wind generation-PHS system. With reference to Fig. 5-2, suppose $P_{d,r}(t)$ is to be committed for the j^{th} -hour and beyond. The dispatch bids will need to be submitted latest at the i^{th} -hour where $i = j - m$. This is because $P_{d,r}(t)$ for the immediate m hours after the i^{th} -hour must not differ from those values committed earlier. Consider firstly the case when the PHS is ready for discharging. Using the forecasted wind power $P_{f,L}(t)$, the proposed approach is to set $P_{d,r}(t)$ as the maximum of $P_{f,L}(t)$ within the interval $j \leq t \leq$

$j + n\tau$, where n is an integer. See Fig. 5-2(a). Note that n must be an integer as $P_{d,r}(t)$ must remain constant within the τ interval.

By setting $P_{d,r}(t)$ to the maximum $P_{f,L}(t)$, the PHS would be expected to discharge over the interval $j \leq t \leq j + n\tau$, i.e. for the $n\tau$ hours. The expected total amount of energy that shall be discharged from the PHS equals to the shaded area shown in Fig. 5-2(a), and it can be readily calculated. Hence, SOC_P at $t = j + n\tau$ can be calculated if $SOC_P(j)$ is known. The estimation of $SOC_P(j)$ shall be explained in the next sub-section. Next, by adjusting n , find the minimum n value, denoted as n_{min} , so that over-discharging of the PHS occurs, i.e. $SOC_P(j + n_{min}\tau) < 1 - d_{P,max}$. In order to prevent over-discharging, decrease n_{min} by 1 and search again for the maximum of $P_{f,L}(t)$ over the interval $j \leq t \leq j + [n_{min} - 1]\tau$. Set $P_{d,r}(t)$ to this maximum level and this new level is represented by the dotted line in Fig. 5-2(b). Re-calculate the total discharged energy over this interval. Clearly at this new discharge level, the PHS will not reach the full discharge state at the $j + (n_{min} - 1)\tau$ hours. So to achieve full discharge of the PHS, $P_{d,r}(t)$ is adjusted to a higher level so that at this increased level, the PHS is fully discharged, i.e., $SOC_P(j + [n_{min} - 1]\tau) = 1 - d_{P,max}$. This is the dispatch power level shown by the solid line in Fig. 5-2(b). Note that the resulting PHS discharging time $\tau_{P,D} = (n_{min} - 1)\tau$, i.e. the PHS discharge time $\tau_{P,D}$ is an integer multiple of τ .

Fig. 5-3 Determination of $P_{d,r}(t)$ for PHS charging operation at $t \geq j^{th}$ -hour

For the case of PHS charging, similar principle as described above applies. Instead of discharging, suppose the PHS is ready for charging at the j^{th} -hour. $P_{d,r}(t)$ will now be set as the minimum of $P_{f,L}(t)$ within the interval $j \leq t \leq j + n\tau$, as shown in Fig. 5-3(a). By

calculating the amount of charging energy in the shaded area in Fig. 5-3(a), the subsequent search is to find the appropriate value of the charging time $\tau_{P,C}$ and $P_{d,r}(t)$ level until the PHS attends the fully charged state at the $j + (n_{min} - I)\tau$ hours. This scenario is represented by the solid line in Fig. 5-3(b). Again the charging time $\tau_{P,C}$ is an integer multiple of τ .

With the determined committed dispatch $P_{d,r}(t)$, one can then obtain the reference quantity $P_{P,r}(t)$ for the PHS output power $P_P(t)$ based on the forecasted $P_{f,L}(t)$. This is done by rewriting (5.1) as

$$P_{P,r}(t) = P_{f,L}(t) - P_{d,r}(t) \quad (5.2)$$

$P_{P,r}(t)$ is also shown in Fig. 5-2(b) and 5-3(b). In Fig. 5-2(b), as $P_{f,L}(t) < P_{d,r}(t)$ over the interval $j \leq t \leq j + [n_{min} - I]\tau$ hours, the PHS needs to discharge, i.e. $P_{P,r}(t) < 0$. Conversely in Fig. 5-3(b), the excess $P_{f,L}(t)$ will be directed to the PHS while delivering the required $P_{d,r}(t)$. Hence $P_{P,r}(t) > 0$ and the PHS is being charged.

Note that although the PHS stored energy capacity is finite at $E_{P,R}$ p.u. MWh, the total duration for the PHS to charge from its $SOC_P = 1 - d_{P,max}$ to 1 and subsequently to discharge from $SOC_P = 1$ to $1 - d_{P,max}$ will vary because the input wind power is varying.

5.2.2 Determination of the PHS $SOC_P(j)$

The previous sub-section explains that the determination of $P_{d,r}(t)$, $t \geq j$, must be done at least m hour in advance, i.e. at the i^{th} -hour, and this in turn requires the PHS SOC_P at the j^{th} -hour to be known. $SOC_P(i)$ is known through on-line measurement of the water level in the PHS upper reservoir. However, between the i^{th} and the j^{th} hours, actual $P_L(t)$ is not known and only the forecasted $P_{f,L}(t)$ is available. Hence, the change in PHS SOC level (ΔSOC_P) over the period $i < t \leq j$ can be estimated as

$$\Delta SOC_{P,ij} = \frac{1}{E_{P,R}} \int_i^j (P_{f,L}(\tau_i) - P_{d,r}(\tau_i)) \cdot d\tau_i \quad (5.3)$$

Whence, the PHS SOC_P at the j^{th} -hour is

$$SOC_P(j) = SOC_P(i) + \Delta SOC_{P,ij} \quad (5.4)$$

$SOC_P(i)$ is the measured PHS SOC_P level at the i^{th} -hour. With the above proposed PHS charging/discharging scheme, the PHS will only change its operating state from charging (pumping) to discharging (generating) when $SOC_P(j)$ evaluated using (5.4) equals 1. Conversely, when $SOC_P(j) = 1 - d_{P,max}$, the PHS will transit from generating to pumping modes. In practice, however, to prevent the PHS from being over-charged and over-discharged due to the forecasting errors in $P_{f,L}(t)$, it will be prudent to include a small positive tolerant ε in the PHS allowable SOC_P operating range. A slightly reduced SOC_P range of $[(1 - d_{P,max} + \varepsilon), (1 - \varepsilon)]$ is suggested. Therefore, the PHS will change from the pumping to generating modes once $SOC_P(j)$ exceeds $(1 - \varepsilon)$. Conversely, when $SOC_P(j)$ falls below $(1 - d_{P,max} + \varepsilon)$, the PHS is ready for pumping.

5.2.3 Revising $P_{d,r}(t)$ m -hour ahead

Having obtained the estimated $SOC_P(j)$, this section serves to explain how to update $P_{d,r}(t)$ m -hour ahead at every τ -interval. This would result in a more precise $P_{d,r}(t)$. From the previous sub-sections, $P_{f,L}(t)$ must be used as the actual $P_L(t)$ is not known when determining the dispatch commitment $P_{d,r}(t)$. However, $P_{f,L}(t)$ and $P_L(t)$ will not be identical due to the inevitable error in the forecast. The present approach uses regular update of the wind power forecast so that the time-horizon of the forecast will be limited to relatively short interval. Therefore, leveraging on the updated $P_{f,L}(t)$, the committed $P_{d,r}(t)$ which is beyond the immediate m -hours shall be revised at every τ -interval.

Fig. 5-4 Revision of $P_{d,r}(t)$ for $t \geq k$ based on the updated $P_{f,L}(t)$ determined at the $(i + \tau)^{\text{th}}$ hour

Figs. 5-2 and 5-3 are used to explain how $P_{d,r}(t)$ is determined at the i^{th} -hour, $t \geq j$. Consider the case of PHS undergoing the charging process, i.e. Fig. 5-3(b) shown expanded in Fig. 5-4. It shows $P_{f,L}(t)$ and the corresponding $P_{d,r}(t)$ as determined at the i^{th} -hour. Since the wind power forecast is updated at the regular interval τ , a revised $P_{f,L}(t)$ is acquired at the $(i + \tau)^{\text{th}}$ -hour and it is also shown in Fig. 5-4. The updated $P_{f,L}(t)$ is likely to differ from the $P_{f,L}(t)$ previously obtained at the i^{th} hour and hence, there is a need to more precisely compute and update $P_{d,r}(t)$ at the $(i + \tau)^{\text{th}}$ -hour, for $P_{d,r}(t)$ that is m hours beyond the $(i + \tau)^{\text{th}}$ -hour, for $t \geq k$, $k = j + \tau$. This in turn requires the PHS SOC_P at the k^{th} hour to be evaluated in the following way.

At the $(i + \tau)^{\text{th}}$ hour, since the SOC_P is monitored on-line, SOC_P at the $(i + \tau)^{\text{th}}$ hour would be known. Only the updated forecast $P_{f,L}(t)$ over the period $(i + \tau) < t \leq k$ is to be used to compute the forecasted change (ΔSOC_P) in the SOC_P of the PHS. The sum of $SOC_P(i + \tau)$ and the computed ΔSOC_P yields $SOC_P(k)$. The computed $SOC_P(k)$ will be subtracted from the upper limit of the PHS SOC_P , i.e. $(1 - \varepsilon)$, which when multiply by the rated PHS energy capacity $E_{P,R}$, yields the remaining amount of the stored energy the PHS is to be charged before the PHS is allowed to go into the discharging mode. Let this remaining energy to be charged be denoted as E_1 . Then following the same procedure as described in Section 5.2.1, the new $P_{d,r}(t)$ is first set to the minimum $P_{f,L}(t)$ within the interval $k \leq t \leq k + q\tau$, where

q is an integer. The amount of energy the PHS is expected to be charged can be readily calculated by evaluating the area between the updated $P_{f_L}(t)$ and the minimum $P_{f_L}(t)$ for $k \leq t \leq k + q\tau$. Find the minimum q , denoted as q_{min} , so that the amount of PHS charging energy is greater than E_l . Once this occurs, decrease q_{min} by 1 and search again for the minimum $P_{f_L}(t)$ over the interval $k \leq t \leq k + [q_{min} - 1]\tau$. Set $P_{d,r}(t)$ to this minimum level. In Fig. 5-4, $k + [q_{min} - 1]\tau$ is denoted as the l^{th} -hour. Obviously, the PHS will not be ready for discharging at the l^{th} -hour at this $P_{d,r}(t)$ level. To elude this, adjust $P_{d,r}(t)$ to an even lower value than the minimum $P_{f_L}(t)$ over the interval $k \leq t \leq l$ so that the amount of energy the PHS is charged over the interval $k \leq t \leq l$ is exactly E_l . Fig. 5-4 also shows the revised $P_{d,r}(t)$ determined at the $(i + \tau)^{th}$ hours. In this way, the PHS is expected ready for discharging at the l^{th} -hour.

Mathematically, $P_{d,r}(t)$ for $k < t \leq l$ for the above scenario is:

$$P_{d,r}(t) = \min_{k < t \leq l} \{P_{f_L}(t)\} - \frac{1}{l-k} \left[(1 - \varepsilon - SOC_P(k)) E_{P_R} - \int_k^l (P_{f_L}(\tau_i) - \min_{k < t \leq l} \{P_{f_L}(t)\}) d\tau_i \right], \quad \text{for } k < t \leq l \quad (5.5)$$

where $\min\{\cdot\}$ is the minimum function of $\{\cdot\}$. The first term on the right-hand-side of (5.5) is to set $P_{d,r}(t)$ to the minimum $P_{f_L}(t)$ over the interval $k \leq t \leq l$. In the second term, $(1 - \varepsilon - SOC_P(k)) \cdot E_{P_R}$ serves to evaluate the amount of energy the PHS can still be charged (E_l) before the PHS is ready for discharging. The third term, $\int_k^l (P_{f_L}(\tau_i) - \min_{k < t \leq l} \{P_{f_L}(t)\}) d\tau_i$ evaluates the PHS charging energy with $P_{d,r}(t)$ set to the minimum $P_{f_L}(t)$ over the interval $k \leq t \leq l$. In the case of the PHS undergoing the charging process, the second term is larger than the third term. Dividing the difference between the second and third terms by the duration $[q_{min} - 1]\tau$, i.e. $(l - k)$ hours, the resulting value is the offset power level to be added to the minimum $P_{f_L}(t)$ over the interval $k \leq t \leq l$. The corresponding PHS charging time $\tau_{P,C}$ shall be $(l - j)$.

Similar reasoning as described above can be applied to the case of the PHS undergoing discharging operation when revising $P_{d,r}(t)$ for $t \geq k$. Assume the PHS is readied for

charging operation at the end of $(k + [q_{min} - I]\tau)^{\text{th}}$ or the l^{th} -hour. Whence, the revised $P_{d,r}(t)$ for $k < t \leq l$ is expressed as

$$P_{d,r}(t) = \max_{k < t \leq l} \{P_{f-L}(t)\} + \frac{1}{l-k} \left[(SOC_P(k) - (1 - d_{P,max} + \varepsilon)) E_{P-R} + \int_k^l (P_{f-L}(\tau_i) - \max_{k < t \leq l} \{P_{f-L}(t)\}) d\tau_i \right], \quad \text{for } k < t \leq l \quad (5.6)$$

where $\max\{\cdot\}$ is the maximum function of $\{\cdot\}$ and the first term is to set $P_{d,r}(t)$ to the maximum $P_{f-L}(t)$ over the interval $k \leq t \leq l$ as is required when the PHS is discharging. The second term: $(SOC_P(k) - (1 - d_{P,max} + \varepsilon)) \cdot E_{P-R}$ evaluates the amount of energy the PHS can still discharge before the PHS is ready for charging. The third term $\int_k^l (P_{f-L}(\tau_i) - \max_{k < t \leq l} \{P_{f-L}(t)\}) \cdot d\tau_i$ yields the PHS discharging energy when $P_{d,r}(t)$ is set to the maximum $P_{f-L}(t)$ over the interval $k \leq t \leq l$. As the PHS is discharging, the third term will be negative. By summing the second and third terms and dividing the result by the duration $(l - k)$, it yields the offset power level to be added to the value of $P_{d,r}(t)$ set at the maximum $P_{f-L}(t)$ over the interval $k \leq t \leq l$. The corresponding PHS discharging time $\tau_{P,D}$ shall be $(l - j)$.

Based on known SOC_P at the end of every τ -interval and using the updated $P_{f-L}(t)$ to revise the m -hour ahead power schedule $P_{d,r}(t)$, the scheme is able to accommodate the errors in wind power prediction. Additionally, the PHS charging/discharging limits will be less likely to be violated using this approach. By following the computational procedures described in this section, $P_{d,r}(t)$ over a given study period T_S can be determined. It is important to note that in the proposed scheme, the PHS shall operate cyclically in the charging (pumping) mode before it goes into the discharging (generating) mode. Furthermore, the charging and discharging durations, $\tau_{P,C}$ and $\tau_{P,D}$, will vary and will depend on the PHS rated energy capacity E_{P-R} . With a larger E_{P-R} , the PHS will take longer time to complete one charge/discharge cycle or equivalently, a lower number of PHS charge/discharge cycles is seen in T_S . The PHS can then be expected to have a longer lifetime as the number of charge-discharge cycles the PHS can operate satisfactorily is

finite. However, the expected longer PHS lifetime is achieved at the expense of higher PHS rated energy capacity, i.e. larger capital investment. Thus, a judicious balance between the PHS useful lifetime and cost needs to be achieved. This is the main objective of the following section.

5.3 A statistical approach to determine PHS power capacity

With the above strategy established in designing the committed dispatch $P_{d,r}(t)$, attention is next directed to determine the PHS power capacity.

5.3.1 Wind power forecast $P_{f,L}(t)$ at given confidence level

Section 5.2 describes how the dispatch commitment $P_{d,r}(t)$ can be determined from $P_{f,L}(t)$ so that the PHS will undergo cyclic charging/discharging operation. Since $P_{f,L}(t)$ is obtained from the wind power forecast $P_{w,f}(t)$, the accuracy of $P_{f,L}(t)$ will be affected by the uncertainty in the forecast $P_{w,f}(t)$ which in turn, will have impact on the design of the dispatch $P_{d,r}(t)$. Similar problem has been recognized by the authors of [54, 55] when they studied wind and renewable power dispatch issue.

As explained in Chapter 2, wind power prediction errors for a single WTG or a wind farm does not assume Gaussian distribution. For the problem at hand, it is necessary to provide day-ahead forecast of the aggregated power $P_w(t)$ which is contributed by a large number of WTGs located over a large area. Hence, in this instance, the output power from the WTGs can be considered uncorrelated and the errors in the forecast $P_{w,f}(t)$ can be assumed to be Gaussian [7, 105]. Also explained in Chapter 2 and for most of the currently available wind power forecasting methods such as that described in [29, 30], the wind power forecast error can be quantified in terms of the Normalized Root-Mean-Square Error (NRMSE), obtained by normalizing the RMSE with respect to the wind power generation installed capacity. Typically, NRMSE increases with the time-horizon of the forecast: NRMSE in a control region can be between 3% for an hour ahead forecast and up to 8% for a day ahead forecast [29]. If the mean (μ_{Pe}) of the forecast error is zero, the error standard deviation (σ_{Pe}) is equaled to the NRMSE. In general, with Gaussian distribution of the forecast error,

$P_{W,f}(t)$ can thus be expressed to lie between an upper forecast $P_{W,fU}(t)$ and a lower forecast $P_{W,fL}(t)$. $P_{W,fU}(t)$ and $P_{W,fL}(t)$ can be obtained by adding to $P_{W,f}(t)$ the values of $(\mu_{Pe} + r\sigma_{Pe})$ and $(\mu_{Pe} - r\sigma_{Pe})$ respectively. The central wind power forecast $P_{W,fC}(t)$ is obtained by the addition of μ_{Pe} to $P_{W,f}(t)$. For example, actual wind power is expected to be within the range of $P_{W,fU}(t)$ and $P_{W,fL}(t)$ with a confidence level of 99.7% when $r = 3$.

Fig. 5-5 A daily plot of $P_{f_{LU}}(t)$, $P_{f_{LC}}(t)$ and $P_{f_{LL}}(t)$

In a manner similar to the processing of $P_W(t)$ as described in Section 5.2, $P_{W,fU}(t)$, $P_{W,fC}(t)$ and $P_{W,fL}(t)$ over the period T , $T_1 \leq t \leq T_2$, can therefore be generated and their corresponding low frequency components, $P_{f_{LU}}(t)$, $P_{f_{LC}}(t)$ and $P_{f_{LL}}(t)$, can then be derived for $T_1 \leq t \leq T_2$. Fig. 5-5 shows an example of $P_{f_{LU}}(t)$, $P_{f_{LC}}(t)$ and $P_{f_{LL}}(t)$. Note that in deriving the upper curve $P_{f_{LU}}(t)$, $P_{f_{LU}}(t)$ will be set equal to the total wind generation rated capacity in the control region if $P_{f_{LU}}(t)$ exceeds the rated capacity. Conversely, when the lower curve $P_{f_{LL}}(t)$ assumes a negative value, $P_{f_{LL}}(t)$ is set to zero as the proposed scheme is not intended to allow the import of power from the grid.

The errors in the wind power forecast for large-scale wind generation can be assumed to be Gaussian have already been explained earlier in this sub-section. However, if it is desired to obtain $P_{W,fU}(t)$ and $P_{W,fL}(t)$ for a single WTG or a wind farm, the method explained in Section 2.2.2.1 can be invoked to determine the mean (μ_{Pe}) and standard deviation (σ_{Pe}) of the forecast error.

5.3.2 Revised $P_{d,r}(t)$ in consideration of the forecast $P_{f,L}(t)$ confidence level

By taking into account the confidence level in the forecast $P_{f,L}(t)$, the computation procedure described in Section 5.2 for the determination of $P_{d,r}(t)$ will need to be modified slightly as follows. The actual $P_L(t)$ can be expected to lie within the range of $P_{f,LU}(t)$ and $P_{f,LL}(t)$ with confidence level p_I , i.e.,

$$Prob\{P_{f,LL}(t) \leq P_L(t) \leq P_{f,LU}(t)\} = p_I \quad (5.7)$$

where $Prob\{\cdot\}$ is the probability of condition $\{\cdot\}$ being satisfied. Consider the case when the PHS is to go into the discharging mode, and one wishes to compute the dispatch $P_{d,r}(j)$ at the i^{th} -hour based on the confidence level p_I of the wind power forecast. $P_{d,r}(t)$ will now be set to the value equal to the maximum value of the upper curve $P_{f,LU}(t)$ which is within the interval $j \leq t \leq (j + n\tau)$. The total amount of PHS discharged energy for the $n\tau$ hours can be computed by integrating the difference in the power levels between the $P_{f,LL}(t)$ and $P_{d,r}(t)$ with respect to t . Search for the minimum value of n until the PHS over-discharges. Then decrease n_{min} by 1 and repeat the search for the appropriate $P_{d,r}(t)$ level such that the stored energy level of the PHS reaches the desired SOC_P lower limit, i.e. $SOC_P(j + [n_{min} - 1]\tau) = 1 - d_{P,max} + \varepsilon$. With $P_{d,r}(t)$ so determined, the reference PHS discharging power $P_{P,r}(t)$ for the interval will now be evaluated using the difference between $P_{f,LL}(t)$ and $P_{d,r}(t)$. At the end of the interval, the PHS is expected to be readied for charging.

Conversely, to charge the PHS, set $P_{d,r}(t)$ as the minimum of the lower curve $P_{f,LL}(t)$ within the interval $j \leq t \leq (j + n\tau)$. Then, compute the total PHS charging energy using the upper curve $P_{f,LU}(t)$ and $P_{d,r}(t)$. Again, reduce n_{min} by 1 when the PHS overcharges and find the suitable $P_{d,r}(t)$ until the PHS is ready to discharge, i.e. $SOC_P(j + [n_{min} - 1]\tau) = (1 - \varepsilon)$. The reference PHS charging power $P_{P,r}(t)$ for the interval is evaluated using the difference between $P_{f,LU}(t)$ and $P_{d,r}(t)$.

The algebraic expression (5.5) for $P_{d,r}(t)$ over $k < t \leq l$ when the PHS is under charging mode now becomes

$$P_{d,r}(t) = \min_{k < t \leq l} \{P_{f_LL}(t)\} - \frac{1}{l-k} \left[(1 - \varepsilon - SOC_P(k)) E_{P_R} - \int_k^l (P_{f_LU}(\tau_i) - \min_{k < t \leq l} \{P_{f_LL}(t)\}) d\tau_i \right], \quad \text{for } k < t \leq l \quad (5.8)$$

Conversely, as expressed by (5.6) for $P_{d,r}(t)$ over $k < t \leq l$ when the PHS is discharging will now be computed as

$$P_{d,r}(t) = \max_{k < t \leq l} \{P_{f_LU}(t)\} + \frac{1}{l-k} \left[(SOC_P(k) - (1 - d_{P,max} + \varepsilon)) E_{P_R} + \int_k^l (P_{f_LL}(\tau_i) - \max_{k < t \leq l} \{P_{f_LU}(t)\}) d\tau_i \right], \quad \text{for } k < t \leq l \quad (5.9)$$

5.3.3 Impact on PHS expected lifetime due to confidence level in the forecast $P_{f_L}(t)$

It is clear that a higher confidence level p_l in the wind power forecast will result in a wider band between $P_{f_LL}(t)$ and $P_{f_LU}(t)$ and the dispatch level $P_{d,r}(t)$ will then be set farther away from that determined using either the central forecast $P_{f_LC}(t)$ or $P_{f_L}(t)$. In addition, during the charging process, the PHS will need to absorb larger amount of energy due to a higher $P_{P,r}(t)$ which is now the difference between the upper band $P_{f_LU}(t)$ and $P_{d,r}(t)$. The converse is also valid: the PHS has to generate larger amount of energy during the PHS discharge mode. With a given rated PHS energy capacity E_{P_R} , the higher charging/discharging energy means shorter charging and discharging times for the PHS. Consequently, determining the dispatch strategy for $P_{d,r}(t)$ based on higher p_l will result in greater confidence level in the committed dispatch being met. However, for PHS with a finite nominal cycle life and E_{P_R} , the expected PHS lifetime will be shorter.

5.3.4 Determination of PHS power capacity

The approaches described above determine the PHS reference charge/discharge power $P_{P,r}(t)$ over a complete study period T_S . To determine the PHS rated power capacity $P_{P,R}$, one can set $P_{P,R}$ to the maximum absolute value of $P_{P,r}(t)$ found over T_S similar to the works of [54, 55]. However, $P_{P,R}$ so determined is for the worst case scenario. Therefore, the statistical method that is utilized in Chapter 4 is deemed more suitable for determining $P_{P,R}$. So in a similar manner, take the absolute value of $P_{P,r}(t)$ and compute its probability density function (pdf) and cumulative probability function (cdf). From the cdf of $|P_{P,r}(t)|$, $P_{P,R}$ is set to a value which gives the corresponding probability of p_2 . By doing so, the extent of successful power dispatch now depends on both the wind power forecast confidence level and the PHS power capacity $P_{P,R}$ selection. Accordingly, let λ , $\phi | \lambda$ and A denote three sets of events: when $P_L(t)$ is within the range $\{P_{f_LU}(t), P_{f_LL}(t)\}$, when $|P_{P,r}(t)| \leq P_{P,R}$, and when power dispatch is successful respectively. Mathematically, the three sets of events above are expressed as

$$\left. \begin{aligned} \lambda &= (P_{f_LL}(t) \leq P_L(t) \leq P_{f_LU}(t)), \\ \phi | \lambda &= (|P_{P,r}(t)| \leq P_{P,R}), \\ A &= (P_{f_LL}(t) \leq P_L(t) \leq P_{f_LU}(t)) \cap (|P_{P,r}(t)| \leq P_{P,R}) \end{aligned} \right\} \quad (5.10)$$

Note that due to $P_{P,r}(t)$ is dependent on $P_{f_LL}(t)$ and $P_{f_LU}(t)$, the second event ($\phi | \lambda$), i.e. $|P_{P,r}(t)| \leq P_{P,R}$, is represented by a conditional event. This is because $P_{P,r}(t)$ is determined based on $P_{d,r}(t)$ which in turn depends on the forecasted lower and upper wind power $P_{f_LL}(t)$ or $P_{f_LU}(t)$.

Since ($\phi | \lambda$) is dependent on λ , the probability of successful power dispatch $Prob\{A\}$, which depends on both the wind power forecast confidence level and power capacity selection, can now be expressed in terms of conditional probability:

$$Prob\{A\} = Prob\{\phi | \lambda\} \times Prob\{\lambda\} \quad (5.11)$$

The procedure to determine the PHS power capacity $P_{P,R}$ and the corresponding successful power dispatch probability $Prob\{A\}$ will now be described. Firstly, the desired confidence level of the forecast $P_{f,L}(t)$ is set at (say) p_1 . From the mean and standard deviation of the error in the forecast plus the forecasted $P_{W,f}(t)$, the upper and lower wind power forecast curves $P_{W,fU}(t)$ and $P_{W,fL}(t)$ can be generated. Next, compute the low frequency components of $P_{W,fU}(t)$ and $P_{W,fL}(t)$, i.e. $P_{f,LU}(t)$ and $P_{f,LL}(t)$ respectively. As $P_{f,LU}(t)$ and $P_{f,LL}(t)$ will be obtained over the study period T_s , the probability of the actual $P_L(t)$ being within $P_{f,LU}(t)$ and $P_{f,LL}(t)$ is p_1 , i.e.

$$Prob\{\lambda\} = p_1 \quad (5.12)$$

From $P_{f,LU}(t)$ and $P_{f,LL}(t)$, compute/revise $P_{d,r}(t)$ using (5.8) and (5.9) via the procedure described in Section 5.3.2. Compute $P_{P,r}(t)$ over T_s by taking the difference between $P_{f,LU}(t)$ and $P_{d,r}(t)$ for PHS charging operation and conversely for discharging the PHS, subtract $P_{d,r}(t)$ from $P_{f,LL}(t)$. Construct the pdf and cdf of $|P_{P,r}(t)|$. Set the PHS power rating $P_{P,R}$. Suppose $P_{P,R}$ is selected at confidence level p_2 , i.e. the probability of $|P_{P,r}(t)|$ not exceeding $P_{P,R}$ will be p_2 , viz.

$$Prob\{\phi/\lambda\} = p_2 \quad (5.13)$$

Thus based on (5.11), the probability of successfully meeting the committed dispatch power with the use of the PHS is

$$Prob\{A\} = p_2 \times p_1 \quad (5.14)$$

In this manner, the above statistical method allows the PHS power capacity to be determined such that successful power dispatch can be met with probability $p_2 \times p_1$.

5.4 Optimal PHS design

In this section, the optimal PHS capacity shall be determined through the maximization of the expected net economic benefit when incorporating the PHS scheme.

5.4.1 Net benefit of incorporating the PHS

With $P_{d,r}(t)$ determined based on the method of Section 5.3.2 and assume known tariff rate, the remuneration the wind farm operators can expect to receive can be readily calculated. Denote this remuneration over T_S as B_P . The committed power dispatch shall be met with the probability of $p_2 \times p_1$.

Next, one determines $P_{d,r}(t)$ without the incorporation of the PHS. Since the statistical distribution of the errors in $P_{w,f}(t)$ can be quantified in terms of μ_{Pe} and σ_{Pe} , one can then set the probability of the actual $P_L(t)$ to be above a lower curve $P_{f_LL}(t)$ at p , i.e.

$$Prob\{P_L(t) \geq P_{f_LL}(t)\} = p \quad (5.15)$$

Then at the i^{th} -hour, when computing $P_{d,r}(t)$ for the interval $j \leq t < k$, $P_{d,r}(t)$ shall be set to the minimum level of $P_{f_LL}(t)$ which appear within the interval $j \leq t < k$. Repeat this procedure over T_S . $P_{d,r}(t)$ evaluated in this manner will be expected to meet the power dispatch commitment at the confidence level p and without the use of the PHS. The corresponding remuneration for the provision of $P_{d,r}(t)$ over T_S without the PHS is denoted as B_W .

Thus the net benefit in using the PHS is $(B_P - B_W)$. Note that for valid evaluation of the net benefit, B_W must be determined at the same confidence level as that used to compute B_P , i.e. $p = p_2 \times p_1$.

5.4.2 Determining the most economical PHS

Section 5.2 shows the designed dispatch strategy shall cause the PHS to operate in a fully-charged and fully-discharged cycle, although the duration of one charging-discharging cycle will differ from the next because the input wind power is random. Nevertheless, one can readily track the charging and discharging processes over the study period and from which, the expected number of charging-discharging cycles (denoted as N_C) over T_s days can be evaluated. The expected life of the PHS is therefore given by

$$E[L_P] = \left(\frac{C_{P,n}}{N_C} \right) \times T_s \quad (5.16)$$

where $C_{P,n}$ is the PHS nominal cycle life and $E[L_P]$ is expressed in days. The capital cost of the PHS can be expressed as

$$C_{PHS} = c_1 \times P_{P,R} + c_2 \times E_{P,R} \quad (5.17)$$

where $P_{P,R}$ and $E_{P,R}$ are the PHS rated power and energy capacities respectively, and c_1 and c_2 are in $\$/MW$ and $\$/MWh$. Therefore, cost/day of implementing the PHS (η_P) is

$$\eta_P = \frac{C_{PHS}}{E[L_P]} \quad (5.18)$$

η_P shall have the unit of $\$/day$. To balance the cost against the benefit of implementing the PHS, the optimal $P_{P,R}$ and $E_{P,R}$ are determined in an iterative computational procedure. The procedure shall be based on the maximization of a dimensionless performance index g , where

$$g = \left(\frac{B_P - B_W}{T_s} \right) / \eta_P \quad (5.19)$$

In (5.19), g is the ratio between the expected net benefit (in \$/day) obtainable in using the PHS to the cost (also in \$/day) in implementing the PHS scheme. Index g differs from that shown in Chapter 4 and [73] where only the lifecycle cost is considered when determining the most economical ESS capacities.

A linear search method shown in Fig. 5-6 is utilized in this investigation to search for the maximum g so that the optimal power and energy capacities of the PHS are obtained. In this method, (5.19) will be the objective function and the variables to be searched for are the respective power and energy capacities of the PHS, $P_{P,R}$ and $E_{P,R}$.

Fig. 5-6 Computational procedure to obtain the optimal PHS capacities

The search begins by specifying the confidence level p_1 of the wind power forecast $P_{W,f}(t)$ and deriving the upper forecast $P_{W,fU}(t)$ and lower forecast $P_{W,fL}(t)$. Then the low frequency components of $P_{W,fU}(t)$, $P_{W,fL}(t)$ and that of the actual historical wind power $P_W(t)$, i.e. $P_{f_LU}(t)$, $P_{f_LL}(t)$ and $P_L(t)$ respectively, are computed using a filtering technique. Next, specify an initial PHS energy capacity E_{P_R} . With the procedures described in Section 5.3.2, compute/revise the committed dispatch $P_{d,r}(t)$ using (5.8) to charge the PHS. Conversely, (5.9) will be used to determine $P_{d,r}(t)$ when discharging the PHS. Over the study period T_S , evaluate the PHS power $P_{P,r}(t)$ by taking the difference between $P_{f_LU}(t)$ and $P_{d,r}(t)$ for PHS charging operation and conversely for discharging the PHS, subtract $P_{d,r}(t)$ from $P_{f_LL}(t)$. Then construct the conditional cdf of $|P_{P,r}(t)|$ and determine the PHS power capacity $P_{P,R}$ for a selected confidence level p_2 . Compute the remunerations with and without PHS over T_S , i.e. B_P and B_W respectively at confidence level $p = p_2 \times p_1$ using the method in Section 5.4.1. Subsequently, evaluate the expected lifetime and the associated costs of the PHS using (5.16) – (5.18). Finally, compute the index g using (5.19). Revise the current PHS energy capacity E_{P_R} by a small value (ΔE_{P_R}). Repeat the above procedure for different PHS energy capacity E_{P_R} and search until the maximum g is obtained. The corresponding $P_{P,R}$ and E_{P_R} at the maximum g shall yield the optimal power and energy capacities of the PHS capable of meeting the committed dispatch obligations at confidence level $p_2 \times p_1$.

5.5 Illustrative example

A hypothetical 1000-MW large-scale wind generation is used in this section to illustrate the proposed PHS design methodology. The 1-year wind power data $P_W(t)$ logged at the NTU S2 described in Section 5.2 was also used in this example. To obtain realistic wind power forecast, error in the forecast $P_{W,f}(t)$ was assumed to be normally distributed and had zero mean. The wind power forecast error could therefore be generated and added to $P_W(t)$ to form $P_{W,f}(t)$. The standard deviation σ_{PE} of the error was assumed to be 5% of the rated power capacity of 1000 MW.

In this investigation, the duration τ in which $P_{d,r}(t)$ is to remain constant is taken to be 1-hour, the m -hour ahead market rule applies and $m = 2$. Next, from $P_{W,f}(t)$, the upper and

lower bounds of the wind power forecast $P_{W,fU}(t)$ and $P_{W,fL}(t)$ are evaluated at various confidence levels p_1 of 50%, 68.2%, 95.4% and 99.7%. Subsequently, the low frequency components of $P_{W,fU}(t)$, $P_{W,fL}(t)$ as well as that of the actual wind power $P_W(t)$, i.e. $P_{fLU}(t)$, $P_{fLL}(t)$ and $P_L(t)$ respectively, were derived using a low-pass filter with the cutoff frequency of 0.093×10^{-3} Hz, a value selected from [15]. With the procedures described in Sections 5.2 and 5.3, the committed dispatch level $P_{d,r}(t)$ and $P_{P,r}(t)$ over the study period T_s are computed. Fig. 5-7 shows an example of $P_L(t)$, $P_d(t)$ as well as $P_P(t)$ evaluated using (5.1) for T_s of 1 day. Clearly using PHS, Fig. 5-7 shows that even as $P_L(t)$ fluctuates, the dispatched power $P_d(t)$ remains constant at hourly interval.

Fig. 5-7 An example of $P_L(t)$, $P_d(t)$ and $P_P(t)$ over a 24-hour period

Fig. 5-8 PHS power rating ($P_{P,R}$) versus PHS energy capacity $E_{P,R}$ for $p_1 = 99.7\%$, 95.4% , 68.2% and 50% while $p_2 = 95\%$

Next, the cdf of $|P_{P,r}(t)|$ was evaluated and the PHS power rating ($P_{P,R}$) was selected for confident level $p_2 = 95\%$. Fig. 5-8 shows the required PHS power rating ($P_{P,R}$) at the various PHS energy capacity $E_{P,R}$ for the range of p_1 . It is seen that $P_{P,R}$ remains relatively constant

with respect to $E_{P,R}$ over the given ranges of p_1 , p_2 values. However, larger $P_{P,R}$ will be required when p_1 increases. This is because the gap between $P_{f,LU}(t)$ and $P_{f,LL}(t)$ becoming wider as p_1 increases, thereby requiring more power to be catered for by the PHS. Hence the PHS power rating has to increase.

In determining the PHS expected life $E[L_P]$, $C_{P,n}$ is assumed to be 25,000 cycles based on data taken from [104]. As can be seen from Fig. 5-9, the PHS expected lifetime $E[L_P]$ increases with PHS energy capacity $E_{P,R}$ for given p_1 , p_2 values. This is due to the reduction in the number of PHS charge/discharge cycles as $E_{P,R}$ becomes larger. However, note that for a given $E_{P,R}$, $E[L_P]$ decreases with increasing p_1 . This is because the PHS will need to absorb/discharge larger amount of energy when the band between the lower and upper wind power forecasts widens. It thereby leads to shorter PHS charging and discharging time. Additionally, when a larger p_2 (say) 98% is selected instead of 95%, a larger power rating ($P_{P,R}$) is called for. Consequently, the PHS shall become more capable of accommodating higher power levels but the number of PHS charge/discharge cycles tends to increase and thereby reduces $E[L_P]$. Although not shown here, the reduction in $E[L_P]$ for $p_2 = 98\%$ is not significant for this example.

Fig. 5-9 PHS expected lifetime at various energy capacity of the PHS $E_{P,R}$ for $p_1 = 99.7\%$, 95.4% , 68.2% and 50% while $p_2 = 95\%$

The performance index g for $p_1 = 95.4\%$, $p_2 = 95\%$ is shown in Fig. 5-10. The ranges of c_1 and c_2 used for determining the PHS cost were taken from [41]: $\$0.7 \times 10^6/\text{MW} \leq c_1 \leq \$1.5 \times 10^6/\text{MW}$ and $\$0.2 \times 10^6/\text{MWh} \leq c_2 \leq \$0.35 \times 10^6/\text{MWh}$. In evaluating the remunerations B_P and B_W , the tariff for exporting $P_{d,r}(t)$ was assumed to be $\$39/\text{MWh}$, a

value taken from [55]. From Fig. 5-10, it is observed that the maximum g occurs close to $E_{P,R} = 600$ MWh. Thus the PHS energy capacity $E_{P,R}$ should be selected as 600 MWh for this example. The required power rating $P_{P,R}$ of 300 MW can be readily inferred from Fig. 5-8 at $p_1 = 95.4\%$, $p_2 = 95\%$ and $E_{P,R} = 600$ MWh. Assuming wind generation capacity factor of 40%, the supplied wind energy, with and without the PHS, were computed to be 3.5×10^6 and 2.8×10^6 MWh per year respectively. Hence, the PHS allows some 30% more energy to be exported to the grid.

Fig. 5-10 Performance index g at various PHS energy capacity for a range of c_1, c_2 values: $p_1 = 95.4\%$, $p_2 = 95\%$

5.5.1 Comparison between the proposed PHS scheme with that based on battery ESS for large-scale wind power generation

A hybrid ESS scheme has been proposed in Chapter 4 to be incorporated with a 100-MW wind farm. In the scheme, a battery ESS was applied to harness most of the energy in the wind, similar to the function of the PHS utilized in this chapter. Therefore it will be interesting to examine whether it is also feasible to use BESS in large-scale integration of wind power generation. To facilitate comparison, it is assumed that there will be ten 100-MW wind farms to emulate the 1000-MW large-scale wind generation assumed earlier in Section 5.5. There shall be one BESS for each wind farm and each BESS shall have the power and energy capacities of 11-MW and 48-MWh respectively. These ratings are determined in Chapter 4 to achieve the probability of successful power dispatch of $p_2 \times p_1 = 0.95 \times 0.95$ or 90.25%. With the cost per MW and cost per MWh of the BESS taken from

Chapter 4 as 125×10^3 and 150×10^3 respectively, the total capital cost of the BESS is $\text{US}\$85.75 \times 10^6$. From Chapter 4, the BESS expected life is about 2.3 years, thus the cost per year of implementing the BESS in the large-scale wind generation is $\text{US}\$37.12 \times 10^6/\text{year}$. With the 90.25% probability of meeting the committed dispatch and wind farm capacity factor of 40%, the expected dispatched wind energy from the 10 wind farms was evaluated to be $3.32 \times 10^6 \text{ MWh}$. Therefore the increase in the energy production cost due to the addition of the BESS is about $\text{US}\$0.011/\text{kWh}$.

To facilitate comparison, the earlier analysis shows that the optimal power and energy capacities of the PHS are 300-MW and 600-MWh respectively. Assuming $c_1 = 1 \times 10^6$ $\$/\text{MW}$ and $c_2 = 0.25 \times 10^6$ $\$/\text{MWh}$, the capital cost of the PHS C_{PHS} is $\text{US}\$450 \times 10^6$. The expected lifetime $E[L_P]$ of the PHS was determined to be close to 25 years. Hence the cost/year (η_P) of implementing the PHS is $\text{US}\$18.07 \times 10^6/\text{year}$. Based on the present scheme, the harnessed energy of $3.5 \times 10^6 \text{ MWh}$ is slightly higher than that based on the method in Chapter 4. The increase in cost of the energy production due to the installation of the PHS is about $\text{US}\$0.005/\text{kWh}$.

From the above analysis, the implementation of the PHS has produced a lower contribution to the increase in the energy production cost. Thus, the proposed PHS scheme is a more cost-effective proposition than that based on the BESS. It reinforces the observation that using PHS to support a number of wind farms dispersed over a large area can be an attractive alternative form of reliable power generation and delivery than that using the BESS.

5.6 Conclusions

The integration of PHS into large-scale wind generation is considered in this work. Through cost analysis, it is verified that PHS can be a viable energy storage medium to integrate with a number of wind farms dispersed over a large geographical area. By assuming Gaussian distribution of the errors in the wind power forecast, a statistical approach is applied to the design of the power dispatch strategy for the combined wind

generation-PHS system such that the short-term dispatch can be committed at given confidence level. The confidence level is shown to be affected by the accuracy of the wind power forecast as well as the power capacity of the PHS. In the manner by which the dispatch strategy was designed, the PHS is able to make full use of its store energy capacity during its cyclical pumping / generating operations and thus ensure longer PHS life span. Additionally, the strategy allows one to determine the number of cycles the PHS has undergone at any given time, thus enabling the expected lifetime of the PHS to be determined much more accurately. To evaluate the optimal PHS capacities, a computational method which takes into account the expected net benefit and the lifecycle cost of implementing the PHS is also developed.

From the analysis and numerical example, it is shown that the power capacity of the PHS increases with the specified confidence level to achieve firm power dispatch. Conversely, the expected lifetime of the PHS decreases as the confidence level increases and with smaller PHS energy capacity. The developed statistical approach is therefore a very useful tool in the design of the PHS for integration of large-scale wind power generation scheme into the grid system.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

The use of energy storage system (ESS) is indeed a viable solution to facilitate higher penetration of wind resource into the grid system and enhance the value of wind power. In this thesis, the objective of achieving wind power dispatchability is studied by analyzing the various pertinent issues necessary for the grid integration of ESS with wind generation. Additionally, different wind-ESS schemes ranging from single wind farm to large-scale wind generation have been proposed. Several approaches have been developed, in the attempt to determine the required ESS capacities as well as the short-term committed power schedules.

In Chapter 2, the unsteady characteristic of wind is introduced to gain an insight into this intermittent resource. Through the analysis of the wind power spectrum in the frequency domain, it is identified that long-term ESS such as the battery ESS (BESS) and pumped hydroelectric storage (PHS) are suitable for maximizing the harnessing of the wind energy. In order to operate the grid-connected wind farms which have random input wind power, it is necessary to use wind prediction tools to estimate the future wind power production. On this topic, a quantitative approach has been undertaken to derive the non-Gaussian wind power error distribution despite the fact that the wind speed prediction error distribution is Gaussian. Consequently, with the knowledge of the resulting wind power error statistical distribution, the corresponding mean and standard deviation of the wind power forecast error can be computed. These in turn shall allow one to evaluate the confidence level by which the actual wind power will be within certain standard deviation from the mean of the wind power forecast error for a single wind turbine generator or a wind farm. An example of this approach has been demonstrated in Chapter 5 where the errors in the wind power forecast are assumed to be Gaussian.

In Chapter 3, it is seen that it is challenging for wind farms to commit short-term firm power dispatch even though spatial smoothing effect can reduce considerably the

fluctuation level in the aggregated wind farm output power. To alleviate this limitation, it is proposed that ESS be used as a power buffer to compensate the mismatch between the committed schedule and the actual wind farm output power. However, the finite ESS power and energy capacities must be judiciously determined as they dictate the effectiveness of the ESS. The ESS design problem is examined from two aspects: planning and operational planning. In the planning phase, the ESS power and energy capacities are determined via a statistical approach. Since planning and operational planning are interrelated, various operational issues including the typical prevailing power market rules and the inevitable errors arising from the use of wind power forecast are also taken into account in the planning method. This is done so that the uncertainty of the wind farm-ESS scheme being unable to commit power reliably into the electric grid will be minimized by the ESS capacities so determined. Once the required ESS ratings have been determined, one then proceeds onto the operational planning phase which dealt with the design of the short-term dispatch for the wind farm. For this purpose, a method which takes into consideration the current energy level in the ESS is described so that the ESS will be utilized more efficiently and also prevent the ESS from being over-charged and over-discharged.

Capitalizing on the several advantages of battery over other types of ESS as an energy storage medium capable of fulfilling energy management role, BESS is proposed to be incorporated with a wind farm to realize the aim of wind-ESS output power dispatchability in Chapter 4. In order to prevent the life span of the BESS from being adversely affected by the high-frequency components of the wind power, supercapacitor energy storage (SC) which acts as a supplementary short-term ESS is then added to the BESS to form a HESS. Consequently, the technical merits of the two ESS mediums are exploited in the design of the HESS, in terms of the differences in their specific power and energy densities and their ability to accommodate different rates of change in the charging / discharging powers. As the planning and operational planning aspects of the wind-HESS scheme are closely interrelated, the short-term dispatch strategy is designed in the planning phase and then incorporated into the planning technique. With a proposed coordinated power flows control strategy in combination with an improved statistical approach, the capacities of the HESS are evaluated without requiring the energy capacities of both the ESS mediums to be treated

as independent design variables. As a result, the drawback of the ESS capacities determination method of Chapter 3 is effectively eluded. In addition, the extent of the wind farm-HESS scheme is able to meet its committed power dispatch obligations successfully is quantified in the proposed planning approach. To deal with the unserved power commitments, a tiered penalty method is presented. From the analysis of the life cycle cost of the HESS, it is verified that SC is indeed not viable as a long-term storage device. Also, the study shows that although the energy production cost of the wind-HESS scheme is about 2 times that produced by typical thermal power stations, the additional cost is not that prohibitive as the scheme allows firm power dispatch commitments from wind power stations. This is because when wind achieves firm power dispatchability, the energy production cost of the grid system can be reduced as the grid will need to carry lower spinning reserve.

In view of the continuing fast take-up rate of wind power generation, a large-scale wind generation-PHS system is examined in Chapter 5. The objective of the investigation is to use the PHS to operate in conjunction with the low frequency components of the wind power to achieve power dispatchability for large-scale wind generation. This is because most of the energy in the wind resource is contained in the low-frequency power components. With a new dispatch strategy designed while the PHS capacities remain undetermined, the aim is to ensure the PHS is operating cyclically between pumping and generating modes. Besides fully utilizing the PHS energy storage capacity, the method also allows the PHS lifetime to be more accurately determined than the energy throughput method of Chapter 4. Subsequently, based on the developed dispatch strategy and assuming the errors in the wind power forecast are Gaussian distributed, the PHS capacities and the short-term dispatch from the combined wind generation-PHS system are determined to meet the committed dispatch at given confidence level. The confidence level is shown to be affected by the accuracy of the wind power forecast as well as the capacities of the PHS. To evaluate the optimum PHS capacities, a more accurate computational method is developed which takes into account the expected net benefit of using the PHS and the PHS life cycle cost. From the cost/year of implementing the PHS and the increase in cost of the energy production due to the addition of the PHS, it is seen that it is more cost efficient to

utilize the PHS as compared to the use of the BESS. It thus verifies that the PHS is a more feasible storage medium as compared to the BESS in supporting large-scale wind power generation.

From all the simulation results obtained, it is seen that all the designed strategies are promising. In all cases of Chapters 3 to 5, the proposed approaches include both the planning techniques to determine the required ESS capacities and also the design of the short-term dispatch strategies for committing the dispatch schedule from the wind power plants. Hence, the proposed techniques are useful tools to achieve power dispatchability from wind generation as the output power of the wind-ESS schemes can be scheduled and committed even when subjected to the condition of varying and uncertain input wind power.

Although the proposed planning and dispatching schemes have only been applied to wind power generation, the proposed methodologies can also be adopted to other renewable energy sources to form a hybrid renewable energy system. In doing so, it is expected that the intermittency and variability of most renewable energy sources can be reduced and smoothened to a larger extent.

6.2 Future works

For future research works and to improve on the proposed schemes studied in this thesis, the following areas are suggested.

6.2.1 Additional voltage regulation functionality from the supercapacitor of the wind-HESS scheme

Currently, the supercapacitor energy storage (SC) in the wind-HESS scheme described in Chapter 4 is used to prevent the useful lifespan of the battery ESS (BESS) from being reduced to an unacceptable level while addressing the shorter-term power quality issues. Besides dealing with the concern on power quality, the SC with its very fast response characteristic can be utilized to provide reactive power compensation to aid voltage

regulation at the wind farm. This voltage control ability can be offered into the ancillary services market to obtain additional economic benefits. With regard to the effectiveness of deploying the SC, the possibility of either installing the SC singly within each individual wind turbine generator in a distributed manner or as an aggregated element connected at the collection bus of the wind farm should also be included as part of the investigation.

6.2.2 Purchase of low cost off-peak electrical energy to increase BESS energy storage capacity utilization

The dispatch strategy of the wind-HESS scheme does not result in the BESS undergoing complete charge-discharge cycles. Consequently, the energy storage capacity of the BESS is often not fully utilized. To alleviate this shortcoming and to increase the utilization of the BESS energy storage capacity, it can be rewarding to explore the possibility of purchasing low cost off-peak electrical energy to charge the BESS and then discharge the BESS during peak energy demand period to derive extra monetary returns.

6.2.3 Additional and alternative benefits for large-scale wind-PHS scheme

By subtracting the remuneration the wind farm operators can expect to obtain without using the PHS from that of using the PHS, the large-scale wind-PHS scheme proposed in Chapter 5 only considers the net benefit of incorporating the PHS. However, it is alluded to in Chapter 1 that when wind power achieves firm power dispatchability, less spinning reserve will need to be carried in the grid system. In view of this advantage, it will be fruitful if the savings resulting from the reduced reserve requirements due to the incorporation of the PHS can be incorporated into the expected obtainable economic gain of the large-scale wind-PHS scheme. Furthermore, since the use of the wind-PHS scheme is deemed capable of displacing conventional fossil fuel power stations, it will be rewarding to also include the metric ton per year (t/year) savings in fossil fuel and in the reduction of carbon dioxide emission. Consequently, one can then convert these advantages into economic benefits to obtain a better measure of the advantage of the PHS scheme.

6.2.4 Design of a suitable filtering scheme for the large-scale wind-PHS system

Since the low frequency components of the output wind power contained most of the wind energy, the wind-PHS scheme focuses on these slow varying components. For the purpose of designing the short-term dispatch strategy and in determining the PHS capacities, both the low frequency components of the actual and the forecasted wind powers are derived using a low pass filter with a cutoff frequency of 0.093×10^{-3} Hz, a value selected from [15]. However, it remains unclear if the choice of another cutoff frequency setting for the filter may yield higher net benefit in incorporating the PHS. It is likely a new performance index may have to be defined and an optimization search procedure to be used to determine the PHS capacities.

6.2.5 Reserve power for ancillary services market

In order to maximize the harnessing of the wind energy from the wind-PHS scheme plus derive additional economic benefit from the available energy contained in the intermediate frequency components of the wind power $P_M(t)$, it is proposed in future that the battery ESS (BESS) be used together with $P_M(t)$ to provide up / down power regulation services into the ancillary services market. Together with $P_M(t)$ and by exploiting the relatively smaller energy capacity of the BESS with its flexible charging / discharging capability, both up power regulation for preventing the sudden loss of large amount of generation and down power regulation for the unexpected decrease of large load can be provided. Note that up / down power regulating services are considered additional fast responsive generation / load capacity that can be made available immediately during emergency or unplanned events. They are unlike load-following regulation in which power plants are designated to regulate their output powers to balance the load and generation for frequency control. In addition, unlike the energy market in which the wind-PHS power dispatch scheme of Chapter 5 is operating in, the ancillary services market rewards regulation service provider for both the committed power capacity (of the regulation) and the energy supplied (if the service is called upon).

Author's Publications

Journal papers:

- [1] **K. W. Wee**, S. S. Choi, and D. M. Vilathgamuwa, "Determination of the optimal storage capacity of a pumped-hydroelectric station to achieve large-scale wind power dispatchability," *IEEE Trans. Sustain Energy*, submitted.
- [2] **K. W. Wee**, S. S. Choi, and D. M. Vilathgamuwa, "Design of a least-cost battery-supercapacitor energy storage system for realizing dispatchable wind power," *IEEE Trans. Sustain. Energy*, vol. 4, no. 3, pp. 786-796, 2013.

Conference papers:

- [3] **K. W. Wee**, S. S. Choi, and D. M. Vilathgamuwa, "Design of a renewable – hybrid energy storage power scheme for short-term power dispatch," presented at *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, China, Jul. 6-9, 2011.
- [4] **K. W. Wee**, S. S. Choi, and D. M. Vilathgamuwa, "Design of a wind turbine – battery energy storage scheme to achieve power dispatchability," presented at *International Power and Energy Conference (IPEC)*, Singapore, Oct. 27-29, 2010.

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