Advanced control of large-scale power systems with integration of renewable energy sources

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**ADVANCED CONTROL OF LARGE-SCALE
POWER SYSTEMS WITH INTEGRATION
OF RENEWABLE ENERGY SOURCES**

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

2020

ADVANCED CONTROL OF LARGE-SCALE POWER SYSTEMS WITH INTEGRATION OF RENEWABLE ENERGY SOURCES

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SCHOOL OF ELECTRICAL & ELECTRONIC ENGINEERING

A thesis submitted to the Nanyang Technological University in partial
fulfilment of the requirement for the degree of
Doctor of Philosophy

2020

Statement of Originality

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

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List of Acronym

RES	Renewable Energy Sources
VSC	Voltage Source Converter
SMIB	Single Machine Infinite Bus
Solar-PV	Solar Photovoltaic
MPPT	Maximum Power Point Tracking
DC	Direct Current
AC	Alternative Current
PMSG	Permanent Magnet Synchronous Generator
PI	Proportional Integral
PID	Proportional Integral Derivative
DFIG	Double Fed Induction Generator
LVRT	Low Voltage Ride Through
IG	Induction Generator
STATCOM	Static Synchronous Compensator
SDBR	Series Dynamic Braking Resistor
SMES	Superconducting Magnetic Energy Storage
VSG	Virtual Synchronous Generator
pu	per unit
PLL	Phase Lock Loop
ESS	Energy Storage System
DFL	Direct Feedback Linearization
ESIR	Energy Source for Inertia Response
CCT	Critical Clearing Time

Abstract

In the past few decades, the world becomes more concerned about environmental protection and climate change. The same concern is shared within the electric industry. Conventional thermal power plants burn fossil fuels as energy sources to generate electricity. On the other hand, Renewable Energy Sources (RES) such as wind, solar, tidal, etc., produce less CO₂ and are less contaminating. However, RESs usually rely on VSC-based converters to connect to the power grid and are usually considered as lacking inertia/zero-inertia. Therefore, the integration of a large amount of RESs affects the transient stability of the existing power system, and researches should be carried out to investigate the influence of RES on transient stability and propose new control methods to enhance the transient response.

Based on the global control principle, controllers are designed for both Single Machine Infinite Bus (SMIB) and multi-machine systems with the integration of RESs. The nonlinear power system models are re-described by multiple nonlinear partial models. Then the nonlinearity is handled by direct feedback linearization. Robust controllers are designed for each of the partial models and are synthesized via membership functions to provide global control over all operating regions. The resulting closed-loop control shows improved transient responses from a simple system to multi-machine systems.

With more and more RESs integrated, the system transient stability should be dependent on both conventional synchronous generators and RESs. Proper control methods should also be designed for RESs by utilizing the properties of RESs' structure. When load changes or faults occur, imbalances of power between energy generation and consumption is the fundamental cause of system instability. Hence, controllers based on the power balancing principle is proposed on various RESs-side during transience. For steady-state operation, RESs operate to provide optimal economic benefits. The steady-state controller and proposed transient frequency controller are synthesized by membership functions to provide weighting and smooth transition. The proposed controller is tested in multi-machine systems with various RESs integrated, and the results show promising performance.

1 Introduction

1.1 Background

The earth where more than 7 billion human beings live on has limited resources as well as a fragile environment. People need energy sources to power livelihood, industry and business activities, etc. Without sufficient energy sources, the world would lose the foundation for development in various aspects. The conventional energy sources such as oil, gas, and coal are non-renewable fossil fuels that have limited capacity and will deplete in the foreseeable future. In addition, the burning of fossil fuels would increase CO₂ emission and causes many polluting problems [1]. To have a sustainable energy profile and to promote environmental protection, Renewable Energy Sources (RESs) such as hydropower, wind, solar, ocean, and bio-fuel have been developed and deployed in the past few decades. RESs power generation and installed capacity have been increasing continuously globally [2].

Figure 1-1 Global power generation capacity 2008-2018 [2]

The usage of energy sources can be categorized into heating/cooling, transport, and electric power. However, it is noteworthy that, electric power generation will be the only focus in this thesis. Figure 1-1 presents the global electricity market by power generation capacity from 2008 to 2018. The total power generation capacity has been increasing steadily over the past decade. Comparing the data from 2008 and 2018, the increase from the non-renewables and hydropower sources is much less than the

increase rate of wind, solar, and ocean which is shown by the orange bar. Figure 1-1 includes three types of energy sources:

- 1) **Non-renewable sources.** Energy sources that will not be replenished in human lifetimes or will deplete eventually. Examples: fossil fuels, nuclear power. The energy sources are used to heat up water and generate steam that drives the rotor of the synchronous generators to produce electricity
- 2) **Hydropower.** Energy/power derived from the flow of water, typically due to gravitational potential energy from falling water. The flow of water drives the rotor of the synchronous generator to produce electricity. Hydropower is one crucial and conventional type of renewable energies that has been harnessed for hundreds of years.
- 3) **Other RESs.** Other renewable energy such as wind power, solar-PV, bio-power, geothermal, ocean power, etc. These types of RESs have received massive attention for the last few decades in electricity generation. However, they adopt different power generation technologies as compared with non-renewable sources and hydropower.

Both ‘hydropower’ and ‘other RESs’ are renewable. It can be seen that the percentage of renewable energy keeps increasing for the past decade. However, the hydropower is listed separately from other RESs due to its high share of electricity generation and the similar power generation techniques to conventional non-renewable sources. Another reason for such categorization is the controllability of the hydropower. Even though hydropower is renewable energy sources, it is highly controllable since the hydro energy can be stored by dams, and the amount of hydropower can be planned similarly as conventional non-renewable sources. Non-renewable energy sources and hydropower rely on the flows of steam or water to drive the turbine/rotor of the synchronous generator to produce electricity. Due to the above-mentioned similarities, hydropower is also considered as a kind of conventional power generation, especially when investigation power system transient stability.

Variable wind energy and solar power tends to play more roles in electricity generations in many countries. In the year 2018, 51% of electricity generation originates from wind power and solar-PV in Denmark [2]. Other countries follow the

trend as well, such as Uruguay(36%), Ireland(29%), Germany (26%) [2]. Variable renewables such as wind and solar need to be harnessed in real-time. It is difficult and inefficient to store such energy for later application, especially for electricity generation purposes. Consequently, Maximum Power Point Tracking (MPPT) is commonly adopted for variable renewables to optimize the economic benefits of free wind and solar. With such power harvesting strategy, wind power and solar-PV would cause challenges to the grid operation, electricity market, frequency regulation, and in the scope of this thesis, transient stabilities.

For transient studies, the hydropower using synchronous generators has similar dynamics as the non-renewable sources, especially when per-unit value is used. Hence, both non-renewable energy sources and hydropower can be treated as synchronous generation that is different from other variable renewables such as wind energy and solar-PV.

For the reason mentioned above, the energy sources used in electric power generation are re-categorized in the following way for the purpose of this thesis.

- 1) **Conventional energy sources:** Energy sources that have a long history in power generation and are mainly based on synchronous generator technologies, which include non-renewable sources and hydropower.
- 2) **Variable renewables*:** Renewable energy sources such as wind power, solar-PV, and ocean power. They are mainly based on power electronic converters with DC circuits or non-synchronized variable speed generators.

*Note that in the remaining of this thesis, RES refers to variable renewables including wind power, solar-PV, and ocean power unless otherwise stated.

Categorization described above enables us to have a better understanding of the new dynamics brought by variable renewables in existing power systems.

Since the population of variable renewables in the electricity generation industry, the academic has placed much effort into the challenges brought by RESs and the corresponding solutions [3] and [4]. For the past few decades, many researchers have proposed different controllers to enhance the transient stability of the power system with RESs. A more detailed literature review is given in Chapter 2, and only a brief

explanation and summarization of state-of-art and recent development is given in the following paragraphs.

In the real world, the power system is never really in steady states. Small disturbances such as changes in load, large disturbances such as short-circuit faults happen from time to time. Hence, for a reliable service, power systems are required to have some resistance to disturbances. The ability to settle at a stable operating point after a fault scenario is referred to as the transient stability [5].

For conventional power systems with limited renewables, the synchronous generators are the source of inertia. The rotating mass in the synchronous generator offers the stiffness to disturbances. The total inertia in the power system is the summation of the inertia of all synchronized rotors. For variable renewables, electricity generation is achieved differently. For example, for wind power and ocean power, the kinetic energy drives the variable speed generator to produce an AC power with a non-grid-synchronized frequency. The AC power is rectified and then inverted by power electronics. On the other hand, solar power is DC power in nature. Power electronics regulates and converts the solar energy into AC form for grid-integration purpose. The application of power converters provides decoupling between RESs and the grid, and makes the RES electricity generation inertia-less. When more renewable generation is integrated and more conventional synchronous generation units replaced, the total inertia in the power system would reduce the overall inertia in the power system. The effective system inertia depletes with the increased penetration of the non-synchronized generation units. The frequency excursion becomes more severe as an influence of RESs.

Consequently, the lack of inertia is one of the main challenges faced by the increased level of renewable energy sources. To solve the challenges of RESs in power system transient stability, many researchers proposed the concept of ‘virtual inertia’, ‘virtual synchronous generator’ to mitigate the problem [6]–[11]. The idea of virtual inertia or virtual synchronous generator comes from the fact that RESs lack inertia as compared with the synchronous generator. It is achievable by simulating a RES in such a way that it imitates the dynamic response of a synchronous generator. Hence,

it will provide virtual inertia that does not physically exist. It provides RESs with droop control, damping mechanics as well as inertia response.

Since the VSG technology was proposed, many derivatives from the basic VSG has been proposed with improved performances [6]–[11] (More details in Section 2.2.2). However, the intension to simulate or copying the characteristics of the synchronous generator and its associated control may not be an efficient way of controlling RESs. The author's justifications are:

- 1) Imitation of synchronous generator and its associated control will insert extra dynamics and control loops in the original VSC-based RESs, resulting in an even higher-order system. Hence making the system more complex and difficult in controller design.
- 2) Imitation of the synchronous generator does not consider the unique characteristics of VSC-based RESs. The new dynamics of variable RESs brings both new challenges and opportunities to the power system. New control methods making use of the property of VSC-based RESs will give better performances in the context.

Hence, it comes to the concerns and motivations of this thesis to thoroughly study the transient stability issue in power systems with the integration of RESs.

1.2 Motivation

This thesis investigates the transient stability issues in the context of power systems with RESs to

- 1) Investigate the impact of increased RESs on power system transient stability and explore the effectiveness of the transient control on the side of synchronous generators.
- 2) Probe into the characteristics of various RESs and propose a new control method that makes use of the property of RESs; to achieve transient control on the side of RESs.

- 3) Test the performance of the proposed controller via computer simulation of Single Machine Infinite Bus (SMIB) system as well as multi-machine power systems.

1.3 Thesis contribution

The integration of RESs in the power system is popular around the world, with the transient stability issue to be addressed. This thesis investigates, analyses and proposes solutions to the transient stability challenges brought by variable renewables from the following aspect:

First, the impact of the RESs on the power system transient stability is studied in simulation software by varying the percentage of the RESs in the system. The observed effect is analysed to provide a more comprehensive understanding and to help in transient stability study and controller design.

Second, the global controller with decentralized robust control is deployed to find out the effectiveness of control from the conventional synchronous generator side while treating the integration of renewables as uncertainties to the system. Simulation of SMIB system and multi-machine system verified the performance of the global control method.

Third, the potential of proper control on the renewable side is analysed and used in the new controller design. The proposed controller utilized the property of renewable sources and developed a direct link between grid frequency and the active power output of the renewables. The proposed methods simplify the control loop and complexity of the system as compared to the popular VSG technique. The proposed control method is tested via multiple simulations. The results show the promising capability of the proposed controller on the renewable-side, proving that the variable renewables have great potential in the transient stability enhancement, especially when making use of their unique characteristics.

1.4 Organization of the thesis

This thesis is organized in the following way:

The concept of transient stability, namely the rotor angle stability is firstly reviewed in Chapter 2. The dynamics of generator rotors are given together with the power angle equation, swing equation. Then the equal-area criterion is explained from the perspective of energy/power balancing. It reveals the relationship between active power balancing and transient stability. In addition, a literature review on the impact of RESs on the power system stability is carried out in wind power, solar-PV, and ocean power. Then, review and analyse is carried out over various control strategies proposed to solve the problem of the lack of inertia in the context of RESs.

Chapter 3 presents the modelling of the variable renewables that are used in this thesis. Wind power model of PMSG-based wind turbine, solar-PV equivalent circuit, and the ocean power schematics are explained in this chapter. Besides, the model of energy storage is also presented.

The impact of the renewables on power system transient stability is the focus of Chapter 4. A SMIB test system is selected for simulation. A wind farm is added as an example of RESs due to its complexity and popularity in RESs. The investigation is first carried out by varying the wind farm power level while maintaining the synchronous generator output. Then simulation is carried out by comparing two different ways of synchronous generator decommission schemes as a result of increased RESs level. It simulates more practical scenarios to reveal the effect of the integration of RESs. Then the global control is introduced as a robust control strategy to study the influence on the conventional synchronous generator and the effectiveness of transient stability enhancement on the synchronous generation side. Last, energy storage with a simple PI control is added to the SMIB system to study the influence and ability of an additional energy source in transient system stability enhancement.

Chapter 5 extends the simulation to a multi-machine power system. A 3-machine 9-bus test system with a wind farm integrated is selected as an example. The design process of the global controller in the multi-machine power system is elaborated. The

performance of global controller and conventional excitation control are compared via simulation. The results are presented in two scenarios: maintaining the total load in the system and increase the load proportionally to the amount of wind power.

In Chapter 6, we analyse the transient stability of VSC-based RESs from the viewpoint of power balancing. The popular virtual synchronous generator technology is reviewed. It is found that there is a drawback of mimicking synchronous generator and omitting the uniqueness of RESs. A new controller that utilizes the VSC-based property is proposed. The proposed control method has a simple structure as compared with VSG. The proposed method is applied to the multi-machine system with wind power. The performance of the proposed method is verified via simulation.

Chapter 7 extends the proposed control to other types of RESs as well as energy storage devices. The simulation is carried out in the context of a multi-machine system with 2 wind farms, 1 solar farm, 1 tidal energy, and a battery energy storage unit. The performance of the proposed methods is further verified via simulation software.

In Chapter 8, we draw the conclusion of this thesis by summarizing the finding in this thesis. The possible directions for future work are proposed based on the results and findings of this thesis.

2 Literature Review

With the scope and objective of this thesis explained in Chapter 1, it is necessary to first review related concepts, theories, and research works in literature.

Section 2.1 provides a review of the concept of transient stability and an elementary view of transient responses in power systems. Then theories such as equal area criterion and swing equation are reviewed as well. Through understanding reviewing related concepts and theories of transient stability, it helps in better understanding of the transient responses and controller design process.

Section 2.2 carries a thorough review of recent works in the area of power system transient stability with the integration of RESs. Current academic research progress is explored, and pending-to-solve challenges are found to be addressed.

2.1 Concept of transient stability

2.1.1 Definition of transient stability

The transient stability or the large-disturbance rotor angle stability is defined as “the ability of the power system to maintain synchronism when subjected to a severe disturbance”[12]. The concept of transient stability exists for over a hundred years since the existence of the power system. It forms an essential part of power system reliability. When large disturbances happen, it is required for the power system to respond with some resilience instead of power system failure. Such disturbances include transmission facility faults, loss of generation units, and loss of a large load. Hence, the power system’s ability to maintain synchronism when such large disturbances happen is defined as transient stability [5], [12].

The synchronism of a generator with respect to other generators or external networks can also be expressed in terms of power angle. Hence, it is also referred to as power angle stability[5].

2.1.2 Theory of swing equation

Consider the classical single machine infinite bus (SMIB) system shown in Figure 2-1, and neglecting resistive loss along the transmission line, the system represents a generator outputting power a relatively large network (represented by an infinite bus). The electrical power equation is

$$P_e = \frac{E'V_B}{X_T} \sin(\delta) = P_{max} \sin(\delta) \quad (2.1)$$

where

- E' is the voltage behind transient reactance X'_d in classical generator model.

- V_B is the voltage of the infinite bus.

- $X_T = X'_d + X_{tr} + X_l$ is the equivalent reactance between E' and V_B which include the transient reactance, transformer reactance and transmission line reactance.

- δ is the angle between E' and V_B .

- P_e is the electrical power delivered from E' to the infinite bus.

Figure 2-1 Classical single machine infinite bus system, single line diagram

When per-unit value is used and the generator speed is assumed to be at a close range from ω_0 , then the swing equation is

$$\frac{2H}{\omega_0} \frac{d^2\delta}{dt^2} = P_m - P_e = P_m - P_{max} \sin(\delta) \quad (2.2)$$

where P_m is the mechanical power, H is the inertia constant.

It can be observed from (2.2) that, the power difference between P_m and P_e causes the rotor angle to accelerate or decelerate. And the dynamics is of second order. For a power system to operate at required frequency (50Hz/60Hz), the swing equation needs to be operating at steady state under normal state and be able to recover when subject to a disturbance. By the math operations that can be found in [5], the following integration function can be obtained

$$\int_{\delta_0}^{\delta_m} \frac{\omega_0}{H} (P_m - P_e) d\delta = 0 \quad (2.3)$$

It states that, the integration of power difference with respect to power angle should equal to zero over a certain interval $[\delta_0, \delta_m]$. In another word, energy must be balanced. Figure 2-2 is the diagram of the P_e and P_m with respect to δ .

Figure 2-2 Equal area criterion illustration

Transient events happen in the range of milliseconds to a few seconds, mechanical power adjustment cannot respond fast enough. Therefore, for transient stability study, P_m can be assumed to be constant. P_e is described by (2.1) which is a sine curve. Prior to the fault, the generator is operating at δ_0 and $P_m = P_e$. When a short circuit fault happens at the sending end of the transmission line, P_e will drop to zero as no active power can be delivered from the generator to the network. Hence area A_1 denotes the energy that accumulated on the rotor during fault. The accumulated energy causes the rotor δ to accelerate. When the fault is cleared, the $P_e - \delta$ relationship returns to the pre-fault curve. Hence, area A_2 denotes the energy released from the rotor after the fault. In this stage, energy starts to be released from the rotor as $P_e > P_m$. The rotor decelerates as a result.

If the system operating point goes beyond δ_m , P_e will be smaller than P_m again, the area of A_2 starts to decrease. Hence δ_m is the unstable operating point that the generator should never exceed. In another word, the critical clear angle δ_c is the maximum angle when the fault is cleared that area A_1 is less than or equal to A_2 . The time at which critical clear angle is reached is referred to as critical clearing time (CCT).

This forms the explanation for (2.3) and equal-area criterion. It also reveals the root of transient stability problem: energy balance, or the basic energy conservation law. The energy accumulated on the rotors during faults should be able to be released in the post-fault stages ($A_1 \leq A_2$). If A_1 is larger than A_2 , then the system would lose synchronism with other generators or the external network. Since energy is the integration of power over time, the transient stability problem can also be explained by the power imbalance. The difference between P_m and P_e determines the stability of the system. If controllers with the capability to minimize the value of $P_m - P_e$ for synchronous generators, then the system stability will be improved as a result.

The swing equation describes the mechanical dynamics of synchronous generators. At the same time, the equal-area criterion gives us an elementary view of the transient stability issue, especially in the first swing and from the perspective of energy/power balancing. The review of the concept of transient stability, swing equation, and equal-area criterion will further promote the analysis and new controller design in later chapters.

2.2 Literature review

Even though there are multiple topics to be discussed in the context of RESs integration such as load frequency, small-signal stability, and voltage stability, only transient stability issues are reviewed in this section. The increased power share from RESs imposes the need to re-examine the transient stability issue of power systems. The first question to answer is, what is the impact of variable renewables on the existing or conventional power system? The answer is given in Section 2.2.1 by reviewing recent research works.

2.2.1 Impact of RESs on the power system transient stability

The review of impact of RESs on power system transient stability is organized in terms of individual RES, namely wind, solar, and ocean power.

The impact of the wind power integration in the power system is presented in [13]–[20]. Many pieces of research reveal that the negative impact is found due to the integration of wind power. [13] shows that constant speed wind turbine has a negative influence on the transient stability, especially when the wind turbines are connected to a weak grid with high resistance and reactance. And variable speed wind turbines show better dynamic stability than constant speed wind turbine. [18] and [20] studied the PMSG-based wind turbine's impact on the transient stability. The results on a 3-area system show a negative impact when no control method is applied on the wind turbine side. [15] and [19] found that, for large-scale DFIG integration, the fault ride-through capability and transient stability of the wind farm can be improved if the fixed voltage operation strategy is applied. However, it will cause the protection schemes to be triggered. Another research on wind power and thermal power with a shared transmission line illustrated that induction generator wind farms give worse influence than DFIG wind farms under different disturbances [16].

Researchers have also carried out investigations on the impact of solar-PV generation in power systems. Researchers from [21] studied the rotor angle stability by maintaining system parameters constant such as active and reactive power. Results show that small-signal stability is improved with solar-PV integration while the transient stability has worsened due to the reduced inertia in the system. Results also indicate the impact of the fault location is undeniable. In a case-study of [22], the impact of both solar-PV penetration levels and the different distribution scenarios of solar-PV, namely, distributed and centralized solar farm, are examined. The results show that the distributed solar generation provides a better impact as compared with centralized solar farms. [23] presents a high-penetration level PV in the context of a multi-machine system without any infinite bus. The results demonstrate that, without LVRT control, system stability is decreased. Similar deterioration of transient stability is observed with the increased level of solar power in literature [24]–[28].

Compared with the wind and solar-PV, researches on the transient stability with interconnected ocean power farms are limited in literature since 1) Ocean power is at its early stage of application with a small percentage of the power industry share. 2) The DFIG and PMSG types of the ocean power generation share high similarity with wind power. Hence, the studies on the ocean power impact on transient stability are restricted in amount. Studies from [29]–[31] reveal the importance of proper control to be applied to the ocean current farm to enhance system stability. STATCOM, and superconducting magnetic energy storage devices and coordination of IG and DFIG are proposed in [30], [32], and [33].

Some researchers investigate the impact of general renewable sources without referring to a specific renewable power source. For example, the author in [34] reveals that renewable sources act like invisible pulling hands with optimal constant forces in a widely used visualized power system network. The invisible hands have no mass but control only. Such dynamics of renewables would decrease the stability in the transient events. The author in [34] points out that, the control of invisible hands (renewables) needs to be redesigned to incorporate in large scale power systems with variable renewables. Researchers from [35] propose an improved damping controller in the context of high RESs penetration with HVDC transmission line. The turbulent renewable sources (fluctuation of feed-in power) is believed to have a negative impact on the stability and quality of power systems[36]. However, such feed-in power fluctuation is only significant for single wind turbines or small-scale wind fields and can be relieved when considering large-scale wind farms. Besides the above-mentioned literature, many others share the same acknowledgment that is summarized below[37]–[41]:

The increased share of RESs in electric power generation affects the power system transient stability significantly because:

- 1) RESs have different dynamics as compared to conventional sources, especially in the aspect of reduced inertia in the power system.
- 2) The popularity of RESs around the world would cause the decommission of conventional synchronous generations.

- 3) The power flow in the power system would be greatly affected by the injection of RESs, especially when considering the high level of intermittency and uncertainty.

It is important to notice that, mostly the negative impact is observed on power system transient stability due to a lack of inertia from converter-based RESs. However, while many researchers found a negative impact from RESs integration, some studies show improved transient stability. For example, some researchers found a positive impact from the increased penetration level of wind power [3]. And an investigation of solar-PV impact by changing the loading levels and control strategies shows that beneficial impact is found when the PV system is partially loaded [42]. In the meanwhile, both negative and positive impact is observed in power system transient stability with an increased penetration level of RESs [14].

Even though most researchers agree that there may be other factors affecting the result, there is no in-depth study to explain the opposite results observed in the literature. Hence, there is a research gap to investigate the impact of RESs on power system transient stability as well as those factors that affect the impact.

Do notice that, besides transient stability, there are other advance stability phenomena such as sun-synchronous oscillations, harmonics, stability issue between paralleled converters have surfaced in the field of RESs integration [38], [43]. However, they are left for future works due to the time limit.

2.2.2 Control methods to enhance the transient stability of power system with variable renewables

There are many research papers that investigated the impact of RESs on the transient stability issue and proposed solutions from different perspectives. There are two main categories of transient stability enhancement solutions available in the power system

2.2.2.1 Subsidiary Devices

As mentioned earlier, unlike synchronous generators from conventional energy sources, variable renewables do not have synchronized rotating mass (inertia) in the

structure. Lack of inertia, the resistivity to disturbances, researchers have been seeking transient stability enhancement from additional devices in a power system such as energy storage, FACTs, and STATCOM etc [44].

The bridge-type current limiter is proposed in [45] to enhance the transient stability. It is a combination of a shunt path and a bridge part. The circuit is designed in such a way that, during the event of the fault, the shunt path is inserted to limit the current. The current flowing through the capacitor and the voltage at the point of the common connection is used to turn on/off the current limiter. The results show improved transient responses as compared to the series dynamic braking resistor (SDBR).

A combined method using SDBR and STATCOM is proposed in [46]. The active and reactive power control abilities from SDBR and STATCOM are combined to enhance the stability in a wind farm. The voltage at the terminal of the wind farm is used as the control input to facilitate the operation of SDBR and STATCOM. The method shows better performances than a single application of SDBR or STATCOM.

Superconducting magnetic energy storage (SMES) is an alternative device that can help in transient stability enhancement[47]. Theoretical analyses of the SMES location and stability enhancement is carried out in a grid-connected wind farm. The simulation results show the effectiveness of the SMES.

Other than the SMES, other energy storage devices are also used in literature. An adaptive neuro-fuzzy controlled-flywheel energy storage system is used in [17]. The energy capacitor system, which consists of power electronics and a double-layer capacitor, is proposed in [48]. The energy capacitor system is tested via simulation in a 9-bus system with 2 wind farms. The results show the promising stabilizing capability of the additional capacitors. Battery energy storage is also applied in grid-connected solar power scenarios [49].

The application of energy storage devices can provide energy buffer to the variable renewables. When disturbances happen, the active power and reactive power become unbalanced, the voltage and frequency of the system start to deviate from steady-state value as well. The addition of energy storage devices provides another degree of freedom to minimize the energy difference, store excess energy, or discharge when

needed. Consequently, the frequency and voltage deviation can be mitigated, and the transient stability can be improved with the help of various types of energy storage.

The application of a current limiter or SDBR provides a way to damp excessive energy when faults happen. Similar to energy storage, such type of methods can reduce the instant power imbalance for certain scenarios. STATCOM changes the equivalent transmission reactance and hence the reactive power flow. It helps in maintaining and restoring the voltage magnitude in the case of faults.

However, the drawback of this type of transient stability enhancement methods imposes extra cost and control when additional devices are needed.

2.2.2.2 Virtual Inertia / Virtual Synchronous Generator (VSG)

Recall in Section 2.1 that, the transient stability in a power system with synchronous generators is a question whether the synchronism can be maintained after a disturbance. Hence the inertia of synchronous generators acts as a keep resistance to disturbances. The inertia constant H is in the denominator in equation (2.2) and (2.3). High value of H means slower speed deviation from steady-state value when disturbances happens, giving longer critical clearing time (CCT).

In variable renewables such as wind, solar, and ocean power, there exist DC links between the grid side and the renewable sides. Such a structure decouples renewable energy from the grid frequency. For example, in wind power, the variable speed generator attached to the wind turbine operates at variable speeds for optimal power tracking. Hence the rotors/turbines are not synchronized with the grid frequency. In other words, RESs provide no inertia to the power system. The total system inertia in a power system would decrease as a result of increased RESs integration. Hence, when disturbances happen, the angular stability/transient stability is greatly impacted by the presence of RESs.

Therefore, the root cause of power system transient dynamics change is actually the lack of inertia in RESs. Obviously, if the controllers of RESs could operate in such a way that it simulates a virtual inertia in the system, then the transient stability can be improved. This leads to the development of virtual synchronous generator technique.

The fundamental idea of VSG in converter-based RESs is to imitate the dynamics of synchronous generators, especially the droop control and mechanical dynamics.

There are many pieces of research done on the VSG control strategy and its derivatives. Converters that mimic synchronous generator are presented in [50] and [51]. The term “synchronverter” was created to describe the concept of operating a converter in the ways of a virtual synchronous generator. The advantage of the VSG technique is that the well-established knowledge from the conventional synchronous generator and its associated control theory and algorithms are ready to be used. In a power system with significant RESs’ penetration level, the active and reactive power can be automatically adjusted via the droop control, and the mechanical dynamics of “rotor” can be incorporated as well.

Figure 2-3 shows some examples of the VSG control strategy. Subfigure (a) is the traditional VSG method [52]. Subfigure (b) is the modified VSG control with alternating inertia. This method adds droop to the inertia such that the inertia is adjusted according to the frequency deviation [6]. Subfigure (c) shows the band pass damping VSG control [53] with inherited advantages of droop control and inertia support. Subfigure (d) is a modified VSG with a time delay [8] in the loop. The results show improvement in frequency deviation and power control.

Figure 2-3 Examples of VSG control strategies [8]

From the various modified VSG control methods, it can be observed that the application of VSG increases the system from a first-order system to a second or even higher-order system [8]. The complexity of control is increased as well. However, it

is questionable to imitate the dynamics of the synchronous generator in the context of converter-based RESs. Therefore, there is a research gap where the unique dynamics of RESs can be utilized such that a new controller without mimicking synchronous generator is possible.

2.2.2.3 Other control methods

Other than the addition of extra equipment in the system and the VSG techniques, some other methods are also proposed in the literature.

For example, in [25], a PID controller with fuzzy gain scheduling is proposed. It changes the gain of the PID controller according to the states of the power system such that the power oscillation when faults happen is reduced. Hence the system stability can be improved.

The comparison of different types of control methods mentioned in this section is summarized in Table 2-1.

Table 2-1 Comparison of different types of control methods in transient stability enhancement with RESs integration

Types of control	Advantages	Disadvantages
Subsidiary Devices -FACTs, STATCOM, Energy Storage, SDBR, etc.	-Additional energy sources/banks when disturbances happen	-Additional cost needed
Virtual Inertia/VSG based controls	-Easy to design with well- established conventional synchronous generator controls -improved transient responses	-Ignoring the unique dynamics that VSC-based RESs could provide -Resulting in higher order systems.
Other control methods	-Incorporate other advanced control techniques in RESs	-The performances and ability to extend to various RESs and large-scale systems needs to be further verified

2.3 Summary

In this chapter, the concept of transient stability and relevant equations and theories are reviewed to have a deep understanding of the rotor angle stability issue. The power/energy imbalance during fault causes the synchronous generator rotor to deviate, hence, causing the system to oscillate or even a power system failure.

The impact of the RESs on the power system stability is reviewed. Many researchers found a negative impact because of RESs, while some found a positive influence. The contradicting findings require an in-depth analyse of the critical factors affecting the impact of the RESs.

Then the related efforts of researches to enhance the stability of power systems with RESs are reviewed. There are mainly two types of control methods available in the literature. The first type relies on additional equipment to provides active power and reactive power during disturbances. Even though the results show promising performance, the additional equipment cost is always a problem in practice. The second type makes use of the concept of virtual synchronous generator to provide virtual inertia. The idea comes from the well-established knowledge of conventional synchronous generator and the fact that RESs are short of inertia. However, mimicking synchronous generators neglect the unique characteristics of RESs, which may give even better performances.

Hence, in this chapter, research gaps are found to be further investigated in this thesis. In the next chapter, the models of different RESs and energy storage are presented.

3 Modelling of Variable Renewables and Energy Storage Device

Chapter 2 presents a detailed review of transient stability issues in power systems with the integration of RESs. Research gaps are found regarding the impact and control of RESs. In this chapter, detailed models of wind power, solar-PV, and ocean power are presented in this chapter. Besides, energy storage models are presented. From the modelling, we can have a deep understanding of the dynamics and associated control in power converter based renewable sources. It enables smooth simulation of power systems with the integration of RES and also helps in the design process of the new controller in Chapters 6-7.

3.1 Modelling of wind power generation (PMSG)

Wind power has been in use for hundreds of years since the windmill's appearance in Persia in the 10th century. The use of wind power in electricity generation has less than 100 years of history and is popular in recent decades [54]. Wind turbines are commercially available and consist of a large portion of RESs in the power systems.

There are generally four types of wind turbines: Type I - fixed speed; Type II - limited variable speed with variable rotor resistance; Type III - variable speed wind turbine with partial-scale frequency converter; Type IV - variable speed wind turbine with a full-scale back-to-back converter. Type III and Type IV are the major types of wind turbine that implemented in wind power plants. Type III is also known as Double Fed Induction Generator (DFIG). It has a partial-scale back-to-back converter on the rotor windings. Permanent Magnet Synchronous Generator (PMSG) with full-scale converters is referred to as Type IV wind turbine.

Type III (DFIG) and Type IV(PMSG) are the most popular types of wind turbine power generation sector. Type III (DFIG) is currently the most popular and widely-used generator around the world. However, Type IV (PMSG) generator is used in this thesis for the following reasons:

- 1) PMSG has full-scaled converters which produces a clearer understanding of the decoupled structure between wind power and power system.
- 2) PMSG gives certain advantages over DFIG especially in the scope of low-medium speed generation. A more detailed discussion of PMSG advantages can be found in [55]. It is estimated that PMSG share will increase in the next few decades. It is estimated that the global share of PMSG will reach 28% by 2030[56]. Hence, there is a need to investigate PMSG for future purposes.

To have a better understanding of decoupled wind generation and power system transient frequency stability, the structural diagram of PMSG-based wind power generation is shown in Figure 3-1.

Figure 3-1 PMSG structural diagram [57]

The flow of air (wind) carries kinetic power, which drives the turbine blades to rotate. The rotor model describes the mechanical dynamics of the wind turbine and PMSG rotor. The mechanical power drives the rotor of the synchronous generator and produces a stator voltage with variable frequency. The power converter on the turbine side converts the variable AC power to DC power. The power converter on the generator side converts the DC power to synchronized AC power that can be connected to the power grid.

It can be seen from the diagram that converters and associated controllers act as key components of active and reactive power control. Traditionally, the turbine side converter regulates rotor speed and active power while grid side converter regulates DC link voltage and voltage at the point of common connection.

Each part of the PMSG-based wind turbine system is briefly explained in Sections 3.1.1-3.1.5.

3.1.1 Wind power model

The amount of power that can be transferred to wind turbines follows aerodynamics theories and is subject to practical constraints. It is well accepted that the following equation gives the relationship between mechanical power and wind speed [58].

$$P_m = \frac{\rho}{2} A \cdot C_p \cdot v^3 \quad (3.1)$$

where

- P_m is the mechanical power received by wind turbine.

- ρ is the density of air.

- A is the wind turbine swept area.

- C_p is the power coefficient

- v is the wind speed.

Wind speed varies with time continuously. However, because of relative short time period (seconds) studied in this thesis, it is reasonable to assume the wind speed to be constant for the studied period. Hence P_m is only dependent on power coefficient C_p whose equation is shown in (3.2) [57].

$$C_p = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \theta - c_4 \theta^{c_5} - c_6 \right) \exp \left(-\frac{c_7}{\lambda_i} \right) \quad (3.2)$$

where

$$\lambda_i = \left[\frac{1}{\lambda + c_8 \theta} - \frac{c_9}{\theta^3 + 1} \right]^{-1} \quad (3.3)$$

- c_1 to c_9 are constant parameters.

$-\lambda$ is the tip-speed ratio.

$-\theta$ is the pitch angle.

With wind speed assumed to be constant, λ is proportional to wind turbine rotor speed.

The values of c_1 to c_9 taken from [57] are shown in Table 3-1.

Table 3-1 Wind turbine power coefficients

Wind Turbine Power Coefficients			
c1	0.73	c6	13.2
c2	151	c7	18.4
c3	0.58	c8	-0.02
c4	0.002	c9	-0.003
c5	2.14		

Combining the above information, it can be found out that wind power is dependent on pitch angle and the tip-speed ratio. The relationship between wind power and tip-speed ratio at different pitch angles is plotted in Figure 3-2.

Figure 3-2 Wind power vs tip-speed ratio

It can be seen from Figure 3-2, wind power first increases with the tip-speed ratio and then decreases. Maximum wind power is achieved at an optimal tip-speed ratio. The optimum tip-speed ratio varies with pitch angle. The curve that passes through maximum wind power is called the MPPT curve [59]. Conventionally, wind power plants are usually operated at MPPT to extract more economic benefits.

3.1.2 Shaft model

The shaft of PMSG is modelled by a lumped mass whose equation is given by [57]

$$\frac{d\omega_m}{dt} = \frac{1}{2H_m} (T_m - T_e) \quad (3.4)$$

where

ω_m is the rotor speed

T_m is mechanical torque

T_e is the electric torque

H_m is time constant of inertia.

Note that the one-mass model is used in this thesis. One-mass model is widely used accepted in wind power system modelling in literature[57], [58]. Some researchers use the two-mass model to deal with flexible modes from shaft stiffness effects[60]–[62]. The limitation of simple one-mass model and application of other models such as the two-mass model might be of interest in future works.

3.1.3 Generator model

The electrical equations for PMSG is described by (3.5)~(3.7) [57].

$$v_{ds} = -R_s i_{ds} - \omega_r \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (3.5)$$

$$v_{qs} = -R_s i_{qs} - \omega_r \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (3.6)$$

$$\psi_{ds} = -(L_{ls} + L_{dm}) i_{ds} + \psi_{pm} \quad (3.7)$$

where

v_{ds} is the stator direct axis voltage;

v_{qs} is the stator quadrature axis voltage;

i_{ds} is the stator direct axis current;

- i_{qs} is the stator quadrature axis voltage;

- R_s is the stator resistance, ω_r is the electric rotor speed;

- L_{ls} is the stator leakage inductance, and L_{dm} is the magnetizing inductances;

- ψ_{pm} is the permanent flux linkage.

- ψ_{qs} equals zero for PMSG.

Electromechanical torque, active power and reactive power are given by [57]

$$T_e = \psi_{ds} i_{qs} - \psi_{qs} i_{ds} \quad (3.8)$$

$$P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \quad (3.9)$$

$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} \quad (3.10)$$

where

- T_e is the electric torque;

- ψ_{ds} is the flux linkage between direct axis and stator;

- ψ_{qs} is the flux linkage between quadrature axis and stator.

PMSG parameters used in this thesis are taken from [57] and shown in Table 3-2.

Table 3-2 PMSG parameters

PMSG Parameters (p.u. value)			
No. of poles	80	R_s	0.02
L_{dm}	1.21	H_m	1.0
L_{qm}	0.606	$Prate$	2MW
L_{ls}	0.121	V_{rate}	690V
wind velocity	12m/s		

3.1.4 Converter and control

For a PMSG based wind turbine, there is a full-scale back-to-back converter. The converter on the turbine side is referred to as the turbine-side converter, and the one on the grid side is referred to as the grid-side converter. The turbine-side converter works as a rectifier that converts variable frequency AC to DC format. On the other

hand, the generator-side converter acts as an inverter that converts DC to AC for the purpose of grid integration. The structure diagram of a PMSG based wind turbine is shown in Figure 3-3. The pitch controller adjusts the facing angle of the turbine blades.

Figure 3-3 Structure of a PMSG based wind turbine

Control strategies on the converters are critical for the wind turbine. The MPPT and DC voltage regulator are essential and cannot be neglected for wind power system. Depending on the application of MPPT and DC voltage regulator, two different types of PMSG-based wind turbine can be found [11].

Type-1: The MPPT control is applied to the turbine-side converter to regulate the speed of the turbine such that the optimal operating point is achieved. The optimal wind power is passed through the DC-link at all times. The transfer of energy from the synchronous generator to the DC-link causes the DC-link capacitor to fluctuate. The grid-side converter regulates the DC-link voltage at the rated value. Equivalently, the active power output to the grid is the same as the optimal wind power. Besides, the grid-side converter also regulates the terminal voltage by varying the reactive power output.

Type-2: The turbine-side converter regulates the DC-link voltage instead. In the meanwhile, MPPT is applied to the grid-side converter. Even though the location of MPPT and DC-link voltage is switched over, the resulting control system can achieve the same function as Type-1 wind turbines. The grid-side converter still regulates the

terminal voltage magnitude by varying the reactive power output from the wind turbine.

3.1.5 Pitch angle model

Blades of variable speed wind turbine are designed to be capable of turn into or out of wind within designed range. Thus, the pitch angle of blades can be controlled to regulate the mechanical power extracted from (3.1) ~ (3.3). Figure 3-4 shows the pitch angle controller [57].

Figure 3-4 Pitch angle controller

When rotor speeds exceed the maximum speed, the value of pitch angle increases to reduce wind power extracted. With the wind turbine dimension becomes larger and larger, the rate of pitch angle actuator usually has a large time constant. Therefore, active power control through pitch angle is slow in the context of the transient frequency stability study.

The rating of single wind turbines is in the range of a few megawatt. There are usually multiple wind turbines within wind power plants. To reduce the complexity of wind power plant model, a single aggregated wind turbine based on PMSG is used to represent a wind power plant.

3.2 Modelling of solar-PV power generation

Solar-PV is a semiconductor-based device that converts the radiation from the sun to a direct current electric source. The physics of solar cells is not discussed here since it is not the focus and will not influence the result. The electric model of solar-PV is given in this section

The electrical equivalent circuit of solar-PV can be represented via the model in Figure 3-5 [63]. The model consists of a current source, a shunt diode, a shunt resistor, and a series resistor.

The current I_{PV} flowing out of solar-PV is described as [63],

$$I_{PV} = I_{ph} - I_s \left(e^{\frac{q(V_{PV} + I_{PV}R_s)}{nKT}} - 1 \right) - \frac{V_{PV} + I_{PV}R_s}{R_{sh}}$$

where I_{ph} is the induced current internally. I_s is the diode saturation current. $q = 1.6e^{-19}C$, $K = 1.38e^{-23} J/K$. n is between 1-2 and T is the temperature. I_{ph} is described as [63],

$$I_{ph} = I_{sc} + \frac{K_i(T_c - T_r)I_r}{1000}$$

where I_{sc} is the short-circuit current, K_i is the current to temperature coefficient, I_r is the sunlight irradiation level in $Watt/m^2$, T_c is the working temperature, and T_r is the reference temperature.

Figure 3-5 Equivalent circuit model of solar-PV [63]

Hence, from the equations of I_{pv} and I_{ph} , it can be found that solar-PV is highly non-linear and very sensitive to the external environment, such as radiation level and temperature. Besides, from Figure 3-5, the output current is also affected by the external circuit connected to the solar-PV. Hence, a DC-DC converter is required for the operation of solar-PV and the deployment of MPPT strategies [63].

Figure 3-6 Current to voltage curve [63]

The current to voltage curve shown in Figure 3-6 describes an example of solar-PV. The current flowing out of the solar-PV remains relative constant when the voltage is low. When the terminal voltage reaches the threshold value and the current start to flow through the diode. Hence the current starts to drop dramatically.

Figure 3-7 Power to voltage curve [63]

Figure 3-7 illustrate the relationship between power and terminal voltage. As can be seen from the curve, there is an optimal operating point where the power is maximized. The MPPT algorithm is need to maintain the solar-PV optimal operation at all time.

Figure 3-8 Voltage sources converter in solar-PV

After the MPPT is achieved in DC-DC converter, the solar power is used to charge the DC-link capacitors as shown in Figure 3-8. To connect the solar-PV to the power grid, a voltage-sourced-converter (VSC) is used to convert DC to AC.

Clearly, the control of VSC forms an important role in the integration of solar-PV as well as in the power system transient stability. Conventionally, the VSC in solar-PV has a similar control strategy as the grid-side converter in wind power facility. It performs synchronization to the grid via a PLL unit. And the DC-link voltage is regulated via a PID controller, and the output of DC-link voltage regulator is fed to the inner voltage/current control of the VSC.

Figure 3-9 Overall solar-PV structure

Figure 3-9 shows the overall schematics of a solar-PV integrated into the power system utility. The series L and shunt C between the VSC and the transformer can reduce the harmonics due to the power electronic interface. Since it is not the focus of this thesis to study the harmonics of power electronics, it is assumed that harmonics in power systems is neglectable and will not affect transient stability.

3.3 Modelling of ocean power generation

Even though ocean power is not as popular as wind and solar power, it is still necessary to be included in our study as it is considered a promising source of energy in the future [64]. There are different types of ocean power harvesting strategies to harvest energy.

The tidal energy comes from the gravity pull from the moon and sun in the form of rising, and falling tides are the first type of ocean power that can be used to produce energy. For example, a hydroelectric plant was put in operation at the dam crosses the Rance River that harvests the flow of tides to produce 540MW of electricity power [65].

Similarly, the tidal energy also comes from the tidal current that moves towards away from the shores. Energy can be harnessed if turbines and generators are designed accordingly.

The seawater is under continuous up-down movement, which is referred to as the wave energy. However, engineers and researchers have been discouraged from extracting wave energy due to the harsh environment and high cost [64] and [65].

For the tidal energy and tidal current energy, variable speed turbines and generators are often used in such scenarios. It has a similar structure design as the wind power using DFIG and PMSG.

Figure 3-10 Turbine-side converter control in ocean power [64]

Figure 3-10 presents the turbine-side converter control in ocean power. It consists of a current controller and a speed controller. The function of the speed controller is to track the optimal operating point of the ocean turbine. Note that subscript ‘1’ represents the turbine-side components.

Then the energy is transfer to the DC-link capacitor whose voltage is regulated by the grid side converter.

Figure 3-11 gives the dynamic model of the grid side converter with the DC-link. Note that the subscript ‘2’ refers to the grid-side components. The voltage of the DC-link is a result of the power delivered from the DC-link to the grid minus the power from the turbine-side converter to the DC-link. The net energy accumulated on the capacitor caused the voltage to change.

Figure 3-11 Grid-side converter and the DC-link model [64]

Figure 3-12 illustrates the grid-side converter control, which consists of a DC-link voltage regulator and a current controller. The DC-link voltage regulator uses a PI controller to control the direct current flowing into the grid.

From Figures 3-11 and 3-12, it can be concluded that. The DC-link voltage controller delivers the energy from the turbine to the grid by regulating the capacitor voltage. This forms the power flow structure of the ocean power system: the turbine-side converter regulate the speed of the turbine such that maximum power is captured by the turbine blades; the ocean power drives the turbine blades and the rotor of the PMSG to generator AC electricity power which is then converted by the turbine side

converter to DC-link; then the energy is delivered to the external grid by regulating the DC-link voltage.

Figure 3-12 Grid-side converter control [64]

3.4 Modelling of energy storage

Various types of energy storage devices are available to improve the transient behaviour. The most competitive energy storage technologies are shown in Table 3-3.

Table 3-3 Energy storage technologies comparison

Energy storage tech.	Flow variable	Energy Storage type
Battery Energy Storage (BES)	Molar flow	Electrochemical
Superconducting Magnetic Energy Storage (SMES)	Flux	Magnetic
Electrochemical Capacitor Energy Storage (ECES)	Electric current	Electrostatic
Compressed Air Energy Storage (CAES)	Mass flow	Fluid
Fly-wheel Energy Storage (FES)	Torque	Rotational

For grid-connected energy storage devices, they are commonly integrated via VSC interface. The common structure that is shared in energy storage devices are shown in Figure 3-13.

Figure 3-13 VSC-based schemes for energy storage integration

There is a capacitor that temporally stores energy. The VSC converts the DC voltage to AC voltage, and the series inductor represents the transmission line as well as a harmonic damping device. The left of the VSC-based schemes for energy storage integration is omitted in Figure 3-13, which varies among different energy storage circuits and dynamics.

Battery Energy Storage (BES)

The common model for rechargeable batteries can be used to model the BES[66]:

$$\dot{Q}_e = \frac{i_b}{3600}$$

$$\dot{i}_m = \frac{i_b - i_m}{T_m}$$

$$v_{oc} = v_p(Q_e, i_m) - v_e e^{-\beta_e Q_e} + R_i i_b + v_b$$

$$v_p(Q_e, i_m) = \begin{cases} \frac{R_p i_m + K_p Q_e}{SOC} & \text{discharge} \\ \frac{R_p i_m}{q_e + 0.1} + \frac{K_p Q_e}{SOC} & \text{charge} \end{cases}$$

$$SOC = \frac{Q_n - Q_e}{Q_n} = 1 - q_e$$

where

$-Q_e$ is the battery capacity

$-i_m$ is the measured battery current with a response time constant T_m

$-i_b$ is the battery current

$-\beta_e$ is the exponential zone time constant inverse

$-R_i$ is the internal resistance

$-v_{oc}, v_p, v_e, v_b$ are the open-circuit voltage, polarization voltage, exponential voltage, and battery voltage.

$-R_p$ and K_p are the polarization resistant and polarization constant

It can be observed that the dynamic response of batteries is not instant as there are exponential terms as well as first-order differential equations in the model. The solution to the above model would involve exponential responses. It reveals the fact that, in practical BES, there is a response delay which is crucial when deploying in the transient enhancement projects. In this thesis, this delay is taken into account by deploying a general model.

Electrochemical Capacitor Energy Storage (ECES)

The ECES devices usually connected to the VSC via a DC-DC converter. The electric model describing ECES is shown below:

Figure 3-14 Schemes of electrochemical capacitor energy storage

The electrochemical capacitor is connected to the DC/DC converter through a series resistance and inductance. The equations describing the circuits are given below[67]:

$$\dot{v}_c = -\frac{1}{C_c} i_c$$

$$\dot{i}_c = \frac{1}{L_c} (v_c - i_c R_c - v_{dc} S)$$

$$i_{dc} = S i_c$$

$$E = \frac{1}{2} C_c v_c^2 + \frac{1}{2} L_c i_c^2$$

where

$-v_c, i_c, v_{dc}, i_{dc}, R_c, L_c$ are respective the voltages, currents, resistance, and inductance as shown in Figure 3-14.

$-S$ is the converter ratio of the DC/DC converter

$-E$ is the energy store in the ECES system which consists of the energy stored in the capacitor and inductor.

The mathematical model for ECES consists of two first-order differential equation. The unavoidable resistance in the ECES affects the response time. Similar dynamics can be observed in other energy storage devices such as SMES, ECES[66]. Other types of energy storage modelling are not discussed here but can be found in literature[68].

For various types of energy storage, the response speed is critical in the transient stability study. The common finding is: the electromagnetic type of storage (ECES, SMES) has the fastest response speed as the energy is stored in the same form as the power grid. When the energy is stored in another form, the energy transformation usually slows down the response time. Therefore, the application prospect in transient stability application is different. Slow responding energy storage devices such as compressed air is seldom studied due to slow response time. Even though different types of energy storage have different flow variables and energy forms, the VSC-based interface used to connect to the grid is the same. Hence a generalized model can be used to represent the energy storage regardless of the technology used.

Figure 3-15 Simplified general model for energy storage devices with transient controller

Figure 3-15 shows the simplified general model for various energy storage. T_f is the delay from the measurement filter, and T_p is the response time constant for energy storage. The value of T_p is dependent on the energy storage technology used. This simplified model is largely dependent on the energy storage dynamics. However, the dynamics of different energy storage are not the focus of this thesis and only battery energy storage devices are used in this thesis. The reasons are:

- 1) BES is commonly used in power systems with renewables for the purpose of demand management. Utilizing the existing devices in the power system transient stability enhancement will reduce the cost
- 2) The response of BES is of medium speed with a medium cost. It serves as a good representation of energy storage in the scope of this thesis.

The feasibility of other types of energy storage in the transient controller design will not be discussed here. It is left open for future works.

3.5 Summary

In this chapter, the modelling of wind power, solar-PV, ocean power, and energy storage is presented in detail. From the models, we can find that there are similarities between different RESs and energy storage. There is a DC-link in all models that are used as an energy buffer. The grid-connected converter is commonly a VSC that regulated the DC-link voltage and delivers the same power that passed to the capacitor to the external grid. Considering the fast response time of power electronics nowadays, the following assumptions are made:

- ideal turbine-side converter control in the wind power and ocean power cases;
- ideal DC-DC converter in solar-PV case;
- ideal MPPT algorithm in the wind power, solar-PV and ocean power cases;

- ideal energy conversion interface from the energy storage unit to the DC-link.

Then the structure shown in Figure 3-13 is valid for variable renewables and energy storage devices mentioned in this chapter.

It can be concluded from this chapter that the power electronics in variable renewables and energy storage contribute to a different dynamic as compared to conventional synchronous generators. On the other hand, similarities have been found among variable renewables and energy storage devices, especially in the DC-link and grid-side converter.

Hence, it is necessary to investigate the impact of variable renewables on the power system transient stability and propose new control methods in the context of RESs. In the next chapter, the impact of RESs on the power system is investigated. Wind power is used as an example to represent RESs in SMIB power system. The robustness of the excitation control on the side of the conventional synchronous generation is tested against different wind power levels.

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4 Transient Stability of Single Machine Infinite Bus (SMIB) System and Impact of Wind Power Integration

With the aim and objective of this thesis explained in Chapter 1 and the modelling details of RESs and energy storage given in Chapter 3, this chapter will study the transient stability issue in power systems with RESs integration for the first time.

To have a solid understanding of the impact of RESs on the power systems, the basic SMIB power system is chosen as a starting point. Even though SMIB has only one generator, one transmission line, and an infinite bus, it provides an excellent and fundamental example for the transient stability study and simulation [5] and [69].

In this chapter, the classic single machine infinite bus (SMIB) system and its modified derivatives are used in the simulation to reveal the impact of wind power on power system stability. Global controller with robust control ability is used to test on the tolerance of the negative impact on power system transient stability due to wind power integration.

The objective of the studies carried out in this section is to

- Investigate the impact of VSC-based renewable energy integration on transient stability;
- Investigate the effects of two different ways of synchronous generator's decommissioning on transient stability;
- Apply global control on the synchronous generator to investigate the impact of VSC-based renewable power sources on the conventional generator side;
- Deploy Energy Storage System (ESS) on the RES side to investigate and analyse the potential of RES and ESS on the transient stability enhancement.

This chapter is organized in the following way: Section 4.1 explains the structure and model of the classical SMIB power system and the modification to the original SMIB in the context of wind power integration. In Section 4.2 the wind farm is set at various power levels to understand the impact of the wind power penetration level. Section

4.3 discusses two different ways of wind power integration/synchronous power decommissions. Simulation provides a more thorough understanding of the effects of RESs integration and decommission of conventional synchronous generators. Section 4.4 explains the derivation of the global controller, and its performance is tested. Section 4.5 adds energy storage to the SMIB system to illustrate the ability of additional energy sources in the power system transient stability enhancement. Section 4.6 draws the conclusion of this chapter.

In this chapter, all simulations are carried out in MATLAB (2019a)/Simulink.

4.1 Single machine infinite bus (SMIB) System

The classical SMIB system refers to a power system with one synchronous machine connected to a constant voltage source through a transmission line. The single-line diagram is shown in Figure 2-1. Researches on classical SMIB system transient stability has been well established in the literature [69]. Many topologies and controllers have been proposed in the literature to enhance transient stability and reduce power oscillations via excitation control and power system stabilizer (PSS). Conventional excitation controllers mentioned in [5], adaptive controllers [70] and , power system stabilizer [69], non-linear voltage controller [71]–[73], robust controllers[55], and [56], and many other types of controllers have been developed based on classic SMIB system.

With RESs well-developed and integrated into the power system, it is significant to re-examine the SMIB system with the integration of RESs. In this chapter, wind power is chosen as an example of RESs integration. The reason for selecting wind power as an example is its popularity around the world with multiple large-scale as well as distributed wind farms coming online around the globe [2].

Figure 4-1 Classical SMIB diagram

The classic SMIB system has been selected as the foundation of this thesis. And it is modified to fit the research purpose. The overall structural diagram of modified SMIB is shown in Figure 4-1. It consists of one synchronous generator connected at Bus-2, one wind farm, and an energy storage system connected at Bus-4. An infinite machine with constant voltage magnitude and infinite inertia represents the infinite bus, which approximates a very large external power network. The single transmission line is replaced with two identical parallel transmission lines with the same equivalent reactance as the classic SMIB. The resistive energy loss over the transmission line is neglected without affecting the general result and conclusion.

The dynamic model of SMIB is based on a simplified dynamic of the synchronous generator. Its classical third-order model based on single-axis approximation is described by (4.1) ~ (4.10) [5] and [76].

Mechanical equations

$$\dot{\delta}(t) = \omega(t) - \omega_0 \quad (4.1)$$

$$\dot{\omega}(t) = -\frac{D}{2H}(\omega(t) - \omega_0) - \frac{\omega_0}{2H}(P_e(t) - P_m) \quad (4.2)$$

where

- $\delta(t)$ is the power angle of the generator;

- $\omega(t)$ is the speed of the generator;

- D is the damping coefficient;

- H is the inertia constant

- P_m is the mechanical power;

- $P_e(t)$ is the electrical power.

P_m in (4.2) is treated as a constant in the scope of this thesis. The justification is that, for synchronous machines, it is usually driven by steam or hydro, which have relative slow governor reaction speed. Therefore, in the scope of transient stability study, the governor's effect is small enough to be neglected to have any significant influence on the result. Hence, mechanical power P_m is assumed to be constant.

Electrical equations

$$\dot{E}'_q(t) = \frac{1}{T'_{do}} (E_f(t) - E_q(t)) \quad (4.3)$$

$$E_q(t) = E'_q(t) + (x_d - x'_d)I_d(t) \quad (4.4)$$

$$E_f(t) = k_c u_f(t) \quad (4.5)$$

$$P_e(t) = \frac{E'_q(t)V_s}{x_{ds}} \sin(\delta(t)) \quad (4.6)$$

$$I_q(t) = \frac{V_s}{x_{ds}} \sin(\delta(t)) = \frac{P_e(t)}{x_{ad}I_f(t)} \quad (4.7)$$

$$I_d(t) = \frac{E'_q(t) - V_s \cos(\delta(t))}{x_{ds}} \quad (4.8)$$

$$I_f(t) = \frac{E_q(t)}{x_{ad}} \quad (4.9)$$

$$V_t(t) = \frac{1}{x_{ds}} (x_s^2 E_q^2 + V_s^2 x_d^2 + 2x_s x_d x_{ds} P_e(t) \cot(\delta(t)))^{\frac{1}{2}} \quad (4.10)$$

where

$E'_q(t)$ is the transient EMF in the q-axis;

$E_q(t)$ is the EMF in the q-axis;

$E_f(t)$ is the equivalent EMF in the field excitation;

T'_{do} is the short circuit time constant in the d-axis;

x_d is the generator reactance in d-axis;

x'_d is the generator transient reactance in d-axis;

$I_d(t), I_q(t)$ are the d-axis and q-axis current;

$u_f(t)$ is the input of the SCR amplifier;

k_c is the excitation gain

$x_s = x_{tr} + x_l$;

$x_{ds} = x_d + x_{tr} + x_l$;

x_{ad} is the mutual reactance between the field coil and stator coil;

V_s is the infinite bus voltage magnitude.

The model parameters of the tested system are:

$\omega_0 = 2\pi 50 \text{ rad/s}$; $D = 0$; $H = 4 \text{ s}$; $T'_{do} = 6.9 \text{ s}$; $k_c = 1$; $x_d = 1.863 \text{ pu}$; $x'_d = 0.657 \text{ pu}$; $x_{tr} = 0.127 \text{ pu}$; $x_l = 0.4853 \text{ pu}$ for single line; $x_w = 0.1 \text{ pu}$.

The constraint of the excitation voltage limit is 6.0 pu. $|k_c u_f(t)| \leq 6.0 \text{ pu}$

In this thesis, per unit calculation method is preferred. Hence, the unit of variables is in terms of pu unless stated otherwise.

4.2 SMIB System with one wind farm running at various power levels

As mentioned in Section 2.2.1, both positive and negative impacts from variable renewables can be found in the literature. However, different researchers use different power systems for testing/simulation. It is necessary to do an in-depth simulation and analysis to reveal the key factors affecting the result using a consistent testing system.

As shown in the Figure 4-1, classic SMIB system is modified by connecting a wind farm to the system via a transmission line ($x_w=0.1 \text{ pu}$). While the wind speed changes with time, the wind farm generates wind power at different levels. This is an undeniable fact due to the intermittency of natural wind [57]. Therefore, it is a significant simulation to investigate the impact of wind power at different power levels.

In this section, the power level of the wind farm is set from 0.1 pu to 0.9 pu to investigate the impact of wind farm integration on transient stability. It is assumed that the synchronous generator output power 0.9 pu and remains unchanged regardless of the wind power variation. The fluctuation of wind power generation is totally absorbed by the infinite bus. The variation of wind farm active power represents the different penetration levels of wind power. The terminal voltage magnitudes of the synchronous generator and wind farm are both 1.0 pu.

The steady-state operating points can be calculated by the power flow equation, and are shown in Table 4-1. The synchronous generator produces an active power of 0.9 pu at a power angle of 74.83 degree. From the equal area criterion in Section 2.1, the synchronous generator is operating at high power angle with limited room for fault

clearing. Hence, such simulation case represents a power system with high loads and a fragile stability.

Table 4-1 Steady-state operating point of SMIB with 0.1 pu wind power and 0.9 pu synchronous

	Voltage Magnitude	Power Angle (°)	Active Power
Infinite bus	1	0	-1.0
Synchronous Generator	1	74.83	0.9
Wind Farm	1	14.73	0.1

Fault sequence:

At time = 0.1s, a three-phase-to-ground short circuit fault happens at Bus-3 as in Figure 4-1. The system enters the during-fault stage.

At time = 0.15s, the fault is cleared after 0.05s by opening the circuit breaker at both ends of the second transmission line. The system enters the fault-clearing stage.

At time = 1s, the fault is cleared and the faulty line is restored to the system. The system enters the post-fault stage.

Case 4-1: Wind farm power level: 0.1 pu

Figure 4-2 shows the transient response when the fault happens. Since the PMSG-based wind farm has no synchronized inertia, the frequency of wind farm is following the grid frequency via the phase-locked loop (PLL). Hence, only the power angle and the frequency of the synchronous generator unit are given in Figure 4-2.

At time=0.1s, the transmission line is shorted at Bus-3. The fault blocks the path of power transmission, causing the active power output (P_e) from both synchronous generator and wind farm to drop to zero. The selected fault for simulation is close to the synchronous generator side. The disturbance is more severe when the fault is closer to the synchronous generator.

When time is between 0.1s and 0.15s, the difference between P_m and P_e drives the rotor of the synchronous generator to accelerate, as shown in the top-right graph in Figure 4-2. In the meanwhile, the controller of the VSC-based wind farm starts to

increase its control action causing the angle of wind power to increase such that it can maintain maximum active power output. However, the actual power output of the wind farm is impossible to increase due to the fault. Therefore, the controller starts to accumulate its control action.

When the fault is cleared by opening the circuit breakers (time=0.15s), the instantaneous active power output of wind farm overshoots due to the accumulated MPPT control signal and decreases to the steady-state value after a few milliseconds. At this instant of time, the synchronous generator is still at a speed higher than the rated value. And it is preferable that synchronous generator can output more active power into the grid to bring down the speed in order to avoid breaking grid code or causing failure of the system. However, as the wind farm with MPPT is transmitting more power than the pre-fault condition, it reduces the amount of active power demand in the grid, resulting in less active power output of synchronous generator. It can be seen that, in shared transmission line scenario, the transient response of the wind farm affects the operation and stability of the synchronous generator.

Figure 4-2 Simulation result of SMIB with 0.1 pu wind power

At time=1s, the fault is cleared, and the second transmission line is restored to the system. The restoration of the second transmission line causes the equivalent reactance of the transmission to drop as compared to the single transmission line situation in the fault-clearing stage. Consequently, from the simulation curves in Figure 4-2, the active power output from the synchronous generator and the wind farm have a step increase of active power, and then the system returns to steady-state after a few cycles of power oscillation.

To summarize, the MPPT control strategy increases the power unbalance during and after the fault. Hence the system is less stable. Therefore, from theoretical analysis, more wind farm power levels will decrease the system transient stability in a power system.

To verify the above conclusion, more simulations are done by increasing wind farm active power output while maintaining other parameters unchanged.

Case 4-2: Wind farm power levels: 0.3 pu, 0.5 pu, 0.7 pu

Figure 4-3 Operating points at various wind power levels

Figure 4-3 shows the operating point changes when the wind farm is running at different power levels. As the wind power increases, the load across the transmission line increases, resulting in a higher operating point for synchronous generator and wind farm. When the wind power is 0.1 pu, the synchronous generator operates at 74.83°. When the wind power is increased to 0.9 pu, the synchronous generator operating point is increased to 82.38°, which is closer to the critical point 90°. The

transient stability would face less room to manoeuvre, causing the stability to decrease. It can be seen from the change of operating point of the synchronous generator that the shared transmission line has a higher load when wind power increases.

Simulations are carried out for Case 4-2. The results of the transient responses are presented in Figures 4-4 and 4-5.

Figure 4-4 shows the power angle responses due to the increased amount of wind power in the system. It is observed that the power angle responses deteriorate in terms of oscillation magnitude. This is the result of increased operating points due to high wind power levels. It can be concluded that, when the system is integrated with more wind power, the system is operated closer to the critical state with less stability.

The synchronous generator's speed deviation responses are shown in Figure 4-5. More severe responses are observed when wind power increases from two aspects: 1) the peak speed deviation increases when wind power increases from 0.1 pu to 0.7 pu. 2) the oscillation of the generator speed is more severe and takes more cycles to settle down to steady-state. Do note that at time=1s, the faulty transmission line is restored, which acts as another disturbance to the power system.

In summary, for a fixed power system with a shared transmission line between synchronous generator and wind power, the increased wind power escalates the burden of the transmission line and drives the synchronous generator to more unstable operating points. Hence, a negative impact of wind power is observed in this simulation scenario. Such negative impact becomes more severe when the wind power increases.

Note that, in Figure 4-5, the synchronous generator initially increasing rate is the same when the fault happens at 0.1s, regardless of the wind power level. This is because of $P_m = 0.9$ pu, and $P_e = 0$ pu for all cases during the fault. Hence, the generator accelerates at the same rates.

Figure 4-4 Power angle responses due to increased amount of wind power integration

Figure 4-5 Synchronous generator speed deviation responses due to increased amount of wind power integration

Case 4-3: Wind farm power level: 0.9 pu

When the wind farm power level continues to increase to 0.9 pu, the same power level as the synchronous generator, the same fault causes the power system to lose synchronism and then collapses eventually. The result is shown in Figure 4-6. The

synchronous generator power angle increases from 82.38 degrees to infinite value, and the synchronism is lost in this simulation case.

Figure 4-6 Simulation result of SMIB with 0.9 pu wind power

The simulation results from Cases 4-1~4-3 reveal that, with increased wind power integrated, the system becomes less stable. There are two causes of the negative impact of wind power.

- 1) The unique characteristics of VSC-based RESs. Its VSC-based converter is controlled by regulating the voltage in the direct/quadratic axis. In other words, it acts as a controllable/programmable voltage source that outputs a voltage of certain voltage magnitude at a certain power angle. The DC-voltage regulator of the wind farm on the grid side will continue trying to output the maximum wind power when a fault happens. This control action will endanger the transient stability of the system further even when the fault is cleared, and the system is restoring.
- 2) The change of power flow of the system and the operating points of synchronous generators. As shown in the simulation result in this section, the higher wind power level of the wind farm pushes the synchronous generator to operate at a higher operating point that is close to the theoretical limit. Hence, once the fault happens, the system is less stable.

In summary, the integration of RESs such as wind power to a fixed power system (synchronous generation remains unchanged) affects transient stability in a negative

way. This urges the need to re-examine the existing control methods and propose new control methods other than MPPT.

4.3 SMIB system with wind farm integration and synchronous generator decommission

In the previous section, a wind farm is set to operate at different power levels in order to investigate the impact of wind integration. During the simulation, the synchronous generator is operating at the same power level across all cases. Therefore, the addition of wind farm increases the total power in the SMIB system, and the shared transmission line bears the integration of wind power. The total power changes from 0.9 pu to 1.8 pu. The inertia of the synchronous generator remains unchanged as well. In practice, this may not be a reasonable approximated scenario. When wind power increases, some of the synchronous generators would be decommissioned.

For a large-scale power system, the synchronous generator in the SMIB power system can be an approximation of a cluster of N number of synchronous generators. When the power demand in the power system remains constant, the addition of renewable power sources would usually cause partial decommission of synchronous generators. In this section, the influence of two ways of synchronous generator decommission is studied in the field of transient stability.

- 1) Conventional synchronous generators reduce the same amount of output active power as the wind power integration while keeping all synchronous generators connected. This way of decommissioning can be simulated by keeping the inertia of the synchronous generator unchanged but reducing the mechanical power input to the synchronous generator.
- 2) The number of synchronous generators is decreased accordingly as the wind farm is integrated. This way of decommissioning can be simulated by reducing both the inertia and the mechanical power input proportionally.

4.3.1 SMIB system with wind farm integration and synchronous generator decommission – the first way

The first way of synchronous generator decommissioning describes the scenario when the integration of RESs does not affect the synchronous generator. In other words, the total inertia in the power system does not change. Case 4-4 is selected as an example.

Case 4-4:

Synchronous generator power level: 0.8 pu (inertia constant unchanged).

Wind farm power level: 0.1 pu

The steady-state power flow is shown in Table 4-2:

Table 4-2 Steady-state operating point of SMIB in Case 4-4

	Voltage Magnitude	Power Angle	Active Power
Infinite bus	1.0	0	-0.9
Synchronous Generator	1.0	71.20	0.8
Wind Farm	1.0	13.25	0.1

Comparing Tables 4-1 and 4-2, it can be found that the operating point of the synchronous generator is improved from 74.83 degrees to 71.2 degrees while the power angle of the wind farm is improved from 14.73 degrees to 13.25 degrees. The fault is the same as in Section 4.2. The simulation results of power angle, speed deviation, and active power are shown in Figure 4-7.

Comparing Figure 4-7 and Figure 4-2, the power angle responses of synchronous generator and wind farm show similar dynamics. However, Figure 4-7 shows less power angle oscillation and speed deviation. This result can be analysed from the synchronous generator dynamic equation (4.2). When H is unchanged, the power difference between P_m and P_e would be the only factor affecting the transient response. The larger the difference, the less stable the system becomes.

In this scenario, the synchronous generator power level is reduced from 0.9 pu to 0.8 pu. In steady-state, $P_m = P_e = 0.8$ pu. When the fault happens, $P_m = 0.8$ pu and $P_e = 0$ pu. Hence, the instantaneous power difference becomes smaller, and hence the system shows a better transient response.

Figure 4-7 Simulation result of SMIB with 0.1 pu wind power and 0.8 pu synchronous generator in the first way of synchronous generator decommission

In addition, the pre-fault power angle of the synchronous generator is 71.2 degrees as compared to 74.83 degrees in Section 4.2. The synchronous generator has more room for fault clearing according to equal area stability theory.

In conclusion, the system stability of SMIB is improved when the synchronous generator is decommissioned in the first way. The same simulation is repeated when the wind farm power level is 0.3 pu, 0.5 pu, 0.7 pu.

Case 4-5:

Synchronous generator power level: 0.6 pu, 0.4 pu and 0.2 pu (inertia constant unchanged).

Wind farm power level: 0.3 pu, 0.5 pu, 0.7 pu respectively

Figure 4-8 Power angle responses of SMIB system at various wind power level in the first way of synchronous generator decommision

Figure 4-8 shows the power angle responses when the system is subject to the fault. The increment of wind power means the same amount of synchronous generator active power is taken away. Therefore, the synchronous generator operating point changes accordingly. With the increase of wind power, the synchronous generator operates at smaller power angles prior to the fault, and the system is more stable.

Figure 4-9 Speed deviation responses of SMIB system at various wind power levels in the first way of synchronous generator decommision

Figure 4-9 shows the speed deviation of the synchronous generator when wind power is increased. When the fault happens, the peak speed deviation is reduced as the synchronous generator is operating at a lower power angle.

From the simulation result of Cases 4-4 and 4-5, it can be concluded that. When the size of the synchronous generator remains unchanged (so is the inertia), the higher wind power level means lower synchronous generator active power level, and the synchronous generator is operating at a lower operating point. Hence, better system stability is observed in terms of the power angle and speed deviation.

4.3.2 SMIB system with wind farm integration and synchronous generator decommission – the second way

In this section, more similar simulation is carried out using the second method of decommissioning that. The synchronous generator inertia reduces according to the active power output. In this way, the model can represent the case that when more and more wind power is integrated in the power system, the number of the synchronous generators in the system will be decreased (so is the total system inertia). It is not economical to keep all synchronous generators connected yet operating at a low operating point. Some of the synchronous generators can be decommissioned when RESs take more roles in electricity production.

Case 4-6:

Synchronous generator power level: 0.8 pu. Inertia constant is changed proportionally to the power level.

Wind farm power level: 0.1 pu

The steady-state power flow is shown in Table 4-3:

Table 4-3 Steady-state operating point of SMIB in Case 4-6

	Voltage Magnitude	Power Angle	Active Power
Infinite bus	1.0	0	-0.9
Synchronous Generator	1.0	71.20	0.8
Wind Farm	1.0	13.25	0.1

Comparing Table 4-3 with Tables 4-1 and 4-2, the operating point of Case 4-6 is the same as Case 4-5, and is improved than Case 4-1. This is because the inertia constant of the synchronous generator does not affect the steady-state operating point.

The simulation result of power angle, speed deviation, and active power is shown in Figure 4-10.

Comparing Figure 4-10 and Figure 4-2, the power angle responses of synchronous generator and wind farm show similar dynamics. However, Figure 4-10 shows less power angle oscillation and speed deviation. Since the inertia constant of the synchronous generator is reduced proportional to the power level, the resulting improved transient response cannot be analysed from the synchronous generator dynamic (4.1) and (4.2).

Figure 4-10 Simulation result of SMIB with 0.1 pu wind power and 0.8 pu synchronous generator in the second way of synchronous generator decommission

The pre-fault power angle of the synchronous generator is 71.2 degrees as compared to 74.83 degrees in Section 4.2. The synchronous generator has more room for fault clearing according to the equal area stability theory.

Hence, the system stability of SMIB is improved when the synchronous generator is decommissioned in the second way due to the change in operating point.

Comparing Figure 4-10 and Figure 4-7, the power angle responses of synchronous generator and wind farm show similar dynamics. The responses are better than Case 4-1 in Section 4.2 but are worse than Case 4-4 in Section 4.3.1. The peak speed deviation in the first cycle of oscillation is 1.854 rad/s as compared to 1.675 rad/s in Figure 4-7.

It can be observed from the simulation result that:

- 1) The transient stability of the power system with RESs is dependent on the operating point of the synchronous generator. When the synchronous generator is operating at a lower power angle, there is more room for transient responses. According to the equal area criterion mentioned in Section 2.1, the lower operating point provides larger area A_2 and longer critical clearing time. Hence the system is more stable.
- 2) The inertia promotes resistance to disturbances. Higher inertia system is more resilient to speed deviation and has less power oscillation and a longer period of oscillation. Hence, the inertia has a positive impact on transient stability. However, the inertia in the system depends on the RESs integration as well as the synchronous generator decommission.

Similar simulations are carried out when the synchronous generator inertia changes proportionally to the wind power level.

Case 4-7:

Synchronous generator power level: 0.8 pu, 0.6 pu, 0.4 pu, 0.2 pu. Inertia constant is changed proportionally to power level.

Wind farm power level: 0.1 pu, 0.3 pu, 0.5 pu, 0.7 pu respectively

Figure 4-11 shows the power angle responses of the synchronous generator when active power is 0.8 pu, 0.6 pu, 0.4 pu, 0.2 pu due to the increasement of wind power. The inertia of the synchronous generator is reduced proportionally to the active power output of the synchronous generator. If the synchronous generator is treated as an aggregation of N number of synchronous generators forming an area, then this simulation is describing the partial decommissioning of the synchronous generation units due to the wind power penetration.

Figure 4-11 Power angle responses of SMIB system at various wind power level in the second way of synchronous generator decommission

From Figure 4-11, it can be observed that wind power is driving the synchronous generator to operate at lower operating points. Hence, the system is more stable even with the integration of wind power. When the wind power output increases, the power angle is further reduced. However, more oscillation is observed when the wind power increases when comparing the wind=0.7 pu case with other cases. And the power angle oscillation frequency is increased with more wind and less synchronous generation in the power system.

Figure 4-12 shows the speed deviation responses of the synchronous generator. The results indicate increased speed deviation when wind power is high, and the speed oscillation becomes worse and shorter oscillating period is observed as well. Note that at time=1s, the fault is cleared, and the faulty transmission line is restored to the system. The change of transmission reactance acts as another disturbance to the system. From the simulation result, we can conclude that the reduction of inertia in the system has a significant impact on the power system stability.

Figure 4-12 Speed deviation responses of SMIB system at various wind power levels in the second way of synchronous generator decommission

In Section 4.3, two different way of synchronous generator decommission are introduced to the tested SMIB system. The objective is to simulate more practical scenarios where the wind power integration affects the operation and decommission of conventional synchronous generators. The simulation results are carefully analysed in Section 4.3 and the findings are summarized as:

- 1) Both decommission ways will increase the transient stability as the synchronous generator operating point is driven to a lower and more stable region.
- 2) The first way of synchronous generator decommission improves transient stability more as compared to the second way. The reason is due to smaller power differences over unchanged inertia. Better operating points are another reason that improves the stability.
- 3) The total inertia in the power system does not change as long as the synchronous generator remains unchanged. The reduction of inertia in the power system is a result of synchronous generator decommission due to the high penetration level of RESs.
- 4) The impact of RESs integration is a combined result of multiple factors such as RESs power levels, synchronous generator operating point, the

decommission schematic, and the control strategy used in RESs. The actual impact of RESs in a power system might be positive in certain scenarios.

Therefore, the new challenges arising from RES integration, such as wind power, need to be addressed carefully.

4.4 SMIB system with wind farm integration and global control

4.4.1 Global control method

It is well known that power systems are complicated networks with a high level of non-linearity and uncertainty. To deal with the non-linear, time varying power system control, many control theory or methods have been employed for the stabilization of non-linear system in the context of uncertainties. Those control methods such as robust control theory, H_∞ , adaptive control achieve stabilizing close-loop feedback controller via Lyapunov's stability theory.

Global control takes advantage of direct feedback linearization, robust control, and heterogeneous control to form a coordinated control strategy of a wide range of operating regions. It requires the knowledge of the complex system characteristics to satisfy control objectives. The global control can be designed in three steps:

Step 1. Partial system identification

Power systems operate in various conditions and operating regions. The conventional linearization technique provides linearization around certain operating point, and the linearized result will change when the system enters another operating region. Hereby, controllers designed based on local linearization cannot give desired performance over wide operating regions. Global control of wide operating regions requires a better linearization technique. A complex power system usually can be classified in several operating regions, such as normal, alert, emergency, restorative, in-extremis [5]. In each of the operating regions, the system dynamics show a sufficient difference that a partial model can be used to describing the system. Therefore, in the first step

of the global control design, the system should be modelled by multiple partial models. The knowledge of the system dynamics and characteristics is crucial in this stage to properly separate the operating regions.

Step 2. Partial controller design

After the system is described by multiple partial models and different operating regions. In each of the operating regions, individual controllers can be designed. First, the partial models are linearized using the direct feedback linearization technique. Then, decentralized robust control can be derived to achieve the control objectives of the system with uncertainties.

Step 3. Controller coordination

With partial controllers obtained, the corresponding membership functions are employed to provide proper transitions between different operating regions. The synthesized controller completes the closed-loop system control. The global control coordinates the partial controllers over multiple operating regions.

In the next subsection, the above steps will be discussed for SMIB system. In Sections 4.2 and 4.3, conventional excitation controller is adopted in the synchronous generator. In this section, the global controller is implemented on the synchronous generator to enhance transient stability.

In SMIB power system, when a fault happens on the transmission line, the system will experience four stages: pre-fault stage, during-fault stage, fault-clearing, and post-fault stage. The system can be decomposed to the above mentioned four stages. Each of the non-linear partial models is then linearized using the DFL technique [77].

4.4.1.1 Direct feedback linearization (DFL)

The structure of the DFL technique is shown in Figure 4-13.

Direct feedback linearization adds a non-linear feedback compensating block, making the equivalent model of the system linear. The resulting system with DFL is linear and can be employed with linear control techniques. This transformation is an exact state feedback instead of a Taylor approximation. Therefore, the DFL can transform the system into linear dynamics over much wider ranges [78].

Figure 4-13 Schemes of global controller [78]

(4.1) -(4.10) describes the dynamics of SMIB power system. First, $E'_q(t)$ is eliminated by differentiating (4.6) and substituting (4.1) -(4.10). Then the following equation is obtained.

$$\begin{aligned} \dot{P}_e(t) = & V_s \dot{E}_q(t) B(t) \sin(\delta(t)) + V_s E_q(t) \dot{B}(t) \sin(\delta(t)) \\ & + V_s E_q(t) B(t) \cos(\delta(t)) \Delta\omega(t) \end{aligned} \quad (4.12)$$

where $B(t)$ is the susceptance. By differentiating (4.4) and substituted (4.3), we have

$$\dot{E}_q(t) = \frac{x_{ds}}{T'_{do} x'_{ds}} (E_f(t) - E_q(t)) - \frac{(x_d - x'_d)}{x'_{ds}} V_s \sin(\delta(t)) \Delta\omega.$$

Let $T' = \frac{T'_{do} x'_{ds}}{x_{ds}}$, and define a new variable $\Delta P_e(t) = P_e(t) - P_m$, then we will have

$$\begin{aligned} \dot{\Delta P}_e(t) = & -\frac{1}{T'} \Delta P_e(t) \\ & + \frac{1}{T'} \left(\frac{P_e(t)}{x_{ad} I_f(t)} k_c u_f(t) \right. \\ & + T'_{do} (x_d - x'_d) \left(\frac{P_e(t)}{x_{ad} I_f(t)} \right)^2 \Delta\omega(t) \\ & + T' (Q_e(t) + V_s^2 B(t)) \Delta\omega(t) - P_m \Big) \\ & + V_s E_q(t) \dot{B}(t) \sin(\delta(t)) \end{aligned} \quad (4.13)$$

where $\dot{B}(t)$ is the derivative of susceptance that is not bounded in the moment of fault or circuit breaker switching. Besides, the switching time is assumed to fast enough to be neglected in this thesis. Therefore, (4.13) is simplified as

$$\begin{aligned}\Delta \dot{P}_e(t) = & -\frac{1}{T'} \Delta P_e(t) \\ & + \frac{1}{T'} \left(\frac{P_e(t)}{x_{ad} I_f(t)} k_c u_f(t) \right. \\ & + T'_{do} (x_d - x'_d) \left(\frac{P_e(t)}{x_{ad} I_f(t)} \right)^2 \Delta \omega(t) \\ & \left. + T' (Q_e(t) + V_s^2 B(t)) \Delta \omega(t) - P_m \right)\end{aligned}\quad (4.14)$$

If there is an equivalent input

$$\begin{aligned}v_f(t) = & \frac{P_e(t)}{x_{ad} I_f(t)} k_c u_f(t) + T'_{do} (x_d - x'_d) \left(\frac{P_e(t)}{x_{ad} I_f(t)} \right)^2 \Delta \omega(t) \\ & + T' (Q_e(t) + V_s^2 B(t)) \Delta \omega(t) - P_m\end{aligned}\quad (4.15)$$

Then (4.14) becomes

$$\Delta \dot{P}_e(t) = -\frac{1}{T'} \Delta P_e(t) + \frac{1}{T'} v_f(t)$$

Rewrite (4.15) in terms of $u_f(t)$, we get

$$\begin{aligned}u_f(t) = & \frac{x_{ad} I_f(t)}{P_e(t)} \left(v_f(t) + P_m - T' (Q_e(t) + V_s^2 B(t)) \Delta \omega(t) \right) \\ & - \frac{x_d - x'_d}{x_{ad} I_f(t)} P_e(t) T'_{do} \Delta \omega(t)\end{aligned}\quad (4.16)$$

where $u_f(t)$ is the new input into the system after DFL is applied and k_c is set to 1. (4.16) is not valid if P_e and I_f are 0, which is not a normal operating region of a synchronous generator. Therefore, it will not affect the application of the DFL. In (4.15) and (4.16), the compensating law is ready to employ as $Q_e(t), P_e(t), I_f(t), \Delta \omega(t)$ are measurable, and I_d, I_q can be calculated. Therefore, the

compensating law is practically applicable and is valid over the whole operating regions except when P_e and I_f are 0 which is not a normal working region.

In summary, after DFL is applied, the new compensated system becomes

$$\begin{cases} \Delta\dot{\delta}(t) = \Delta\omega(t) \\ \Delta\dot{\omega}(t) = -\frac{D}{2H}\Delta\omega(t) - \frac{\omega_0}{2H}\Delta P_e(t) \\ \Delta\dot{P}_e(t) = -\frac{1}{T'}\Delta P_e(t) + \frac{1}{T'}v_f(t) \end{cases} \quad (4.17)$$

which is linear with respect to the state variable. The compensated system can be used to design a robust controller for power systems with uncertain parameters.

4.4.1.2 Robust controller design for partial models

If all parameters of the power system are well known, the design of a controller would be efficacious forever. However, practical power systems got uncertainties from parameters, system load profile change, switching of transmission plans, etc. To design of controller that can handle uncertainties, the robust controller is chosen.

In (4.16), the parameter T' and $B(t)$ changes with time. If we replace T' and $B(t)$ with the average value $\bar{T}'$ and $\bar{B}(t)$, then (4.16) becomes:

$$\begin{aligned} u_f(t) = & \frac{x_{ad}I_f(t)}{P_e(t)} \left(v_f(t) + P_m - \bar{T}'(Q_e(t) + V_s^2\bar{B}(t))\Delta\omega(t) \right) \\ & - \frac{x_d - x'_d}{x_{ad}I_f(t)} P_e(t) T'_{do} \Delta\omega(t) \end{aligned} \quad (4.18)$$

Then (4.17) can be written as

$$\begin{aligned} \Delta\dot{P}_e = & -\left(\frac{1}{\bar{T}'} + \frac{1}{\bar{T}' + \Delta T'} - \frac{1}{\bar{T}'}\right)\Delta P_e(t) + \left(\frac{1}{\bar{T}'} + \frac{1}{\bar{T}' + \Delta T'} - \frac{1}{\bar{T}'}\right)v_f(t) \\ & + \left(\frac{1}{\bar{T}'} + \frac{1}{\bar{T}' + \Delta T'} - \frac{1}{\bar{T}'}\right)(\Delta T' Q_e(t) \\ & + \frac{1}{x_{ds} + \Delta x_{ds}} \Delta T' V_s^2) \Delta\omega(t) \end{aligned} \quad (4.19)$$

Here, let $\alpha(t) = \left(\frac{1}{\bar{T}' + \Delta T'} - \frac{1}{\bar{T}'} \right)$ and $\beta(t) = \left(\frac{1}{\bar{T}'} + \alpha(t) \right) (\Delta T' Q_e(t) + \frac{1}{x_{ds} + \Delta x_{ds}} \Delta T' V_s^2)$.

$\Delta T', \Delta x_{ds}$, denote the uncertainty in respective parameters. $\Delta T', \Delta x_{ds}, \alpha(t), \beta(t)$ are bounded in each of the partial models.

Since state vector $x(t) = [\Delta \delta(t) \Delta \omega(t) \Delta P_e(t)]^T$, the generator model in (4.17) is in the form of

$$\dot{x}(t) = (A_l + \Delta A_l(t))x(t) + (B_l + \Delta B_l(t))v_f(t)$$

$$\text{where, } A_l = \begin{bmatrix} 0 & \frac{1}{D} & 0 \\ 0 & -\frac{D}{2H} & -\frac{\omega_0}{2H} \\ 0 & 0 & -\frac{1}{T_l'} \end{bmatrix}, \Delta A_l(t) = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & \beta_l(t) & -\alpha_l(t) \end{bmatrix}$$

$$\text{and } B_l = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T_l'} \end{bmatrix}, \Delta B_l(t) = \begin{bmatrix} 0 \\ 0 \\ \alpha(t) \end{bmatrix}, A_l, B_l \text{ are constant known real matrix while}$$

$\Delta A_l(t), \Delta B_l(t)$ are the uncertainty and time varying matrix.

$\Delta A_l(t), \Delta B_l(t)$ can be decomposed in the following format:

$$[\Delta A_l(t) \quad \Delta B_l(t)] = L_l F_l(t) [E_{1l} \quad E_{2l}] \quad (4.20)$$

where L_l, E_{1l} and E_{2l} are constant matrix and $F_l(t)$ satisfies $F_l^T(t)F_l(t) \leq I$. I is unitary matrix.

Then the following theorem is true [75].

If there is a positive symmetric solution P_l for the algebraic Riccati equation (4.21), then a stabilizing state feedback law is given by (4.22) given the uncertainties are bounded.

$$(A_l - B_l R_l^{-1} E_{2l}^T E_{1l})^T P_l + P_l (A_l - B_l R_l^{-1} E_{2l}^T E_{1l}) + P_l (L_l L_l^T - B_l R_l^{-1} B_l^T) P_l + E_{1l}^T (I - E_{2l} R_l^{-1} E_{2l}^T) E_{1l} + Q_l = 0 \quad (4.21)$$

where, Q_l is a positive definite symmetric matrix that is chosen by the designer. $R_l = E_{2l}^T E_{2l} > 0$. l represents the number of partial models.

$$v_{fl} = -R_l^{-1}(B_l^T P_l + E_{2l}^T E_{1l})x_l(t) \quad (4.22)$$

Following the procedure in this subsection, state-feedback controllers for each of the partial models can be calculated as:

$$v_{f1}(t) = V_{f4}(t) = 68.46\Delta\delta + 7.72\Delta\omega - 80.83\Delta P_e$$

$$v_{f2}(t) = 12.12\Delta\delta + 6.34\Delta\omega - 20.39\Delta P_e$$

$$v_{f3}(t) = 98.79\Delta\delta + 15.55\Delta\omega - 75.03\Delta P_e$$

The partial control laws are obtained can then be integrated together using membership functions from heterogeneous control.

4.4.1.3 Controller coordination

When fault happens, the $\Delta\omega, \Delta P_e$ react immediately to the disturbances. In addition, the circuit breaker switching time is another information that can be used to construct the membership. The following membership functions are used with $x = (\Delta\omega^2 + \Delta P_e^2)^{\frac{1}{2}}$ and $z = \text{time}$.

$$mf_1 = \frac{1}{1 + e^{-120(x+0.4)}} - \frac{1}{1 + e^{-120(x-0.4)}} \quad (4.23)$$

$$mf_2 = 1 - mf_1 \quad (4.24)$$

$$mf_3 = \frac{1}{1 + e^{-200(z-t_1)}} - \frac{1}{1 + e^{-200(z-t_2)}} \quad (4.25)$$

$$mf_4 = 1 - mf_3 \quad (4.26)$$

where t_1 is the opening of the circuit breakers, t_2 is the reclosing time. 0.4 in (4.25) is the threshold value to denote the boundary of steady-state operation. It is assumed, during steady state or close-to-steady state, the value of x is less than 0.4. When x is larger than the threshold, the system is under large disturbances such as during-fault states. The membership function of variable x and z is shown in Figure 4-14.

The value of $mf_1 * mf_4$ denotes the pre-fault stage while $mf_2 * mf_4$ denotes the during-fault stage. In the meanwhile, the fault-clearing stage can be denoted by mf_3 and the post-fault stage is the same as the pre-fault stage.

Figure 4-14 Membership function of variable x and z

4.4.2 Application of global control in SMIB system with wind farm

In Section 4.4.1, the design process of the global controller is presented. In this section, the global controller designed is applied to the SMIB system with wind power integration in simulation software. The diagram of the modified SMIB system can be found in Figure 4-1.

The following scenario is chosen for the simulation.

Case 4-8:

Synchronous generator power level: 0.6 pu

Wind farm power level: 0.3 pu

The inertia of the synchronous generator remains unchanged. This simulates the first way of synchronous generator decommissioning as a result of the increased power level of wind power. The selection of decommissioning schemes does not affect the results since the focus in this section is to verify the performance of global control and the influence of the wind power on the synchronous generator side.

Figure 4-15 shows the transient responses of SMIB system with conventional control and global control. Graphs on the right-hand side are responses with conventional excitation control, and those on the left-hand side are responses with the global controller.

Figure 4-15 Transient responses of SMIB with 0.3 pu wind power and 0.6 pu synchronous power- Left: conventional excitation control. Right: global control

The power angle curve with conventional excitation control shows adverse transient responses with worse power angle oscillation as compared with the global controller. The power angle oscillation is greatly depressed, and the system regains steady-state

after 1 cycle. From the simulation results, it can be concluded that the global controller can improve the power angle response by reducing the peak value from 89.51 degrees to 82.75 degrees. The speed deviation also shows improvement in terms of oscillation amplitude and time to return to steady-state. Note that the speed change at time=1s is the result of the circuit breaker reclosing of the second transmission line.

The excitation control output shows different control responses of conventional control and global control, as shown in Figure 4-15. The control output from the conventional linear excitation controller (ST1A [5]) has moderate responses while the global controller gives a control output with faster and more substantial output. The results verify the performance of the global controller.

In Case 4-8, the synchronous generation is higher than the wind power generation. To further verify the results, another simulation case with higher wind power penetration is selected.

Case 4-9:

Synchronous generator power level: 0.2 pu

Wind farm power level: 0.7 pu

Figure 4-16 shows the transient responses of SMIB with 0.7 pu wind power and 0.2pu synchronous power. Compared with conventional excitation controllers, global control improves the power angle response with fewer cycles of oscillation and faster recovery speed from the fault. A similar observation is made on the speed deviation.

Note that the faulted transmission line is restored at time=1s, which acts as another disturbance to the power system. This is the reason for the abrupt change of speed at time=1s.

Combined with the observation of simulation Case 4-8, the simulation results verify the performance of the global controller. It is valid over wide operating regions and tolerant of uncertainties. It proves the global controller as a robust controller with the DFL technique.

On the other hand, the oscillation in the system is more severe in Case 4-9 as compared with Case 4-8. It takes a longer time for the system to return to a steady-state. In Case 4-8, the disturbances from the fault are depressed quickly within 1 cycle with the help of the global controller. However, in Figure 4-16, the oscillation continued for more than three cycles. This is because of the negative impact of increased wind power penetration levels. The MPPT control strategy will cause transient instability in the system.

Figure 4-16 Transient responses of SMIB with 0.7 pu wind power and 0.2 pu synchronous power- Left: conventional excitation control. Right: global control

To further illustrate the impact of increased wind power and the effectiveness of the global controller, simulation results of different levels of wind power scenarios are given in Figure 4-17.

Figure 4-17 Power angle responses of synchronous generator in SMIB system with different wind power level and global controller

Figure 4-17 shows the following findings:

- 1) The increase of wind power in the SMIB system would effectively reduce the load on the synchronous generator for a fixed-size system. The resulting phenomenon is improved operating points for the synchronous generator. The steady-state operating point is improved from ($P = 0.6$ pu , $\delta = 61.81$ degrees), ($P = 0.4$ pu , $\delta = 49.69$ degrees) to ($P = 0.2$ pu , $\delta = 32.99$ degrees). Based on equal area criterion, a lower operating point means more room unbalanced power, longer critical clearing time, and better transient stability.
- 2) The negative impact of wind power in the system transient stability is observed. When the wind power is 0.3 pu, there is a minimum oscillation in the power angle response, as shown in Figure 4-17. However, as wind power increases, the oscillation becomes more phenomenal. This is a result of the solely MPPT control strategy on the wind power side. It urges the need for proper control on the wind power to participate in the frequency response.
- 3) The performance of the global controller is verified at different wind power/synchronous power ratios. Figure 4-18 shows the improvement of the power angle peak deviation after the fault. The peak power deviation is improved

from 27.73 degrees to 19.94 degrees for the case of 0.3 pu wind power; from 25.57 degrees to 20.77 degrees for the case of 0.5 pu wind power; from 24.95 degrees to 22.36 degrees for the case of 0.3 pu wind power.

Figure 4-18 The reduction of peak power angle deviation as a result of global controller

In conclusion, the increased power penetration of RESs such as wind power imposes burdens on the synchronous generator side. Conventional synchronous generation provides ancillary services to the system, such as frequency regulation as well as mechanical dynamics to resist disturbances. However, in the new context of power systems with high levels of RESs, it is not sufficient to rely only on the conventional generators to mitigate the negative impact of RESs. Control on the RESs side is necessary and imminent.

4.5 SMIB system with wind farm and energy storage

In Section 4.4, the global controller is used on the synchronous generator side. The results reveal the impact of wind power penetration level on the synchronous generator side power.

Renewable energy usually has a high level of uncertainty and is hard to predict accurately. Besides, the peaks of RESs usually do not match the peaks of electricity demand. Hence, it is common to include an energy storage system to achieve load shifting. Since the fast development of RESs, the importance of energy storage has been investigated in frequency regulation, reliability of the system, continuity of

power supply, etc. A battery energy storage system is added on the side of the wind farm in this section for the following purpose:

- 1) To study the effect of the energy storage on the system transient stability.
- 2) To investigate the potential of energy storage system in transient stability enhancement.

The energy storage model used in this section is a simplified general model, as shown in Figure 3-15. The battery energy storage which is commonly adopted in literature with relatively fast response speeds and high-power ratings. The selection of battery as an example of energy storage does not affect the simulation result. Other types of energy storage devices can be simulated similarly but are not discussed here. The battery energy storage device is set at 0.2 pu active power rating, and the response time is set as 0.1s. Prior to the fault, the battery is idle with 0 active power output. A PI controller is added to study the effectiveness of energy storage in the context of transient stability. The frequency is used as the control input. The following simulation is carried out.

Case 4-10

Synchronous generator power level: 0.2 pu

Wind farm power level: 0.7 pu

Excitation control: Conventional excitation ST1A, and global control, PI control @ ES.

Figure 4-19 Simulation results of SMIB with 0.7 pu wind power, 0.2 pu synchronous power, and energy storage – synchronous generator power angle

Simulation is carried out for a high wind power penetration scenario with 0.7 pu wind power. When conventional excitation control is applied, and no energy storage is involved, the MPPT controller at the wind power ties to continuously producing maximum power at all times. Such control strategies will endanger the system stability, as shown in Sections 4.2 and 4.3. From the power angle of synchronous generator response in Figure 4-19, the conventional control gives the worst results with the highest power angle deviation and the longest time to return to steady-state. The speed deviation in Figure 4-20 shows a similar observation of the peak speed deviation and speed of recovery. Note that, at time=1s, the second transmission line is restored, which acts as another disturbance to the system.

Figure 4-20 Simulation results of SMIB with 0.7 pu wind power, 0.2 pu synchronous power, and energy storage – synchronous generator power angle

When the energy storage is included on the wind farm side, the results show great improvement. From Figure 4-19, the peak power deviation is improved from 57.94 degrees to 51.35 degrees and the power angle oscillation is largely depressed. A similar observation can be found in Figure 4-20.

When combining the PI controller on the energy storage and global controller on the synchronous generator side, the transient response is further improved. As shown in the blue curve in Figures 4-19 and 4-20, the peak power angle deviation is improved to 49.98 degrees, and the peak speed deviation is enhanced to 1.02 rad/s.

From Figure 4-21, the energy storage starts to charging when the fault occurs. Part of the excessive wind power during fault is absorbed by the battery. When the speed of the synchronous generator drops below rated value, the battery starts to discharge.

In conclusion, even though the energy storage is only rated 0.2 pu, the effect of energy storage with a simple PI controller is evident and significant. When energy storage is included and controlled, the performance is better than conventional control or global controller.

Figure 4-21 ES output power, positive value means ES discharging

4.6 Summary

In this chapter, the impact of the RESs on the power system is first analysed, and wind power is used as an example of RESs due to its popularity around the world. SMIB power system is used as an example system for the purpose of this chapter. The classical SMIB power system is modified by integrating a wind farm.

First, simulation of different wind power levels at the same SMIB power system is carried out. The results show that with an increasing percentage of wind power in SMIB power system. The transient stability will decrease as a result.

Second, two different ways of synchronous generator decommission are constructed to simulate practical scenarios better. The first way keeps the size and number of synchronous generation units unchanged and the synchronous generator running at

lower operating points due to the increased wind power levels. The second way reduces the inertia of the synchronous generator to simulate the possibility that some of the synchronous generation units are decommissioned when wind power increases. Both ways show better stability as the synchronous generator is running at better operating points in selected scenarios. The first way, which the inertia of the synchronous generator remains the same, performs better as compared to the second way. However, it may be questionable to keep the size and number of synchronous generation units while they are running at low load. It may not be economically efficient due to high operating and maintenance costs. Note that it is not the focus of this thesis to find the optimal way of decommissioning. By considering both cases of decommissioning, the simulation results show the new challenge brought by RESs integration: Proper control is required in the power system with the integration of RESs to enhance transient stability.

Global control method, which takes advantage of multiple techniques such as DFL, robust control, heterogeneous control, is applied to SMIB power system with wind power. The results show the effectiveness of the global controller in terms of better transient response, less oscillation, and faster recovery speed.

The advantage of global control can be summarized as:

- 1) The application of DFL technique provides a linearized model over a wide operating range. The design of the controller and parameter setting can be easily achieved with DFL.
- 2) Global control is a robust control that is tolerant of parameter uncertainty. The uncertainty from the integration of renewable energy can be well-handled which has been shown through simulation in this chapter.
- 3) Global control uses locally measurable/calculatable variables for controller design. It does not rely on the information of the whole system. Hence the global control can be applied multi-machine systems with any number of generators, buses, and loads.

In the next chapter, the global control method is applied to multi-machine power system to test its effectiveness and performance.

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5 Transient Stability of Multi-machine Power System with Wind Power Integration and Global Controller

In Chapter 4, transient stability of SMIB power system with wind power is simulated. The contradicting influence of RESs that can be found in literature is investigated in detail. Results show degraded transient stability due to an increased percentage of wind power for a fixed-power synchronous generation system, as shown in Sections 4.2 and 4.3. Positive influence is found when the integration of RESs causes the reduction of the synchronous generator load level. The global controller developed from robust control, direct feedback law, and fuzzy logic shows improved transient response of SMIB system. In addition, the addition of energy storage and a simple frequency controller improves the system dynamics and stability.

In this chapter, the global control application is extended further to multi-machine power systems.

This chapter is organized in the following way: Section 5.1 explains the example system and its model used in the simulation. Section 5.2 explains the design of the global controller in a multi-machine power system environment. Section 5.3 presents the global control application in 3-machine-9-bus system with single wind farm integration. The transient response of conventional controller and global controller is compared and analysed to verify the effectiveness of the global controller further. Section 5.5 concludes this chapter.

In this chapter, the simulations are carried out in MATLAB (2019a)/Simulink.

5.1 Multi-machine power system

In this chapter, power systems with N synchronous machines are considered. The dynamics of N interconnected generators can be represented by a classical model where synchronous generators are modelled as quadratic voltage behind direct transient reactance. Such a simplified model provides a sufficiently accurate result of the transient response as well as good simulation speed.

The model of N-machine power system can be described by several equations that can be categorized into three groups [5] and [76].

Mechanical dynamics:

$$\Delta\dot{\delta}_i(t) = \omega_i(t) - \omega_0 \quad (5.1)$$

$$\Delta\dot{\omega}_i(t) = -\frac{D_i}{2H_i}(\omega_i(t) - \omega_0) - \frac{\omega_0}{2H_i}(P_{ei}(t) - P_{mi}) \quad (5.2)$$

Electrical dynamics:

$$\dot{E}'_{qi}(t) = \frac{1}{T'_{doi}}(E_{fi}(t) - E_{qi}(t)) \quad (5.3)$$

Electrical equations

$$E_{qi}(t) = E'_{qi}(t) - (x_{di} - x'_{di})I_{di}(t) \quad (5.4)$$

$$E_{fi}(t) = k_{ci}u_{fi}(t) \quad (5.5)$$

$$P_{ei}(t) = \sum_{j=1}^n E'_{qi}E'_{qj} B_{ij}(t)\sin(\delta_{ij}(t)) \quad (5.6)$$

$$Q_{ei}(t) = -\sum_{j=1}^n E'_{qi}E'_{qj} B_{ij}(t)\cos(\delta_{ij}(t)) \quad (5.7)$$

$$I_{di}(t) = \sum_{j=1}^n E'_{qj} B_{ij}(t)\cos(\delta_{ij}(t)) \quad (5.8)$$

$$I_{qi}(t) = \sum_{j=1}^n E'_{qj} B_{ij}(t)\sin(\delta_{ij}(t)) \quad (5.9)$$

$$E_{qi}(t) = x_{adi}I_{fi}(t) \quad (5.10)$$

Multi-machine power systems are usually large-scale interconnected systems. The non-linearity and uncertainty in a multi-machine power system increase in terms of complexity and interconnectivity.

Table 5-1 3-machine-9-bus system parameters

Per unit system	
Total loads	315MW/115MVar
Base Power	100MVA
Rated transmission network voltage	230kV
Bus-1,2,3 rated voltages	16.5kV/18kV/13.8kV

The 3-machine-9-bus power system shown in Figure 5-1. It consists of 3 synchronous generators, 3 loads, and 9 buses. Loads at Bus-5, Bus-6, and Bus-8 are set to have $(125+50j)$ MVA, $(90+30j)$ MVA, and $(100+35j)$ MVA, respectively. All loads are modelled as constant impedance load without loss of generality.

Figure 5-1 3-machine-9-bus power system diagram

A wind farm is connected to the power system at Bus-7 as an example of RESs in the power system.

5.2 Global controller design

In practice, power systems are multi-machine systems with large number of generators, buses, and loads. The challenges of multi-machine systems lie in the controller design in the following aspects:

- 1) There are communication delay and loss of communication risk in geographically separated sensors. The performance and reliability of non-decentralized controls method cannot be guaranteed at all times. Hence decentralized control such as global control used in Chapter 4 can be implemented in multi-machine scenarios.

- 2) The integration of various RESs in multi-machine power systems would bring more uncertainties into the system. The system's robustness is challenged.

Multi-machine power systems can be treated as N subsystems connected together. For each of the subsystem, decentralized control that maintains the system stability can be designed in a similar way as Chapter 4. The design procedure is shown in this section.

When a fault happens in a multi-machine system, there will be four different stages happening: pre-fault stage, during-fault stage, fault-clearing stage, and post-fault stages. Each of the stages can be treated as a natural separated partial model with different parameters. The partial model needs to be linearized using direct feedback linearization technique.

5.2.1 Direct feedback linearization of multi-machine power system

The following DFL steps can be applied in each of the partial models.

To eliminate the immeasurable variable $\dot{E}'_{qi}(t)$, (5.6) is differentiated on both sides using the differentiation by parts and chain rule. The following equation is obtained.

$$\begin{aligned}\dot{P}_{ei}(t) = & \sum_{j=1}^n \dot{E}'_{qi}(t) E'_{qj}(t) B_{ij}(t) \sin(\delta_{ij}(t)) + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t) B_{ij}(t) \sin(\delta_{ij}(t)) \\ & + \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t) B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_{ij}(t) \\ & + \sum_{j=1}^n E'_{qi}(t) E'_{qi}(t) \dot{B}_{ij}(t) \sin(\delta_{ij}(t))\end{aligned}$$

Since the circuit breaker switching time is small enough to neglected, the above expression can be further simplified using (5.9) as

$$\begin{aligned}
\dot{P}_{ei}(t) &= \dot{E}'_{qi}(t)I_{qi}(t) + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t)B_{ij}(t) \sin(\delta_{ij}(t)) \\
&\quad + \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t)B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_{ij}(t) \\
&= \dot{E}'_{qi}(t)I_{qi}(t) + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t)B_{ij}(t) \sin(\delta_{ij}(t)) \\
&\quad + \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t)B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_i(t) \\
&\quad - \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t)B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_j(t)
\end{aligned}$$

Substituting (5.7), then

$$\begin{aligned}
\dot{P}_{ei}(t) &= \dot{E}'_{qi}(t)I_{qi}(t) - Q_{ei}(t)\Delta\omega_i(t) + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t)B_{ij}(t) \sin(\delta_{ij}(t)) \\
&\quad - \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t)B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_j(t)
\end{aligned}$$

Further substitution by (5.3) and (5.4), we have

$$\begin{aligned}
\dot{P}_{ei}(t) &= \frac{1}{T'_{doi}}(E_{fi}(t) - E_{qi}(t))I_{qi}(t) - Q_{ei}(t)\Delta\omega_i(t) \\
&\quad + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t)B_{ij}(t) \sin(\delta_{ij}(t)) \\
&\quad - \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t)B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_j(t)
\end{aligned}$$

$$\begin{aligned}
&= \frac{1}{T'_{doi}} \left(E_{fi}(t) - E'_{qi}(t) + (x_{di} - x'_{di})I_{di}(t) \right) I_{qi}(t) - Q_{ei}(t)\Delta\omega_i(t) \\
&\quad + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t) B_{ij}(t) \sin(\delta_{ij}(t)) \\
&\quad - \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t) B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_j(t) \\
&= \frac{1}{T'_{doi}} \left(E_{fi}(t) + (x_{di} - x'_{di})I_{di}(t) - P_{ei}(t) \right) I_{qi}(t) - Q_{ei}(t)\Delta\omega_i(t) \\
&\quad + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t) B_{ij}(t) \sin(\delta_{ij}(t)) \\
&\quad - \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t) B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_j(t)
\end{aligned}$$

Let $\Delta P_{ei}(t) = P_{ei}(t) - P_{mi}$, then

$$\begin{aligned}
\dot{\Delta P}_{ei}(t) &= \frac{1}{T'_{doi}} \left(E_{fi}(t) + (x_{di} - x'_{di})I_{di}(t) - \Delta P_{ei}(t) - P_{mi} \right) I_{qi}(t) \\
&\quad - Q_{ei}(t)\Delta\omega_i(t) + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t) B_{ij}(t) \sin(\delta_{ij}(t)) \\
&\quad - \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t) B_{ij}(t) \cos(\delta_{ij}(t)) \Delta\omega_j(t)
\end{aligned}$$

where

$$E_{fi}(t) = k_{ci}u_{fi}(t)$$

Let

$$\begin{aligned}
v_{fi}(t) &= (k_{ci}u_{fi}(t) + (x_{di} - x'_{di})I_{di}(t) - P_{mi})I_{qi}(t) \\
&\quad - T'_{doi}Q_{ei}(t)\Delta\omega_i(t)
\end{aligned} \tag{5.11}$$

Then the new compensated multi-machine power system dynamic equations are obtained

$$\Delta \dot{\delta}_i(t) = \Delta \omega_i(t) \quad (5.12)$$

$$\Delta \dot{\omega}_i(t) = -\frac{D_i}{2H_i} \Delta \omega_i(t) - \frac{\omega_0}{2H_i} \Delta P_{ei}(t) \quad (5.13)$$

$$\begin{aligned} \Delta \dot{P}_{ei}(t) = & -\frac{1}{T'_{doi}} \Delta P_{ei}(t) + \frac{1}{T'_{doi}} v_{fi}(t) \\ & + \sum_{j=1}^n E'_{qi}(t) \dot{E}'_{qj}(t) B_{ij}(t) \sin(\delta_{ij}(t)) \\ & - \sum_{j=1}^n E'_{qi}(t) E'_{qj}(t) B_{ij}(t) \cos(\delta_{ij}(t)) \Delta \omega_j(t) \end{aligned} \quad (5.14)$$

where $x_i(t) = [\Delta \delta_i(t) \ \Delta \omega_i(t) \ \Delta P_{ei}(t)]^T$ is the state vector.

Rewrite (5.11) in terms of u_{fi} , we have

$$\begin{aligned} u_i(t) = & \frac{1}{k_{ci} I_{qi}(t)} (v_{fi}(t) - (x_{di} - x'_{di}) I_{di}(t) I_{qi}(t) + P_{mi} \\ & - T'_{doi} Q_{ei}(t) \Delta \omega_i(t)) \end{aligned} \quad (5.15)$$

Note that (5.11) is valid as long as $I_{qi}(t)$ is not zero, which is not the normal operating state for synchronous generators and can be neglected. Therefore, the new DFL compensating law is achievable.

The variable $P_{ei}(t)$, $Q_{ei}(t)$, $I_{fi}(t)$ are readily measurable variables and the variable $I_{di}(t)$, $I_{qi}(t)$ can be calculated using measurable variables. Hence, (5.15) is practically applicable. Note that, for each of the partial model, the derivation procedure is similar even though the parameters vary.

5.2.2 Decentralized robust controllers

For each of the partial models, the following process can be used for designing a decentralized robust controller [74], [78]–[80].

The generator parameter T'_{doi} may contain uncertainty $\Delta T'_{doi}$. The new compensation law (5.15) can be replaced by:

$$v_{fi}(t) = k_{ci}I_{qi}(t)u_{fi}(t) + (x_{di} - x'_{di})I_{di}(t)I_{qi}(t) - \bar{T}'_{doi}Q_{ei}(t)\Delta\omega_i(t) - P_{mi} \quad (5.16)$$

where $\bar{T}'_{doi}$ is the average value of T'_{doi} .

Then (5.14) can be expressed as:

$$\begin{aligned} \Delta\dot{P}_{ei}(t) = & -\left[\frac{1}{\bar{T}'_{doi}} + \frac{1}{\bar{T}'_{doi} + \Delta\bar{T}'_{doi}} - \frac{1}{\bar{T}'_{doi}}\right]\Delta P_{ei}(t) \\ & + \left[\frac{1}{\bar{T}'_{doi}} + \frac{1}{\bar{T}'_{doi} + \Delta\bar{T}'_{doi}} - \frac{1}{\bar{T}'_{doi}}\right]v_{fi}(t) \\ & - \left[\frac{1}{\bar{T}'_{doi}} + \frac{1}{\bar{T}'_{doi} + \Delta\bar{T}'_{doi}} - \frac{1}{\bar{T}'_{doi}}\right]\Delta T'_{doi}Q_{ei}(t)\Delta\omega_i(t) \\ & + \sum_{j=1}^n E'_{qi}(t)\dot{E}'_{qj}(t)B_{ij}(t)\sin(\delta_{ij}(t)) \\ & - \sum_{j=1}^n E'_{qi}(t)E'_{qj}(t)B_{ij}(t)\cos(\delta_{ij}(t))\Delta\omega_j(t) \end{aligned} \quad (5.17)$$

Let $\alpha_i(t) = \frac{1}{\bar{T}'_{doi} + \Delta\bar{T}'_{doi}} - \frac{1}{\bar{T}'_{doi}}$ and $\beta_i(t) = \left[\frac{1}{\bar{T}'_{doi}} + \frac{1}{\bar{T}'_{doi} + \Delta\bar{T}'_{doi}} - \frac{1}{\bar{T}'_{doi}}\right]\Delta T'_{doi}Q_{ei}(t)$ then,

$$\begin{aligned} \Delta\dot{P}_{ei}(t) = & -\left[\frac{1}{\bar{T}'_{doi}} + \alpha(t)\right]\Delta P_{ei}(t) + \left[\frac{1}{\bar{T}'_{doi}} + \alpha(t)\right]v_{fi}(t) - \beta(t)\Delta\omega_i(t) \\ & + \sum_{j=1}^n E'_{qi}(t)\dot{E}'_{qj}(t)B_{ij}(t)\sin(\delta_{ij}(t)) \\ & - \sum_{j=1}^n E'_{qi}(t)E'_{qj}(t)B_{ij}(t)\cos(\delta_{ij}(t))\Delta\omega_j(t) \end{aligned} \quad (5.18)$$

(5.12), (5.13), and (5.18) form the partial model for the l th linearized partial system that matches the following general format.

$$\begin{aligned} \dot{x}_i(t) = & \left(A_{i,l} + \Delta A_{i,l}(t)\right)x_i(t) + \left(B_{i,l} + \Delta B_{i,l}(t)\right)v_{fi}(t) \\ & + \sum_{j=1}^N \sum_{k=1}^M [G_{kij,l} + \Delta G_{kij,l}(t)]g_{kij,l}(x_i, x_j) \end{aligned} \quad (5.19)$$

where $A_{i,l}, B_{i,l}, G_{kij,l}$ are constant matrix, and $\Delta A_{i,l}(t), \Delta B_{i,l}(t), \Delta G_{kij,l}(t)$ represent the uncertainties varying with time. M is the number of nonlinearities and interconnections with other generators. $g_{kij,l}(x_i, x_j)$ is the functions of the nonlinearities and interconnections between i th and j th subsystem. $x_i(t) = [\Delta\delta_i(t) \Delta\omega_i(t) \Delta P_{ei}(t)]$ is the state vector. l is the number of partial models.

$$A_{i,l} = \begin{bmatrix} 0 & 1 & 0 \\ 0 & -\frac{D_i}{2H_i} & -\frac{\omega_o}{2H_i} \\ 0 & 0 & -\frac{1}{T'_{doi}} \end{bmatrix}; B_{i,l} = \begin{bmatrix} 0 \\ 0 \\ \frac{1}{T'_{doi}} \end{bmatrix}; \Delta A_{i,l} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & -\beta_{i,l}(t) & -\alpha_{i,l}(t) \end{bmatrix};$$

$$\Delta B_{i,l} = \begin{bmatrix} 0 \\ 0 \\ -\alpha_{i,l}(t) \end{bmatrix}; G_{1ij,l} = G_{2ij,l} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}; \Delta G_{1ij,l} = \begin{bmatrix} 0 \\ 0 \\ \gamma_{1ij,l}(t) \end{bmatrix}; \Delta G_{2ij,l} = \begin{bmatrix} 0 \\ 0 \\ \gamma_{2ij,l}(t) \end{bmatrix};$$

$$g_{1ij,l}(x_i, x_j) = \sin(\delta_i(t) - \delta_j(t)); g_{2ij,l}(x_i, x_j) = \Delta\omega_i(t);$$

$$\gamma_{1ij,l}(t) = E'_{qi,l}(t)\dot{E}'_{qj}(t)B_{ij}(t); \gamma_{2ij,l}(t) = -E'_{qi,l}E'_{qj}(t)B_{ij}(t)\cos(\delta_{ij}(t))$$

The uncertainty matrices $\Delta A_{i,l}(t), \Delta B_{i,l}(t), \Delta G_{kij,l}(t)$ can be decomposed into the format below.

$$[\Delta A_{i,l}(t) \Delta B_{i,l}(t)] = L_{i,l}F_{i,l}(t)[E_{i,1l} E_{i,2l}] \quad (5.20)$$

$$\Delta G_{kij,l} = L_{kij,l}F_{kij,l}(t)E_{kij,l} \quad (5.21)$$

$$\text{where } L_{i,l}(t) = \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}; E_{1i,j}(t) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & |\beta_{i,l}(t)|_{max} & 0 \\ 0 & 0 & |\alpha_{i,l}(t)|_{max} \end{bmatrix};$$

$$E_{2i,l}(t) = \begin{bmatrix} 0 \\ 0 \\ -|\alpha_{i,l}(t)|_{max} \end{bmatrix}; F_{i,l}(t) = [0 \quad -\frac{\beta_{i,l}(t)}{|\beta_{i,l}(t)|_{max}} \quad -\frac{\alpha_{i,l}(t)}{|\alpha_{i,l}(t)|_{max}}]; E_{kij,l}(t) = 1;$$

$$L_{kij,l}(t) = [0 \quad 0 \quad |\gamma_{kij,l}(t)|_{max}]^T; F_{kij,l}(t) = \frac{\gamma_{kij,l}(t)}{|\gamma_{kij,l}(t)|_{max}}.$$

The above-mentioned decomposition satisfies the following requirement.

$$F_{i,l}^T(t)F_{i,l}(t) \leq I \text{ and } F_{kij,l}^T(t)F_{kij,l}(t) \leq I$$

Since

$$|\dot{E}_{qj}'| \leq \left| \frac{E_{fj}(t) - E_{qj}(t)}{T'_{doj}} \right| \leq 5 \frac{|E_{qj}(t)|_{max}}{|T'_{doj}|_{min}}$$

Therefore,

$$|\gamma_{1ij,l}(t)| = |E'_{qi,l}(t)\dot{E}'_{qj}(t)B_{ij}(t)| \leq 5 \frac{|P_{qj}(t)|_{max}}{|T'_{doj}|_{min}}$$

and

$$|\gamma_{2ij,l}(t)| \leq |E'_{qi,l}(t)\dot{E}'_{qj}(t)B_{ij}(t)| = |P_{ei,l}(t)|_{max}$$

$g_{1ij,l}(x_i, x_j) = \sin(\delta_i(t) - \delta_j(t))$, $g_{2ij,l}(x_i, x_j) = \Delta\omega_j(t)$ should satisfy and be able to be decomposed as

$$\begin{aligned} \|g_{kij,l}(x_i, x_j)\| &\leq \|W_{ki,l}x_i(t)\| + \|W_{kij,l}x_j(t)\| \\ \|g_{1ij,l}(x_i, x_j)\| &= \|\sin(\delta_i(t) - \delta_j(t))\| \leq \|\delta_i(t) - \delta_j(t)\| \\ &= [1 \ 0 \ 0]x_i(t) + [1 \ 0 \ 0]x_j(t) \end{aligned}$$

where

$$W_{1i,l} = [1 \ 0 \ 0]; W_{1ij,l} = [1 \ 0 \ 0]$$

and

$$\|g_{2ij,l}(x_i, x_j)\| = \|\Delta\omega_j(t)\| = [0 \ 1 \ 0]x_j(t)$$

where

$$W_{2i,l} = [0 \ 0 \ 0]; W_{2ij,l} = [0 \ 1 \ 0]$$

With the above decomposition and maximum value calculated, if there exist a solution $P_{i,l}$ to the algebraic Riccati equation below, then a stabile control law exists as (5.22) [75].

$$\begin{aligned}
& (A_{i,l} - B_{i,l}R_{i,l}^{-1}E_{2i,l}^TE_{1i,l})^TP_{i,l} + P_{i,l}(A_{i,l} - B_{i,l}R_{i,l}^{-1}E_{2i,l}^TE_{1i,l}) \\
& + \sum_{j=1}^N \sum_{k=1}^M (W_{ki,l}^TW_{ki,l} + W_{kij,l}^TW_{kij,l}) + P_{i,l}\{L_{i,l}L_{i,l}^T - B_{i,l}R_{i,l}^{-1}B_{i,l}^T \\
& + \sum_{j=1}^N \sum_{k=1}^M [G_{kij,l}(I - \varepsilon_{kij,l}^2E_{kij,l}^TE_{kij,l})G_{kij,l}^T + \frac{1}{\varepsilon_{kij,l}^2}L_{kij,l}L_{kij,l}^T]\}P_{i,l} \\
& + Q_{i,l} = 0
\end{aligned}$$

where $Q_{i,l}$ is symmetric positive matrix and can be selected by user.

$$u_{i,l}(t) = -R_{i,l}^{-1}(B_{i,l}^TP_{i,l} + E_{2i,l}^TE_{1i,l})x_i(t) \quad (5.22)$$

5.2.3 Partial model controller synthesis

Following the procedure mentioned in Section 5.2.2, the partial model controllers can be calculated as below:

$$\begin{aligned}
v_{f1,1}(t) &= v_{f1,4} = 146.3\Delta\delta_1 + 102.18\Delta\omega_1(t) - 287.43\Delta P_{e1} \\
v_{f1,2}(t) &= v_{f1,3} = 279.7\Delta\delta_1 + 159.62\Delta\omega_1(t) - 603.27\Delta P_{e1} \\
v_{f2,1}(t) &= v_{f2,4} = 223.13\Delta\delta_2 + 89.19\Delta\omega_2(t) - 297.61\Delta P_{e2} \\
v_{f2,2}(t) &= v_{f2,3} = 713.44\Delta\delta_2 + 189.57\Delta\omega_2(t) - 813.78\Delta P_{e2} \\
v_{f3,1}(t) &= v_{f3,4} = 156.58\Delta\delta_3 + 129.18\Delta\omega_3(t) - 297.64\Delta P_{e3} \\
v_{f3,2}(t) &= v_{f3,3} = 168.71\Delta\delta_3 + 130.53\Delta\omega_3(t) - 531.56\Delta P_{e3}
\end{aligned}$$

The same heterogeneous membership function as in Section 4.4 is used in this section to synthesize the partial model controllers.

5.3 Simulation of global controller in example multi-machine System

Based on the calculation process and design steps mentioned in Section 5.3, the global controller for the example 3-machine-9-bus power system can be achieved. In this section, the simulation is carried out to verify the performance of the controller.

Fault sequence:

At time = 0.1s, a three-phase-to-ground short circuit fault happens at the mid-point on the second transmission line between Bus-7 and Bus-8.

At time = 0.22s, the fault is cleared by opening the circuit breaker on both ends of the transmission line.

At time = 1.4s, the faulty line is restored to the system. Hence, the fault is a temporary disturbance.

Wind Farm: 50MW (0.5pu) connected at Bus-7 through $X=0.2j$ transmission line.

The following simulation cases are chosen as

Case 5-1: the loads in the system remain unchanged.

Case 5-2: the loads in the system increase by the same amount as the wind farm output power

Simulation of Case 5-1 is carried out first which describes the scenarios when the overall system loads do not change significantly, but part of the existing synchronous generation is replaced by RESs. In this case, the loads at Bus-5, 6, and 8 remain unchanged, and wind power (0.5pu) replaces the electric power output from G1, which is designed to be the slack bus in the system.

The simulation results of Case 5-1 are shown in Figure 5-2. On the right-hand side, the transient responses with the global controller are shown. On the left-hand side, the transient responses with the conventional controller (ST1A) are shown.

*The power angle and speed deviation curve are plotted by taking the G1 as the reference. Therefore, the power angle and speed deviation curve for G1 is not plotted.

Figure 5-2 Simulation results of 3-machine-9-bus system with wind power - Case 5-1

The power angle curve in Figure 5-2 shows great improvement in peak power angle deviation from 79.3 degree to 76.53 degrees for G2, from 65.12 degrees to 62.54 degrees. Besides, there is a significant reduction in the number of cycles and time needed to restore the system back to a steady-state.

The speed deviation curves also show a reduction of the peak value from 2.13 rad/s to 1.961 rad/s for G2, from 1.514 rad/s to 1.249 rad/s for G3. The power oscillation is also improved for all three generators and the wind farm. From the controller output curves, we can observe that the global controller has a faster and stronger response as compared to the conventional linear excitation controller.

Note that, at time=1.4s, there is another disturbance because of the reclosing of the faulty line. As a result, there is an abrupt change of active power output and controller output in Figure 5-2.

To further verify the effectiveness of the global controller as well as to investigate the effect of increased wind power penetration, more simulation is done for Case 5-1 by varying the wind power level. The steady-state operating points for the tested system under different wind power levels are shown in Table 5-2.

Table 5-2 Steady-state operating points for 3-machine-9-bus power system under different wind power levels - Case 5-1

		G1	G2	G3	Wind
	Generator type	Slack bus	PV bus	PV bus	PV bus
	Initial terminal voltage(pu)	1.040	1.025	1.025	0.996
0.1 pu Wind	Power angle δ (degree)	4.61	61.30	55.22	6.10
	Active power P_e (pu)	0.62	1.63	0.85	0.10
0.3 pu Wind	Power angle δ (degree)	3.20	63.40	56.43	10.72
	Active power P_e (pu)	0.43	1.63	0.85	0.30
0.5 pu Wind	Power angle δ (degree)	1.81	65.32	57.47	15.35
	Active power P_e (pu)	0.25	1.63	0.85	0.50

The simulation results of the synchronous generator power angle are selected as an example to reveal the impact of different wind power levels and the performance of the global controller. The power angle responses of G2 and G3 are shown in Figures 5-3 and 5-4.

Figure 5-3 G2 power angle responses at different wind power levels with global controller - Case 5-1

Figure 5-4 G3 power angle responses at different wind power levels with global controller - Case 5-1

The following observations can be obtained from Figures 5-3 and 5-4:

- 1) When the system loads remain unchanged, the increase of wind power means a reduction of active power output from G1, which is the slack bus in the system. Hence, the power flow in the system changes as a result of wind power integration. The relative power angles of G2 and G3 with respect to G1 increase with the wind power level. Hence, transient stability decreases.
- 2) The loss of synchronism is referring to the scenario when one machine loses synchronism with others. For a power system with no infinite bus, when a fault happens, generators accelerate at different rates. For the 3-machine system, G1 has the highest inertia and rating, yet the lowest load level. It accelerates the slowest. On the other hand, G2 has the highest acceleration, as can be seen from the simulation results. Hence, G2 is the critical generator in the system with the highest operating points and load level.
- 3) The global controller provides excellent performance across all cases, which proves the effectiveness and robustness of the global control method.

Figure 5-5 Performance comparison of global control and conventional control - Case 5-1

Figure 5-5 shows the performance comparison of global control and conventional control. As can be observed in the peak power angle deviation of G2 and G3, the global controller provides enhancement as compared with conventional control. The peak speed deviation is also another indicator of transient stability. Figures 5-5 (c) and (d) show an improvement of the speed deviation from global control.

It can also be observed from Figure 5-5 that, both the peak power angle and speed deviation become worse with the increase of the wind power. It again verifies the negative impact of wind power on the power system transient stability. Besides, the performance of the global controller is consistent across all wind power levels.

Case 5-1 keeps the loads in the system unchanged. The addition of wind power takes away the load from G1 while G2 and G3 output active power are unchanged. The amount of wind power that can be integrated is limited. Therefore, Case 5-2 is selected to verify the findings further so far. In Case 5-2, the same amount of load is increased as the integration of renewable wind power. And the increasement of the load is distributed proportionally among the three load units. The steady-state operating points of Case 5-2 with wind power level at 0.5 pu, 1.0 pu, and 1.5 pu are shown in Table 5-3.

Table 5-3 Steady-state operating points for 3-machine-9-bus power system under different wind power levels - Case 5-2

		G1	G2	G3	Wind
	Generator type	Slack bus	PV bus	PV bus	PV bus
	Initial terminal voltage(pu)	1.040	1.025	1.025	0.996
0.5 pu Wind	Power angle δ (degree)	5.44	61.58	53.64	11.75
	Active power P_e (pu)	0.74	1.63	0.85	0.50
1.0 pu Wind	Power angle δ (degree)	5.60	62.15	52.15	19.89
	Active power P_e (pu)	0.77	1.63	0.85	1.00
1.5 pu Wind	Power angle δ (degree)	5.79	61.98	50.11	28.37
	Active power P_e (pu)	0.81	1.63	0.85	1.50

Figure 5-6 Simulation results of 3-machine system with wind power - Case 5-2

The simulation results of Case 5-2 with 0.5 pu wind power are shown in detail in Figure 5-6. It includes the transient response of the power angle, speed deviation, active power, and excitation control output.

The power angle curve of the left-side curve shows great oscillation damping with the help of global controller. The power angle returns to steady-state after 1 cycle of oscillation. On the contrary, the power angle on the right-hand side takes 3 cycles to stabilize.

A similar observation can be made on the speed deviation curves. The speed deviation responses are enhanced with the help of a global controller in terms of peak speed deviation and cycles to stabilize. The global controller provides faster speed recovery.

The active power output from each of the generation units explains the root force causing speed deviation and power angle oscillation. When the fault happens, the active power P_e of three synchronous generators is reduced, causing the rotors to accelerate. Note that, at time =1.4s, the faulty transmission is restored to the system. The abrupt change of active power curves and excitation control output is a result of this event.

Figure 5-3 also shows the control signal from the controller. The designed controller exhibits faster reaction speed and larger control action magnitude. Therefore, the effectiveness of the global control method in a multi-machine system with RES.

Hence, from the simulation results, the performance of the global controller is verified. It proves its effectiveness in enhancing the power system stability and improve the transient responses.

Comparing Figure 5-2 with Figure 5-6, we can find that the latter case shows slightly better transient responses. The reason is due to the different load profiles in both cases. In Case 5-1, G1 output power is only 0.2465 pu, while the G2 has an active power of 1.63 pu. The load levels on the generators are highly uneven as compared to Case 5-2. This causes more severe speed deviation and less stability in Case 5-1.

*Figure 5-7 G2 power angle responses at different wind power levels with global controller
- Case 5-2*

*Figure 5-8 G3 power angle responses at different wind power levels with global controller
- Case 5-1*

Figures 5-7 and 5-8 show the cross-comparison of global controller performance at different wind power levels. The wind power varies from 0.5 pu to 1.5 pu. The G2 and G3 power angle responses show that:

- 1) The integration of wind power changes the power flow in the system as well as the operating points. The steady-state operating point of G2 is slightly affected while the one of G3 is more influenced by the integration of wind

power. The steady-state power angle of G3 is 53.64, 52.15, 50.11 degree when wind power is 0.5, 1.0, 1.5 pu respectively.

- 2) The power angle responses of G2 and G3 is similar for different wind power levels. This observation further verified the effectiveness and robustness of the global control method. It also reveals that, in Case 5-2, the load levels of three synchronous generators remain nearly unchanged regardless of wind power levels.
- 3) The wind power is increased to 1.5 pu, which is close to half of the original system size (3.15 pu). The simulation examines the scenario of high wind power penetration.

Figure 5-9 Performance comparison of global control and conventional control - Case 5-2

Figure 5-9 shows the performance comparison of Case 5-2 with global control and conventional excitation control respectively. Figure 5-9 (a) shows the G2 power angle peak deviation from the steady-state value because of the fault. The power angle deviation increases from 14.02 to 16.07 degrees due to the wind power increasement. This indicates decreased stability for G2. On the other hand, the power angle of G3 (Figure 5-9 (b)) shows improvement due to the wind power increasement. It indicates

improved stability for G3. Anyway, the global controller exhibits good performance in all cases as compared with the conventional excitation control.

Figure 5-9 (c) shows the speed deviation enhancement of the global controller. The peak speed deviation is reduced to different degrees with the help of the global controller at different wind power levels. On the other hand, the speed deviation of G3 shows a decreasing pattern as the wind power increases.

Comparing the results from Figures 5-5 and 5-9, the performance of global control on the synchronous generator side is verified. In addition, the impact of wind power on the system is dependent on the actual influence of the operating points and power flow in the system.

5.4 Summary

In this chapter, the design of the global controller is extended to multi-machine systems. For a large-scale power system, the number of generation units may be too large to apply a centralized controller. The global control method utilizes the advantages of decentralized robust control. Therefore, the controller uses locally measurable or ready-to-calculate variables as input, making the controller easy to design and implement.

A 3-machine-9-bus system with a wind farm integrated is used as an example for simulation. The simulation results are verified with multiple cases. The results show that the global controller can enhance the transient responses and improve system stability significantly as compared to conventional control. The effect of wind farm integration is mitigated as well. Therefore, we can conclude that global control is successful in the context of complex multi-machine power system with integration of RES.

The 3-machine-9-bus testing system serves as a good example for multi-machine systems. The validity of global control is not limited to the 3-machine-9-bus system. The design of the global control is a robust control with locally measurable/calculatable variables as mentioned in Section 5.2.1. For practical large-scale power systems with any number of generators and buses, it is important that the

controller is locally realizable. The global control is a decentralized robust control method that can be practically implemented.

The design and theoretical verification of the global controller are based on the general N-multi-machine power systems. The conclusion is universal regardless of the system size. For simulation purposes, a 3-machine system is used in this chapter. However, both the application of the global control method and the conclusion can be extended to any multi-machine systems.

The design of the global controller in this chapter focuses on the solution from the synchronous generation side. It relies on the proper control of the existing synchronous generators to tolerance the negative effect from the RESs and ensures transient stability. With more and more RESs integrated, the variety and percentage of RESs will require new control for the RESs to play a role in the power system transient stability.

Hence, in the next chapter, a new control method is proposed to apply on RESs-side and to take advantage of the characteristics of RESs.

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6 Transient Stability of Multi-machine System with Wind Power Integration and Frequency Control on the RES side

In Chapters 4 and 5, the impact of RES on the power system transient stability is well understood via simulation and theoretical analyse. The global controller is used to control power systems with RES (wind power as an example). The global controller takes frequency, power angle, active power as control input, and excitation voltage as the controller output. It acts on a conventional synchronous generator-side to enhance the transient stability issue brought by RES.

As a matter of course, it comes to the new question: Will proper control on the RESs-side enhance power system transient stability?

In this chapter, the answer to the above question will be given by a transient controller on the RES-side.

This chapter is organized in the following way: Section 6.1 presents the theoretical analyse of transient stability issues brought by RESs and the potential of RESs in enhancing power system stability. The design process of the proposed frequency controller is also illustrated. Section 6.2 presents the verification of the proposed controller via simulation in the 3-machine-9-bus system. Section 6.3 further verifies the proposed control method via more simulation cases. Section 6.4 concludes this chapter.

In this chapter, the simulations are carried out in MATLAB (2019a)/Simulink.

6.1 Transient control on RES-side

6.1.1 Virtual synchronous generator

RESs have been integrated into power systems for the past decades. The percentage of installed RESs capacity has been increasing from neglectable percentage to 33 % (as of 2018) [2]. In the initial stage of RESs power generation, no frequency

regulation or control was required to be installed on the RES-side. The RESs power generating units were operated to capture and deliver maximum power to the power grid at all times. The resulting phenomenon is reduced power system transient stability, as shown in Sections 4.2 and 4.3.

When the installed capacity of RESs in power generation becomes larger and larger, it is not reasonable to operated RESs as it is and only the existing synchronous generating units provide transient control and inertia to power system.

The root of transient stability is the instant power imbalance between mechanical power and electric power that drives the rotor to accelerate or decelerate. For RESs with a general structure as shown in Figure 6-1, there is no physical synchronized rotor. The frequency of the RES unit that is connected to the power grid via converters is dependent on the sensing device (PLL). In other words, the frequency of the RES unit follows the one at the point of common connection and does not have a mechanical dynamic like synchronous generators. Some researchers refer to this characteristic as “zero inertia”. Lack of inertia in the power system would reduce the resistivity of disturbances during transient events.

To solve the problem of decreased inertia in the power system, Virtual Synchronous Generator (VSG) concept has been brought to widespread discussion [6], [7], [9]–[11], and [53]. It has the advantage of supporting voltage and frequency responses by imitating the characteristics of the synchronous generator. Its control principle is to operate RESs with power electronics in a similar way as the synchronous generator. The design process of the VSG control can save a lot of effort as the synchronous generator, and its control system are well-understood for decades and can be used for a reference straight away.

Figure 6-1 shows the schematic diagram of VSG. The voltage and current control block represent the basic control of VSC. The active droop and reactive droop are concepts from conventional synchronous generators to regulate voltage and frequency. The inertia and damping block in Figure 6-1 imitate the mechanical dynamics of the conventional synchronous generator. It provides transient dynamics and responses in VSC-based RESs.

More detailed review of existing VSG based control methods can be found in Chapter 2. The advantages and disadvantages of different control methods are discussed in Section 2.2.2.

Figure 6-1 VSG Schematic

Note that in this chapter, the reactive power and voltage control is not the focus. Hence Reactive power control is assumed to be ideal, and the voltage magnitude at the terminal of RESs is set to 1 pu.

The active power droop control is expressed as

$$P_m - P_{ref} = -K_d(\omega - \omega_0)$$

K_d is the droop coefficient.

The equation states that when frequency varies, the active power responses inversely. The input of droop control is the measured frequency of the grid through PLL. P_{ref} is the reference point at a steady-state. For RESs, P_{ref} is the output of MPPT, which varies with time and has high levels of intermittency.

The inertia and damping mechanics are described as

$$2H \frac{d\omega}{dt} = P_m - P_e - D\omega_0\Delta\omega$$

Assume ω_0 is 1 pu. H is the inertia constant, and D is the damping coefficient. Unlike synchronous generators, the value of H and D are up to the controller designer's choice. Hence, H in VSG is referred to as virtual inertia, which does not physically

exist in RESs. The freedom of H and D selection makes the VSG a novel control solution to frequency control and transient stability. Many pieces of research have been developed from the VSG techniques by varying H and D 's design and trying to solve the contradicting active power dynamics between steady-state and non-steady-state.

However, this might not be the optimal solution since the characteristics of VSC-based RES are different from the conventional synchronous generator, and imitation may not fully unleash the potential of RESs. The following paragraphs explain the differences between the conventional synchronous generator and VSC-based RESs that will help in developing a new controller with inherited advantages over VSG.

The first difference between conventional synchronous generator and VSC-based RES is the origin and definition of "Frequency". As mentioned before in this section, synchronous generators have electrically synchronized rotors as one of the key characteristics. The rotors have considerably large mass and rotating inertia that gives the mechanical dynamics as described by (4.1) and (4.2). Nevertheless, this is not the case in RESs. There is no rotor in solar power, and the rotors in wind power and ocean power are decoupled and not synchronized with the grid. Hence, the frequency concept in the RESs does not have a physical meaning. The building of a virtual mechanical dynamics with frequency and rotor inertia may not be efficient or optimal.

The second difference between synchronous generators and RESs is the usage of power electronics. In VSC-based RESs, power electronics are commonly used for the grid integration. The interface between RESs' DC link and grid is power electronic converters that have a much faster speed of response as compared to the dynamics of conventional synchronous generators. Such property makes the RESs capable of more aggressive controls.

From the two above-mentioned differences, new controllers can be built to utilize the property of various RESs fully.

6.1.2 Design of the proposed controller

In this section, the design of the proposed controller is elaborated in detail.

As mentioned in Section 6.1.1, the frequency in the VSC-based RESs lacks physical meaning as it is a self-synchronizing unit with the grid frequency. From the base control of converters, it also reveals that there is no frequency control involved. VSG introduces the frequency/active power droop and the mechanical dynamics of synchronous generators only to increase the order and complexity of the system.

Since the response time of power electronics is much shorter than the power system dynamics, it is assumed that the power electronics is ideal with no energy loss and acts as a controlled voltage source.

From (5.6) - (5.9), the active power and reactive power is dependent on the voltage magnitudes and angle differences. Therefore, it is further assumed that the voltage magnitude at the RESs terminal is 1 pu. Hence, the output power of RESs to the grid is influenced by the angle of the voltage only from the RES-side.

When designing a transient controller on the RES-side, the ultimate goal is to minimize the power imbalance due to disturbances. Hence, controlling of the voltage angle is the most direct way for VSC-based-RESs. The voltage angle of the VSC controller is a result of v_d , v_q magnitudes from the voltage control.

From the theoretical analyse, to design a transient controller on the RES-side, the most direct way is to use grid frequency as the input and generate a voltage reference output for the VSC. In this way, the complexity of the system is greatly reduced as compared with the VSG technique. Hence, the problem would be how to design such a controller that takes in the grid frequency as the input and generated a voltage reference for the VSC. The second problem needs to consider is how to solve the contradicting active power control objectives between steady-state and non-steady-state.

Note that the non-steady-state is referring to the scenarios when large disturbances happen.

During steady-state, the RESs active power output should be at maximum power to harvest more economic benefits. However, when large disturbances happen, the power imbalance between P_m and P_e for synchronous generators, causing the stability issue. To contribute to this transient stability issue, the active power output

from the RESs needs to respond to the transient event. For short-circuit faults, the active power output from the RESs should decrease, whereas the contradiction comes in. RESs regain steady-state.

Figure 6-2 Proposed controller schematic

Clearly, different operating regions exist in power systems with RES integration.

- 1) Pre-fault steady-state stage: RESs operate at maximum power with the MPPT controller.
- 2) During fault stage: If RESs continue to operate at maximum active power output, the system will be less stable. Hence, the new transient controller takes the role during this stage to enhance stability.
- 3) Post-fault stage: When the fault is cleared, the system enters the recovery stage where oscillation will occur, and RESs regain steady-state.

The controller for pre-fault and post-fault stage follows the conventional design for RESs, which include MPPT control and DC-link voltage regulation. During a fault, new controllers should follow the schematic diagram in Figure 6-2. In this chapter, PI controller is used for the purpose of testing the proposed controller structure and design procedure. More advanced controllers such as model predictive control, adaptive control might be deployed in future work.

After partial controllers for different operating regions are designed, proper syncretization is needed to provide a smooth transition and proper weighting. Membership function from fuzzy logic control is used to achieve the controller syncretisation.

6.2 Simulation of the proposed controller in multi-machine power system

In order to validate the proposed control method, simulation is carried out in the same multi-machine power system as in Chapter 5 (Figure 5-1). A wind farm integrated at Bus-7 is used as an example of RESs in the 3-machine 9-bus power system, as shown in Figure 5-1.

6.2.1 Design of the proposed controller for wind power

For PMSG-based wind farm, there are many types of MPPT control available in the literature that can be classified into two categories: MPPT on the machine side, MPPT on the grid side. Since the difference is only the location of MPPT is applied, the controller design procedure is similar. Hence, only the MPPT on the machine side case is considered in this thesis.

Figure 6.3 shows the schematic diagram of the proposed controller for wind power. The transient controller is a PI controller with frequency as the input.

Figure 6-3 Proposed controller design for wind power

When a fault happens, the grid frequency tends to increase, and the controller would generate an equivalent control action to decrease the voltage angle of the grid-side

converter. Therefore, the contradicting control actions of the two controllers should be properly synthesized.

In addition, switching between the two controllers should not be abrupt. If it is abrupt, the controller switching would be a large disturbance to the system by itself. Together with the fault, the system would be even more unstable. Therefore, smooth switching is required.

The following membership function is used to switch smoothly between the two controllers.

$$mf_1 = \frac{1}{(1 + e^{-k_1*(t-t_1)})} - \frac{1}{(1 + e^{-k_2*(t-t_2)})}$$

$$mf_2 = 1 - mf_1$$

$$control = Trans_{ctrl} * mf_1 + Vdc_{ctrl} * mf_2$$

where

- t_1 is the time when a fault happens.
- t_2 is the time when DC-link voltage regulator is restored.
- k_1 determines how sharp the switching from DC-link voltage regulator to transient controller is.
- k_2 determines the sharpness of the switching from transient controller to DC-link voltage regulator.
- $Trans_{ctrl}$ is the controller output from transient controller.
- Vdc_{ctrl} is the controller output from the Vdc regulator.

Here, k_1 is set to 200 and k_2 is set to 0.2. Simulation results are shown below.

6.2.2 Simulation results

To verify the effectiveness of the proposed control method, the following case is chosen for simulation.

Case 6-1: Low wind power penetration scenario

Fault sequence:

At time = 0.1s, a three-phase-to-ground fault happens at the mid-point on the second transmission line between Bus-7 and Bus-8.

At time = 0.22s, the faulty transmission line is opened by the circuit breakers at both ends.

At time=1.4s the faulty transmission line is restored, and the system is in post-fault stage.

Wind Farm: 50MW (0.5 pu) connected at Bus-7 through $X=0.2j$ transmission line.

Figure 6-4 Simulation results of 3-machine-9-bus system with 0.5 pu wind power - Case 6-1

Two simulations are carried out in this section: simulation with conventional excitation control and simulation with the proposed controller. The simulation results

of conventional excitation control are shown in Figure 5-2 in Chapter 5. The simulation results of the proposed controller are shown in Figure 6-4.

When the fault happens, the active powers from the synchronous generators drops below mechanical power, causing the rotors to accelerate. After the faulty line is disconnected, the system goes through a power oscillation process. Comparing Figure 6-4 with Figure 5-2, it can be found that the proposed controller can greatly reduce the power oscillation and peak power angle deviation as compared with the conventional excitation controller.

When the fault happens at 0.1s, the frequency increases, the proposed controller starts to respond with a decreased wind power output. When the fault is cleared, and the system tends to be stable and returns to the steady-state. Note that, when the faulty transmission line is restored, the system undergoes another transient event, causing the simulation results in Figure 6-4 to experience an abrupt change in response.

Figure 6-5 shows the voltage angle response of the wind farm with reference to the slack bus.

Figure 6-5 Voltage angle response of the wind farm with proposed controller - Case 6-1

From the voltage angle curve, it can be observed that: Prior to the fault, the wind farm produces an active power of 0.5 pu at a power angle of 15.35 degrees. When the fault happens, the voltage angle of the wind farm increases as the DC-link voltage

regulator is still playing the main role. Then the transient controller starts to take place and bring the voltage angle down. This control action effectively reduces the active power output of the wind farm such that the synchronous generator power imbalance ($P_e - P_m$) is mitigated.

Figure 6-6 shows the DC-link voltage response in pu. When the fault happens, the DC-link starts to accumulate energy. And the voltage returns to steady-state value after 2s. Even though the DC-link voltage rises to 1.58 pu of the steady-state value, there is usually some headroom when designing the wind power system. Besides, power electronic capacitors are often designed and tested with some tolerance of temporary overvoltage, which can be found in [81] and [82]. Hence, the proposed controller is practically implementable.

Figure 6-6 DC-link voltage response with proposed controller - Case 6-1

From the simulation results of Case 6-1, we can find that the proposed controller responds to the frequency surge and produce a control action to bring down the wind power output to the system. Therefore, the performance of the proposed control method is proved.

To further verify the effectiveness and robustness of the proposed control method, another simulation with high wind power penetration level is carried out.

Case 6-2: High wind power penetration scenario

Fault sequence: The same fault is applied as in Case 6-1.

Wind Farm: 150MW (1.5 pu) connected at Bus-7 through $X=0.2j$ transmission line.

Figure 6-7 Simulation results of 3-machine-9-bus system with wind power - Case 6-2

Case 6-2 increases the wind power to 150 MW which is close to half the original system size of the 3-machine system. It simulates the scenario of high wind power level. Note that, the loads in the 3-machine system are increased proportionally for the balance of power generation and demand.

The detailed simulation results are shown in Figure 6-7. The subfigures on the left-hand side are the system responses without the proposed control method. The subfigures on the right-hand side are the system responses with the proposed control method.

Comparing the power angle response, we can find that the proposed control methods provides great reduction in the peak power angle deviation of G2 from 83.2 degrees to 67.55 degrees. The improvement of the peak power angle deviation indicates enhanced system transient stability. Besides, the proposed control method reduces the oscillation to less than 1 cycle.

Similar improvement can be observed from the speed deviation curves. The speed response of G2 and G3 is greatly improved by the proposed control method. The peak speed deviation and speed oscillation is significantly reduced. Note that, when the faulty transmission line is restored, the system undergoes another transient event.

Figure 6-8 DC-link voltage response with proposed controller - Case 6-2

Figure 6-8 shows the DC link voltage response with the proposed controller. And the wind farm terminal voltage angle is shown in Figure 6-9. The response of the terminal voltage angle is a result of the proposed controller. When the fault happens at time= 0.1s, the active power output from the wind farm is reduced as a result. And energy starts to accumulate on the DC-link capacitor as can be shown in Figure 6-8. The increase of capacitor voltage causes the Vdc regulator to accumulate control actions. The terminal voltage angle keeps increases in during-fault stage with the control objective to bring down Vdc.

Figure 6-9 DC-link voltage response with proposed controller - Case 6-2

When the circuit breakers are opened at time = 0.22s, the transient frequency controller starts to take the role and brings down the active power output. Hence, the $P_m - P_e$ difference for the synchronous generators is improved and the system stability increases.

From the simulation of Cases 6-1 and 6-2, it can be concluded that, the proposed controller provides great transient stability enhancement at different wind power penetration levels. The performance of the proposed control method is proved.

Figure 6-10 Comparison of peak power angle deviation with 1) conventional excitation only; 2) global control; 3) proposed control; 4) proposed control + global control

Figure 6-11 Comparison of peak speed deviation with 1) conventional excitation only; 2) global control; 3) proposed control; 4) proposed control + global control

In this section, the potential of the RESs on the transient stability enhancement is explored by the proposed control method. To compare different control methods and the compatibility of the proposed control method, Case 6-2 is extended to 4 scenarios: 1) Conventional excitation only; 2) Global control; 3) Proposed control; 4) Proposed control + Global control.

Figures 6-10 and 6-11 show the comparison of different control method. When only conventional control is applied, the peak power angle deviation is 27.01 degrees for G2, 8.35 degrees for G3. The results are significantly improved when global control is applied on the synchronous generator side or the proposed control is applied on the RESs side. Best results are achieved when global control and the proposed control are combined.

From Figure 6-11, when only conventional control is applied, the peak speed deviation is 2.548 rad/s for G2, 0.923 rad/s for G3. The results are significantly improved when global control is applied on the synchronous generator side or the proposed control is applied on the RESs side. Best results are achieved when global control and the proposed control are combined. The peak speed deviation is improved to 1.49 rad/s for G2 and 0.4 rad/s for G3.

6.3 Effect of fault location on proposed controller in multi-machine power system

In this section, more simulations are carried out with different fault locations to further verify the performance of the proposed controller and effect of fault locations on the power system transient stability.

Case 6-3:

Fault location: let k be the relative distance of the fault location with respect to Bus-7. If $k = 0$, the fault happens at Bus-7. If $k = 0.5$, the fault happens at the middle of the second transmission line between Bus-7 and Bus-8, and so on.

Wind Farm: 50MW (0.5 pu) connected at Bus-7 through $X=0.2j$ transmission line.

The simulation results of the power angle response are shown in Figure 6-12. When the fault location is closer to Bus-7, the power response is more severe than in other cases. In other words, when the fault is closer to the G2 (the critical synchronous generator), the same fault would produce more threats to the power system transient stability.

Figure 6-13 presents the speed deviation response of G2 at different fault locations. When $k=0.01$, the fault happens at a location very close to the critical generator G2, causing the worst speed deviation response. The peak speed deviation is highest when $k=0.01$. With the fault location moving further away from G2, the same fault causes less severe speed deviation response for G2.

Figure 6-12 G2 power angle response with the proposed controller and different k values - Case 6-3

Figure 6-13 G2 speed deviation response with the proposed controller and different k values - Case 6-3

Figure 6-14 DC-link voltage with proposed controller and different k values - Case 6-3

The corresponding DC-link voltage is also a critical variable to consider, which is shown in Figure 6-14. When $k=0.01$, the DC-link voltage overshoot to 2.05 pu. It imposes an extra burden to the DC-link capacitor. With the fault location moving away from G2, the DC-link voltage response is improved.

From the simulation results shown in this section, we can conclude that:

- 1) The location of faults affects the transient stability of the power system. When the fault location is closer to the critical generator G2, the system stability decreases.
- 2) The proposed method is effective across all cases.

6.4 Summary

In this chapter, the potential of RES-side transient control is explored. First, the structure and property of RESs are compared with those of conventional synchronous generator. Two key differences are found to be beneficial to the new controller design. Then the VSG technology is analysed. The drawback of the VSG technique and the characteristics difference between RESs and synchronous generators is analysed and used in developing a new control method.

A new control method that utilizes the unique characteristics of RESs from the perspective of active power balancing/control is proposed. It has the advantage of less complexity and direct response to the grid frequency. A multi-machine power system with a wind farm integrated is used as an example test system to simulate the proposed controller. The simulation results verified the effectiveness of the controller under different fault locations. It shows the promising potential of the proposed control method in practical application.

The design of the proposed method is valid for VSC-based variable renewables and energy storage devices. The proposed control controller is a type of decentralized controller that uses locally measurable inputs and parameters. Hence, the application of the proposed method can be extended to any N-multi-machine power system. The tested system used in this chapter is an example system. It does not affect the general conclusion.

In this chapter, the 3-machine-9-bus testing system with a single wind farm serves as a good example for multi-machine systems. Do note that the validity of the proposed control in the context of RESs integration is not limited to the example system. The design of the controllers and the input used in the controller are locally measurable variables. It is further verified in Chapter 7 with an 8-machine-14-bus testing system under different scenarios.

Note that, part of the contents in this chapter has been submitted to a peer-review journal [83].

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7 Transient Stability Improvement of Multi-machine System with Various RESs and Energy Storage

Chapter 6 gives the proposed frequency controller on RES side, and its simulation results in 3-machine-9-bus power system. In this chapter, a complex system with multiple RESs units (wind power, solar-PV, tidal power) and energy storage is considered. Unlike previous chapters where wind power is used as an example of RESs in transient stability research, various types of RESs are employed with the proposed frequency controller.

This chapter is organized in the following way: Section 7.1 introduces the 8-machine-14-bus power system built for simulation. Section 7.2 presents the simulation results of the proposed frequency controller in the context of 8-machine-14-bus power system. Section 7.4 concludes this chapter.

In this chapter, the simulations are carried out in MATLAB (2019a)/Simulink.

7.1 Multi-machine power system with various RESs and energy storage

7.1.1 Application of the proposed control method

As mentioned in Section 2.1, the root cause of transient stability issues is the instant power/energy imbalance when disturbances happen. Therefore, if the power imbalance can be minimized, then the transient stability of the power system can be improved. To achieve the purpose of active power control, there should be an energy source for inertia response (ESIR) [84].

The ESIR for wind power, as illustrated in Chapter 6, can be the DC-link capacitor. The DC-link capacitor is designed to store excess energy for a short period of time at the cost of over-voltage. Another ESIR is the rotating energy in the rotor and turbine for wind power. If coordinated control of the turbine-side and grid-side converter is achieved, the excessive energy will cause the acceleration of the rotor of the wind

turbine while maintaining the DC link voltage. This may cause problems to the wind turbine and might be a direction for future work.

Similar to wind power, the ESIR in solar-PV is the DC-link capacitor. If coordinated control of DC-DC converter and VSC is applied. The excessive energy can be dissipated in the form of heat while maintaining the capacitor voltage.

The design of the control strategy on ESIR in ocean power is the same as in wind power.

Energy storage itself is an ESIR, it can be used as a transient response source in a power system with integration of various variable renewables.

Hence, the proposed control method can be applied to various VSC-based RESs and energy storage devices.

7.1.2 8-machine-14-bus power system

Figure 7-1 Schematic diagram of 8-machine-14-bus system

The word ‘machine’ in the 9-bus 3-machine system refers to 3 synchronous generators, which are denoted by G1, G2, G3. RESs and energy storage added into the system can be treated as “machines” as well. To investigate a more complex case with multiple types of RESs, the 3-machine-9-bus system has been extended to 8-machine-14-bus system, which includes 2 wind farms, 1 solar farm, 1 tidal farm, and 1 energy storage unit. The details schematic of the modified system is included in Figure 7-1.

7.2 Simulation of proposed transient controller in 8-machine-14-bus system

Simulation Case 7-1:

Table 7-1 Steady-state operating point of 8-machine-14-bus power system - Case 7-1

Machine location	Active power	Voltage	δ_0
G1@Bus-1	0.1370	1.0400	0.9916
G2@Bus-2	1.6300	1.0250	66.5530
G3@Bus-3	0.8500	1.0250	60.3330
ES@Bus-10	0	0.9957	-1.2481
Wind Farm-1@Bus-11	0.30	1.0261	10.5349
Tidal Farm@Bus-12	0.10	1.0252	0.4056
Wind Farm-2@Bus-13	0.10	1.0120	1.1254
Solar Farm@Bus-14	0.10	1.0322	7.4570

The total load in the system remains unchanged. Since G1 is the slack bus, the active power of G1 decreases along with the increase of renewable power. Therefore, the active power of G1 is reduced from 0.7164 pu to 0.1370 pu with the total integration of renewable power of 0.6 pu.

Fault sequence:

At time = 0.1s, a three-phase-ground fault happens at the mid-point of the second transmission line, as shown in Figure 7-1.

At time = 0.25s, the faulty line is disconnected when the circuit are tripped. The system steps into the fault-clearing stage.

At time = 1.4s, the isolated transmission line is reconnected to the grid. Assume the fault is temporary. The system enters the post-fault stage.

Case 7-1 is built to compare the performance of conventional control with the proposed controller. The proposed controller is a combination of the Vdc controller and transient controller synthesized via membership function described in Section 6.2.1.

Figure 7-2 Transient response of 14-bus system with conventional excitation control - Case 7-1

In Figure 7-2, the top-left graph shows the relative power angles of G2, G3, with reference to G1. The top-right graph shows the relative speed deviation with respect to G1. The bottom-left graph is the active power output from each ‘machine’, while the bottom-right graph is a zoom-in view of the active power responses.

From Figure 7-2, it can be observed that, when the fault happens at time=0.1s, the active power output of each ‘machine’ experience a step change. G2 and wind farm-1, which both are connected to Bus-7, experience a step-down change due to the fault. In the meanwhile, other ‘machines’ experience small step-up changes as they are located far from the fault. Before the fault, part of the load is powered by G2 and wind farm-1. When the fault happens, the power from G2 cannot be delivered to loads. Hence, the loads take more power from other ‘machines’ and cause step-up changes to active power.

In the during-fault stage, the rotor of G2 accelerates, as shown by the speed deviation curve. The speed deviation causes the power angle to increase as well.

Figure 7-3 Transient response of 14-bus system with proposed controller

When the circuit breakers open at time=0.25s, oscillation is observed in speed, angle, and active power. When the faulty line is restored at time=1.4s, the system experiences another step change, and the system returns to the steady-state after a few cycles of oscillation.

The simulation results of the power system exhibit excessive oscillation after the fault happens. The oscillation is an unwanted response to the power system.

Then, the simulation is repeated with the proposed controllers on the side of RESs and energy storage, while remaining all other parameters unchanged. The simulation results are shown in Figure 7-3.

When the fault happens at time=0.1s, the immediate active power response is similar to the previous scenario. However, the proposed controllers at RESs and energy storage capture the change in frequency and take actions to bring the speed differences among G1, G2, and G3. For example, wind farm-1 is close to the critical synchronous generator-G2. In the during-fault stage, the wind farm-1 active power output is reduced by the proposed controller. Energy starts to accumulate on the DC-link capacitor, causing the capacitor voltage to rise. When the fault is cleared, the accumulated energy needs to be discharged to the grid.

Around time=5s, the Vdc regulator starts to reduce the DC-link voltage by increasing the active power output from wind farm-1. A similar analysis can be used to explain the responses of other RESs and energy storage.

The simulation results show improved transient response and better recovery speed to steady-state with less oscillation. The peak power angle deviation is reduced from 122.92 degrees to 102.89 degrees. The speed deviation of G2 when the circuit breaker is opened is reduced from 7.453 rad/s to 4.695 rad/s. The improvement of transient stability proves the effectiveness of the proposed control method.

Besides, the classic excitation control cannot bring the system back to a normal state when the fault clearing time is between 0.29s and 0.30s. With the proposed controller, the fault clearing time can be extended to 0.40s without jeopardizing the system.

In summary, the proposed controller at RESs and the energy storage side can improve the performance of the system via the utilization of VSC-based dynamics.

The renewable energy has a high level of intermittency. The power level of wind farms varies with the local wind speed. Similarly, solar power depends on the local irradiation, and the ocean power depends on the tidal flow. Use the two wind farms in the 14-bus system as an example. The wind speed distribution varies from time to

time. The following scenarios are selected to investigate the effect of different speed distribution on the transient stability and the performance of the proposed control method.

- Scenario 1: Wind farm-1 active power 0.3 pu-- Wind farm-2 active power 0.1 pu
- Scenario 2: Wind farm-1 active power 0.2 pu-- Wind farm-2 active power 0.2 pu
- Scenario 3: Wind farm-1 active power 0.1 pu-- Wind farm-2 active power 0.3 pu

All three scenarios are simulated and the results are summarized in Figure 7-4.

Figure 7-4 Results comparison of 14-bus system with different wind speed distribution.

The top chart from Figure 7-4 illustrates the peak power angle deviation for 3 scenarios, while the bottom chart shows the peak speed deviation results. Even though the difference is small across 3 scenarios, we can discover the following findings.

- 1) The wind power level has an impact to the power system transient behaviour, especially when there are multiple renewables in the system. When 0.3 pu wind power is generated at wind farm-1, G2 shows worse peak power angle deviation and speed deviation. G2 is the most heavily loaded unit in the system. Hence it is more sensitive the negative impact of wind power integration
- 2) The simulation result proves the performance and effectiveness of the proposed control method over different wind energy distribution scenarios. This variation of wind power in different wind farms can be a result of the following factor: Geometric wind speed difference, sizing of wind farm, or the change of operating plans.

The design procedure in Section 6.2.1 used the wind farm as an example of renewables. The design procedure can be extended to other renewables as long as they are VSC-based. The proposed control method takes locally measurable or calculatable variables as input. Hence it is decentralized control that is application to multi-machines + multi-renewables system. The testing system and scenarios does not affect the general conclusion of the proposed method.

7.3 Impact of long transmission impedance on transient stability and the proposed control method

Wind farm's construction requires a large area for operation. And the location is often where wind power is rich. Hence, wind farms are usually integrated via long transmission lines with high impedance [85]–[87]. For example, the Gansu wind farm project under construction in China is located in the desert area [88]. The total transmission line reaches 1000km. Therefore, it is important to understand the impact of long transmission impedance on the transient stability and proposed control method.

A new simulation is constructed to study this problem.

Simulation Case 7-2:

The original impedance ($X=0.2j$) of the transmission line from wind farm-1 to Bus-7 (Figure 7-1) is changed to $X= 0.6j$, while everything else remains unchanged.

The simulation results of Case 7-2 are presented in Figures 7-5 and 7-6. Figure 7-5 shows the transient responses of the 14-bus system with conventional the excitation control method. The top-left graph shows the relative power angles of G2, G3 with reference to G1. When comparing with the simulation results in Figure 7-2, we can find that a more severe oscillation in the system. The number of oscillations is increased from 6 cycles to 8 cycles due to the high transmission impedance. The top-right graph shows the relative speed deviation with respect to G1. The system speed recovery takes a longer time to return to the steady-stage. The bottom-left graph is the active power output from each ‘machine’, while the bottom-right graph is a zoom-in view of the active power responses. Deteriorated responses and stability are observed because of the increased transmission impedances.

Figure 7-5 Transient response of 14-bus system with conventional excitation control - Case 7-2

Figure 7-6 presents the simulation results of the proposed control method.

The power angle responses and speed deviation responses show improvement as compared with the case of conventional excitation control. There is a reduction of

peak values of power angle oscillation from 130.31 degrees to 107.01 degrees. The peak speed deviation is decreased from 7.48 rad/s to 4.689 rad/s. The number of oscillations in the power system is reduced from 8 cycles to 4 cycles. When the fault happens, the transient frequency controllers in RESs and energy storage devices play the role in transient stability enhancement. When the system is returning to the steady-state, the accumulated/depleted energy of the DC-link capacitor is restored around time=5s. The simulation results again verify the negative impact of high transmission impedance as well as the effectiveness of the proposed control method.

Figure 7-6 Transient response of 14-bus system with global control - Case 7-2

Table 7-2 summarizes the simulation result of Cases 7-1 and 7-2. It can be concluded from the simulation result that:

- 1) The long transmission line with high impedance causes the power system to be less stable. It results in higher magnitudes and longer oscillation in the power system.
- 2) The proposed method is robust and valid over various scenarios as shown in the simulation result in Sections 7-1 and 7-2.

Table 7-2 Results comparison of 14-bus, $X=0.2j, 0.6j$

	G2 Peak power angle (degree)	G2 Peak speed deviation (rad/s)
Conventional control (x=0.2j)	122.92	7.453
Proposed control (x=0.2j)	102.89	4.695
Conventional control (x=0.6j)	130.31	7.48
Proposed control (x=0.6j)	107.01	4.689

7.4 Summary

In this chapter, the proposed control method is extended to the application of multiple RESs and energy storage devices. A modified multi-machine power system with integration of 2 wind farms, 1 solar farm, 1 ocean power farm, and 1 energy storage is applied.

The shortcomings of existing control methods that are reviewed in Section 2.2.2 are overcome by the proposed control method:

- 1) The design of the proposed controller makes uses of the dynamics of VSC-based variable renewables and energy storage devices.
- 2) It does not require additional devices from the RESs-side. Hence the cost of implementation is reduced.
- 3) The proposed control method is incorporated with MPPT strategy and can guarantee economic benefits and transient stability enhancement in one controller.

Simulation is carried out in different wind speed distribution scenarios as well as a long transmission line scenario.

The simulation results further verify the effectiveness of the proposed control method. The power angle oscillation and speed deviation of synchronous generators show improvement. The CCT is increased as a result of the proposed control method. Hence, the idea of design a transient controller based on the unique properties of RESs and VSC technology is proved to be in the right direction. The enhancement of transient stability from the elementary view of power/energy balancing is achievable.

The proposed method is not limited to the system size of the power system or the type of VSC-based RES or ESS as shown in this chapter. Because the design procedural is based on all VSC-based RESs and the theoretical verification is based on the energy balancing principle that is valid regardless of system size. The testing system used in this Chapter is only one example for case study and simulation purposes. The proposed method is implementable for power systems with any size or VSC-based RES/ESS.

Note that, part of the contents in this chapter has been submitted to a peer-review journal [83].

8 Conclusion and Future Work

8.1 Conclusion

This thesis focuses on the impact of the variable renewables on the power system transient stability, and the author works towards finding solutions to the negative impact of RESs and enhance the transient stability in the large-scale power system. The finding and contributions of this thesis are summarized in the following subsections.

8.1.1 The impact of the RESs on transient stability

Both positive and negative conclusions can be found in related researches in literature. There is a lack of deep analyse of the factors affecting the impact of RESs and the reason for opposite findings in the literature.

After simulation of wind power integration in various ways in the SMIB power systems. The following factors are found to influence the result.

- 1) The load level of the synchronous generator. In a power system with both synchronous generation and non-synchronous generation, only the synchronism of synchronous generators is influenced by the disturbances. The reason is that the non-synchronous generation does not face the problem of loss of synchronism as there is no physical inertia involved. Hence, the load level of the synchronous generator prior to the fault is critical to the transient response.
- 2) The inertia of the synchronous generator. From (4.2), the inertia constant H appears in the denominator of the differential equation. Hence, the larger the inertia, the smaller the power angle oscillation and speed deviation and better stability.
- 3) The generator active power output when fault happens. During the fault, the active power of synchronous generators drops to a low value. The P_e during fault plays an important role in transient stability as well, according to (4.2).

The value of P_e is dependent on the location and type of fault. However, fault type and location are not controllable in reality. Similarly, the time of fault clearing is another factor that affecting the transient stability yet not controllable.

- 4) The reactance of the transmission line and the generator internal reactance also affects transient stability. A low value of reactance improves the pre-fault operating point.
- 5) The excitation control of the synchronous generator. As illustrated in Chapter 4, the excitation control plays an important role in power oscillation reduction. The application of global controller can enhance transient stability.
- 6) The location of RESs. The integration of RESs would affect the power system power flow and operation. For example, when the power level of wind power is high, the load on the synchronous generator is reduced, causing the system to be more stable. On the other hand, for a heavily loaded transmission line that is shared between RESs and synchronous generator. The power transmission path for the synchronous generator is limited when the RESs are at a high-power level. Therefore, the location of RESs may have both positive and negative impacts on the system.
- 7) The control methods applied to RESs. For conventional control of RESs, MPPT is often preferred. The MPPT control strategy might unstable the system as it would reduce the P_e of the synchronous generator during and after the fault.
- 8) The decommission of synchronous generators because of RESs. When high RESs penetration happens, how the synchronous generators are decommissioned is affecting the transient stability. If synchronous generators remain connected yet operate at low load, it will improve the transient stability. However, this scenario is not economically beneficial.

Hence, in summary, the impact of the RESs on the power system is dependent on not only the existing parameters of the power system but also the location, control, and planning of the RESs. Therefore, both positive impact and negative impact can be observed in a power system regards to the transient stability issue.

Based on the deep study of this thesis and other research works in literature, it can be concluded that for a certain power system with all other parameters fixed, the increased level of RESs would promote the importance of transient controller to enhance the transient system stability.

8.1.2 Global controller on the synchronous generator-side

The theoretical analyse and proved robust control method shows the effectiveness of excitation control on the synchronous generator side. The global control separates the power system operating into different stages: pre-fault, during-fault, fault-clearing, and post-fault stages. In each of the stages, a partial model is developed using direct feedback linearization technique. Then for each of the partial models, a robust controller is designed to cope with the uncertainty in the power system. Lastly, the partial controllers are synthesized to form a global controller.

Simulation is carried out in SMIB system as well as multi-machine power systems. The performance of the global controller in the context of RESs is verified.

8.1.3 Proposed control method on the RES-side

From the theoretical analyse of the synchronous generator dynamics, it is found that the root of transient stability issues lies in power balancing. In literature, virtual inertia or virtual synchronous generator method is a popular type of transient enhancement methods. The VSG strategy tries to mimic the synchronous generator dynamic; hence, virtual inertia is introduced to the system. However, there are two drawbacks of the VSG technique: 1) it increases the complexity of the system by increasing the order of the system. 2) it does not utilize the advantage of the power electronics in the RESs.

Therefore, a new transient controller that overcome the drawbacks of VSG is introduced. It has a simple structure, yet utilizing the fast response time of the power electronic converters.

The performance of the proposed method is tested in wind power, solar-PV, ocean power as well as energy storage. The simulation results show promising performance in transient stability enhancement in large-scale power systems with the integration of various variable renewables.

8.1.4 Concluding remarks

This thesis is dedicated to addressing the transient stability issues of modern large-scale power systems with the integration of RESs. In this thesis, the problem of increased uncertainty and degraded transient response bring our attention to enhance the transient stability in the new context.

This problem is addressed in the following ways:

- 1) First, the impact of the RESs on transient stability is deeply investigated via literature review as well as computer simulations. The in-depth understanding of the root cause of the transient stability issues leads us to the need for a new controller design.
- 2) The problem is divided into two sides: the synchronous generator side and the RES side. The synchronous generator side represents the conventional electricity generation that mainly uses synchronous generators. The global control method adopted in Chapters 4 and 5 is decentralized robust control that uses DFL technique. The design procedure is achievable with only locally measurable/calculatable variables. And the uncertainty brought by RESs can be handled by the robustness of global control. The stability is theoretically proved in Sections 4.4.1.2 and 5.2.2. There is no limitation on the system size or complexity in the proving and design process. Therefore, the testing systems used in this thesis are only examples for case study and simulation. The stability and robustness are guaranteed in any multi-machine system in practice.
- 3) After the work is done on the synchronous generator-side, the attention is forwarded to the RES side. The proposed control method makes uses of the fast responding dynamics of the RESs. The design principle is based on the

energy balancing theory derived from the equal area criteria. Its validity is straight-forward as shown in Section 6.1.2. In addition, the proposed control method is based on the general VSC-based structure and is decentralized control as well. Therefore, the testing systems used in this thesis are only examples for case study and simulation. The stability and robustness are guaranteed in any multi-machine system in practice. There is no limitation on the system size and can be applied in any VSC-based RESs or ESS.

- 4) Hence the overall power system stability with RESs integration can be enhanced through both the global control on the synchronous generator side and the proposed control on the RES side. The combined controllers work concurrently to improve the transient stability.

Figure 8-1 Thesis scheme for multi-machine power systems

Figure 8-1 depicts the overall stability enhancement schemes. Therefore, this thesis provides a systematic, effective, and complete solution to large-scale power system transient control with the integration of RESs.

8.2 Future Work

Based on the work and contributions from this thesis, recommendations for future work are given in this section.

8.2.1 Cloud computing and big data in future power systems with high penetration of RES.

To mitigate the negative impact of the RESs, the planning and operation of the power system should take the transient stability into consideration. In a network of both RESs and conventional synchronous generation, the transient stability or the rotor angle stability refers to the synchronous generator. The converter-based renewable generation does not have physical inertia, and its frequency is a result of its associated controller only. Hence, the transient stability relies on the synchronous generator mechanical dynamics, which is described by (4.2). The electric power P_e during the disturbance is dependent on the fault type and location and the inertia of the generator. Therefore, the load level of synchronous generators plays an important role in the transient stability study. If the operation of power systems can achieve a goal that the active power output of synchronous generators is evenly distributed, the transient stability can be improved.

The impact of the RESs can be a positive influence, and the following factors of the RESs affect the result.

- 1) The location of the RESs and the design of transmission system. When RESs are planned at locations closer to the highly loaded synchronous generations, the load level of the synchronous generator can be reduced, hence improving the transient stability. The transmission system also affects the power flow in the power system and the load level of synchronous generators. In addition, if RESs and synchronous generation have a shared transmission line, it will reduce stability.

- 2) The decommission of synchronous generators. As the RESs penetration level increases, the decommission schemes of existing synchronous generators also affects transient stability.
- 3) The RESs have a high level of intermittence, which is affected by weather, season, and geometrics. The power generated from RESs varies with time. Besides, the power demand in the power system has a time-varying pattern. Therefore, the power level of synchronous generators is affected by RESs and changes with time.

In summary, the operation of power systems is a complex problem that is dependent on massive time-varying information that comes from enormous agents in the power systems. Hence, the optimal system operation solution to enhance the transient system stability need a powerful real-time solver. Due to the massive size of power systems, a cloud-based centralized optimizer might be a possible solution to the problem. With the help of smart sensors/meters, the data from various sources can be gathered to describe the system states in real-time. The big data technology can be a possible solution to store, transfer, analyse the massive data. Other possible directions regarding getting optimal system operation solutions are data security, computational load scheduling, data encryption, etc. The fast-growing of computing technology offers many cross-disciplinary opportunities.

8.2.2 Coordinated controller in PMSG-based wind turbine

The decoupled structure in the PMSG-based wind power generation system causes the turbine-side and generator-side converters to have different functions. Typically, one converter is in charge of regulating DC-link voltage while the other one realizes the MPPT. Such an arrangement may cause a problem in the transient state. As shown in Chapter 6, the fault would cause energy to accumulate on the DC-link capacitor. Even though the capacitor is designed to tolerate temporary over-voltage, yet it is now preferable due to safety concerns. Besides, the limited rating of the capacitor means only a small amount of energy imbalance can be handled by the DC-link.

On the other hand, the wind turbine and generator data in the wind power system have large inertia that can easily cope with the power imbalance during transience. As shown in [57], the typical range for generator rotor inertia constant is 0.4-0.8s, and the one for wind turbine inertia constant is 2.0-6.0s.

To achieve the goal of utilizing the wind turbine and generator rotor as an energy source for transient response, a coordinated control should be design to achieve coupled reaction of the turbine-side controller and grid-side controller.

Similar directions can be proposed for the solar-PV system, ocean power system.

8.2.3 Inertia-less power system

In the past few decades, the following trends are observed in the power system.

- 1) Increased penetration of VSC-based RESs and energy storages.
- 2) Popularity of high voltage direct current (HVDC) transmission.
- 3) Popularity of variable frequency drives such as air-conditioning units.

The trends mentioned above have decoupled structure in common, which provides zero-inertia to the system. When the conventional energy sources continue to drop and variable renewables increase, power systems with zero inertia might appear in the future. Especially in remote/islanded areas, the application of micro-grid technologies increases the appearance probability of the zero-inertia system. The study of such systems' response in transient states is essential to ensure a reliable service level. The operating and control of such an inertia-less system would be different and full of unexplored potentials.

References

- [1] IEA, “Global Energy & CO₂ Status Report 2018,” *International Energy Agency*, 2019. <https://webstore.iea.org/global-energy-co2-status-report-2018> (accessed Jan. 01, 2020).
- [2] A. Zervos, “Renewables 2019 Global Status Report,” 2019. <https://www.ren21.net/reports/global-status-report/> (accessed Jan. 02, 2020).
- [3] M. Rampokanyo and P. Kamera, “Impact of Increased Penetration Levels of Distributed Inverter-Based Generation on Transient Stability,” in *2018 IEEE PES/IAS PowerAfrica*, 2018, pp. 573–578.
- [4] S. Wei, Y. Zhou, and Y. Huang, “Synchronous Motor-Generator Pair to Enhance Small Signal and Transient Stability of Power System With High Penetration of Renewable Energy,” *IEEE Access*, pp. 11505–11512, 2017.
- [5] P. Kundur, N. J. Balu, and M. G. Lauby, *Power System Stability and Control*. McGraw-Hill, 1994.
- [6] J. Alipoor, Y. Miura, and T. Ise, “Power System Stabilization Using Virtual Synchronous Generator With Alternating Moment of Inertia,” *IEEE J. Emerg. Sel. Top. Power Electron.*, pp. 451–458, 2015.
- [7] H. Xu, X. Zhang, F. Liu, R. Shi, C. Yu, and R. Cao, “A Reactive Power Sharing Strategy of VSG based on Virtual Capacitor Algorithm,” *IEEE Trans. Ind. Electron.*, pp. 7520–7531, 2017.
- [8] Y. Wang, B. Liu, and S. Duan, “Transient Performance Comparison of Modified VSG Controlled Grid-Tied Converter,” in *2019 IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2019, pp. 3300–

3303.

- [9] X. Zheng, Y. Liu, S. Pang, Z. Liu, Y. Li, and C. Wang, "Sliding Mode Combined VSG Control to Microgrid Inverters," in *IECON 2018 - 44th Annual Conference of the IEEE Industrial Electronics Society*, 2018, pp. 2453–2456.
- [10] D. Li, Q. Zhu, S. Lin, and X. Y. Bian, "A Self-Adaptive Inertia and Damping Combination Control of VSG to Support Frequency Stability," *IEEE Trans. Energy Convers.*, pp. 397–398, 2017.
- [11] J. Xi, H. Geng, G. Yang, and S. Ma, "Inertial Response Analysis of PMSG-Based WECS with VSG Control," *J. Eng.*, pp. 897–901, 2017.
- [12] P. Kundur *et al.*, "Definition and Classification of Power System Stability IEEE/CIGRE Joint Task Force on Stability Terms and Definitions," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1387–1401, 2004.
- [13] H. Ouyang, P. Li, L. Zhu, Y. Hao, C. Xu, and C. He, "Impact of Large-scale Wind Power Integration on Power System Transient Stability," in *IEEE PES Innovative Smart Grid Technologies*, 2012, pp. 1–6.
- [14] D. Gautam, V. Vittal, and T. Harbour, "Impact of Increased Penetration of DFIG-Based Wind Turbine Generators on Transient and Small Signal Stability of Power Systems," *IEEE Trans. Power Syst.*, pp. 1426–1434, 2009.
- [15] R. Ou, X. Xiao, Z. Zou, Y. Zhang, and Y. Wang, "Cooperative Control of SFCL and Reactive Power for Improving the Transient Voltage Stability of Grid-Connected Wind Farm With DFIGs," *IEEE Trans. Appl. Supercond.*, pp. 1–6, 2016.
- [16] Z. Liu, C. Liu, Y. Ding, and G. Li, "Transient Stability Studies of Power System with Shared Transmission of Wind Power and Thermal Power,"

- in *2nd IET Renewable Power Generation Conference (RPG 2013)*, 2013, pp. 1–4.
- [17] T. A. Taj, H. M. Hasanien, A. I. Alolah, and S. M. Mueen, “Transient Stability Enhancement of a Grid-connected Wind Garm Using an Adaptive Neuro-fuzzy Controlled-Flywheel Energy Storage System,” *IET Renew. Power Gener.*, pp. 792–800, 2015.
 - [18] S. M. Mueen, R. Takahashi, T. Murata, J. Tamura, and M. H. Ali, “Transient Stability Analysis of Permanent Magnet Variable Speed Synchronous Wind Generator,” in *2007 International Conference on Electrical Machines and Systems (ICEMS)*, 2007, pp. 288–293.
 - [19] P. Han, M. Ding, and B. Li, “Study on Transient Stability of Grid-Connected Large Scale Wind Power System,” in *The 2nd International Symposium on Power Electronics for Distributed Generation Systems*, 2010, pp. 621–625.
 - [20] D. Wang, J. L. R. Torres, A. Perilla, E. Rakhshani, P. Palensky, and M. A. A. M. van der Meijden, “Enhancement of Transient Stability in Power Systems with High Penetration Level of Wind Power Plants,” in *2019 IEEE Milan PowerTech*, 2019, pp. 1–6.
 - [21] E. Munkhchuluun, L. Meegahapola, and A. Vahidnia, “Impact on Rotor Angle Stability with High Solar-PV Generation in Power Networks,” in *2017 IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe)*, 2017, pp. 1–6.
 - [22] B. Tamimi, C. Cañizares, and K. Bhattacharya, “System Stability Impact of Large-Scale and Distributed Solar Photovoltaic Generation: The Case of Ontario, Canada,” *IEEE Trans. Sustain. Energy*, pp. 680–688, 2013.
 - [23] M. Yagami, S. Ishikawa, Y. Ichinohe, K. Misawa, and J. Tamura, “Power System Transient Stability Analysis in the Case of High-

- penetration Photovoltaics (part 2),” in *2015 IEEE Eindhoven PowerTech*, 2015, pp. 1–6.
- [24] R. K. Panda, A. Mohapatra, and S. C. Srivastava, “Impact of VSG Parameters on Transient Performance of Solar PV Based System,” in *2018 20th National Power Systems Conference (NPSC)*, 2018, pp. 1–6.
 - [25] T. Chaiyatham and I. Ngamroo, “Improvement of Power System Transient Stability by PV Farm With Fuzzy Gain Scheduling of PID Controller,” *IEEE Syst. J.*, pp. 1684–1691, 2017.
 - [26] A. Hoballah, “Power System Dynamic Behavior with Large Scale Solar Energy Integration,” in *2015 4th International Conference on Electric Power and Energy Conversion Systems (EPECS)*, 2015, pp. 1–6.
 - [27] G. Li, Y. Qi, L. Bai, T. Jin, Z. Zheng, and C. Pei, “Influences of Large Scale Wind/Solar Integration on Distribution System Transient Stability,” in *2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2)*, 2018, pp. 1–6.
 - [28] Y. Zhang, S. Zhu, R. Sparks, and I. Green, “Impacts of Solar PV Generators on Power System Stability and Voltage Performance,” in *2012 IEEE Power and Energy Society General Meeting*, 2012, pp. 1–7.
 - [29] H. H. H. Aly and M. E. El-Hawary, “Small Signal Stability Analysis of Tidal Current Turbine Using ddpmsg with and without Controller,” in *2011 IEEE Electrical Power and Energy Conference*, 2011, pp. 239–243.
 - [30] M. H. Shawon, A. Al-Durra, and S. M. Mueen, “Stability Augmentation of Interconnected Offshore Wind and Marine Current Farms,” in *IECON 2011 - 37th Annual Conference of the IEEE Industrial Electronics Society*, 2011, pp. 961–966.
 - [31] L. Wang, J. Y. Yu, and Y. T. Chen, “Dynamic Stability Improvement of

- an Integrated Offshore Wind and Marine-Current Farm Using a Flywheel Energy-Storage System,” *IET Renew. Power Gener.*, pp. 387–396, 2011.
- [32] L. Wang and C. Hsiung, “Dynamic Stability Improvement of an Integrated Grid-Connected Offshore Wind Farm and Marine-Current Farm Using a STATCOM,” *IEEE Trans. Power Syst.*, pp. 690–698, 2011.
- [33] L. Wang, S. Chen, W. Lee, and Z. Chen, “Dynamic Stability Enhancement and Power Flow Control of a Hybrid Wind and Marine-Current Farm Using SMES,” *IEEE Trans. Energy Convers.*, pp. 626–639, 2009.
- [34] N. W. Miller, “Keeping It Together: Transient Stability in a World of Wind and Solar Generation,” *IEEE Power Energy Mag.*, vol. 13, no. 6, pp. 31–39, 2015.
- [35] M. Darabian, A. Jalilvand, and M. Azari, “Power System Stability Enhancement in the Presence of Renewable Energy Resources and HVDC Lines Based on Predictive Control Strategy,” *Int. J. Electr. Power & Energy Syst.*, vol. 80, pp. 363–373, [Online]. Available: <http://dx.doi.org/10.1016/j.ijepes.2016.01.050>.
- [36] K. Schmietendorf, J. Peinke, and O. Kamps, “The Impact of Turbulent Renewable Energy Production on Power Grid Stability and Quality,” *Eur. Phys. J. B*, vol. 90, no. 11, p. 222, 2017, [Online]. Available: <https://doi.org/10.1140/epjb/e2017-80352-8>.
- [37] A. Ulbig, T. S. Borsche, and G. Andersson, “Analyzing Rotational Inertia, Grid Topology and their Role for Power System Stability,” *IFAC-PapersOnLine*, vol. 48, no. 30, pp. 541–547, 2015, [Online]. Available: <http://dx.doi.org/10.1016/j.ifacol.2015.12.436>.

- [38] G. Papaefthymiou and K. Dragoon, "Towards 100% Renewable Energy Systems: Uncapping Power System Flexibility," *Energy Policy*, vol. 92, pp. 69–82, May 2016, [Online]. Available: <http://dx.doi.org/10.1016/j.enpol.2016.01.025>.
- [39] T. Kerdphol, F. S. Rahman, and Y. Mitani, "Virtual Inertia Control Application to Enhance Frequency Stability of Interconnected Power Systems with High Renewable Energy Penetration," *Energies*, vol. 11, no. 4, 2018, [Online]. Available: <http://dx.doi.org/10.3390/en11040981>.
- [40] D. Remon, A. M. Cantarellas, J. M. Mauricio, and P. Rodriguez, "Power System Stability Snalysis under Increasing Penetration of Photovoltaic Power Plants with Synchronous Power Controllers," *IET Renew. Power Gener.*, vol. 11, no. 6, pp. 733–741, May 2017, [Online]. Available: <http://dx.doi.org/10.1049/iet-rpg.2016.0904>.
- [41] P. N. Papadopoulos and J. V Milanovic, "Probabilistic Framework for Transient Stability Assessment of Power Systems with High Penetration of Renewable Generation," *IEEE Trans. Power Syst.*, vol. 32, no. 4, pp. 3078–3088, Jul. 2017, [Online]. Available: <http://dx.doi.org/10.1109/TPWRS.2016.2630799>.
- [42] A. Ghosh, R. Patel, M. Datta, and L. Meegahapola, "Investigation of Transient Stability of a Power Network with Solar-PV Generation: Impact of Loading Level & Control Strategy," in *2017 IEEE Innovative Smart Grid Technologies - Asia (ISGT-Asia)*, 2017, pp. 1–6.
- [43] B. Wen, D. Dong, D. Boroyevich, R. Burgos, P. Mattavelli, and Z. Shen, "Impedance-Based Analysis of Grid-Synchronization Stability for Three-Phase Paralleled Converters," *IEEE Trans. Power Electron.*, vol. 31, no. 1, pp. 26–38, 2016.
- [44] F. H. Gandoman *et al.*, "Review of FACTS Technologies and Applications for Power Quality in Smart Grids with Renewable Energy

- Systems,” *Renew. Sustain. Energy Rev.*, vol. 82, pp. 502–514, 2018, [Online]. Available: <http://dx.doi.org/10.1016/j.rser.2017.09.062>.
- [45] G. Rashid and M. H. Ali, “Transient Stability Enhancement of Doubly Fed Induction Machine-Based Wind Generator by Bridge-Type Fault Current Limiter,” *IEEE Trans. Energy Convers.*, pp. 939–947, 2015.
- [46] S. M. Mueen, “A Combined Approach of Using an SDBR and a STATCOM to Enhance the Stability of a Wind Farm,” *IEEE Syst. J.*, pp. 922–932, 2015.
- [47] H. Jiang and C. Zhang, “A Method of Boosting Transient Stability of Wind Farm Connected Power System Using S Magnetic Energy Storage Unit,” *IEEE Trans. Appl. Supercond.*, pp. 1–5, 2019.
- [48] S. M. Mueen, R. Takahashi, M. H. Ali, T. Murata, and J. Tamura, “Transient Stability Augmentation of Power System Including Wind Farms by Using ECS,” *IEEE Trans. Power Syst.*, pp. 1179–1187, 2008.
- [49] C. A. Hill, M. C. Such, D. Chen, J. Gonzalez, and W. M. Grady, “Battery Energy Storage for Enabling Integration of Distributed Solar Power Generation,” *IEEE Trans. Smart Grid*, pp. 850–857, 2012.
- [50] Q. Zhong, “Four-quadrant Operation of AC Machines Powered by Inverters that Mimic Synchronous Generators,” in *5th IET International Conference on Power Electronics, Machines and Drives (PEMD 2010)*, 2010, pp. 1–6.
- [51] Q. Zhong and G. Weiss, “Synchronverters: Inverters That Mimic Synchronous Generators,” *IEEE Trans. Ind. Electron.*, pp. 1259–1267, 2011.
- [52] N. Soni, S. Doolla, and M. C. Chandorkar, “Improvement of Transient Response in Microgrids Using Virtual Inertia,” *IEEE Trans. Power Deliv.*, pp. 1830–1838, 2013.

- [53] J. Liu, Y. Miura, and T. Ise, "Comparison of Dynamic Characteristics Between Virtual Synchronous Generator and Droop Control in Inverter-Based Distributed Generators," *IEEE Trans. Power Electron.*, pp. 3600–3611, 2016.
- [54] V. Nelson, *Wind Energy: Renewable Energy and the Environment*, 3rd ed. CRC Press, 2018.
- [55] C. C. Pavel *et al.*, "Substitution Strategies for Reducing the Use of Rare Earths in Wind Turbines," *Resour. Policy*, vol. 52, pp. 349–357, 2017, [Online]. Available: <http://www.sciencedirect.com/science/article/pii/S0301420717300077>.
- [56] L. A. Roberto and S. G. Javier, "2014 JRC Wind Status Report," *Publ. Off. Eur. Union*, 2015.
- [57] T. Ackermann, *Wind Power in Power Systems*, 2nd ed. Wiley, 2012.
- [58] C. R. S. Junior and F. K. A. Lima, "Wind Turbine and PMSG Dynamic Modelling in PSIM," *IEEE Lat. Am. Trans.*, pp. 4115–4120, 2016.
- [59] C. Wei, Z. Zhang, W. Qiao, and L. Qu, "An Adaptive Network-Based Reinforcement Learning Method for MPPT Control of PMSG Wind Energy Conversion Systems," *IEEE Trans. Power Electron.*, pp. 7837–7848, 2016.
- [60] B. Boukhezzar and H. Siguerdidjane, "Nonlinear Control of a Variable-Speed Wind Turbine Using a Two-Mass Model," *IEEE Trans. Energy Convers.*, vol. 26, no. 1, pp. 149–162, 2011.
- [61] V. Morteza pour, H. Lesani, and A. Abbaszadeh, "Stator Transient Current of DFIG - Influence of Two-mass Model and Leakage Flux Saturation," in *2009 International Conference on Electric Power and Energy Conversion Systems, (EPECS)*, 2009, pp. 1–6.
- [62] A. Gaidi, H. Lehouche, S. Belkacemi, S. Tahraoui, M. Loucif, and O.

- Guenounou, “Adaptive Backstepping Control of Wind Turbine Two Mass Model,” in *2017 6th International Conference on Systems and Control (ICSC)*, 2017, pp. 168–172.
- [63] O. Ibrahim, N. Z. Yahaya, N. Saad, and M. W. Umar, “Matlab/Simulink Model of Solar PV Array with Perturb and Observe MPPT for Maximising PV Array Efficiency,” in *2015 IEEE Conference on Energy Conversion (CENCON)*, 2015, pp. 254–258.
- [64] D. O. Raymond Alcorn, *Electrical Design for Ocean Wave and Tidal Energy Systems*. The Institution of Engineering and Technology, London, United Kingdom, 2013.
- [65] R.H. Charlier; C.W. Finkl, *Ocean Energy Tide and Tidal Power*. Springer-Verlag Berlin Heidelberg 2009, 2009.
- [66] Á. Ortega and F. Milano, “Generalized Model of VSC-Based Energy Storage Systems for Transient Stability Analysis,” *IEEE Trans. Power Syst.*, vol. 31, no. 5, pp. 3369–3380, 2016.
- [67] F. A. Inthamoussou, J. Pegueroles-Queralt, and F. D. Bianchi, “Control of a Supercapacitor Energy Storage System for Microgrid Applications,” *IEEE Trans. Energy Convers.*, vol. 28, no. 3, pp. 690–697, [Online]. Available: <http://dx.doi.org/10.1109/TEC.2013.2260752>.
- [68] S. Sabihuddin, A. E. Kiprakis, and M. Mueller, “A Numerical and Graphical Review of Energy Storage Technologies,” *Energies*, vol. 8, no. 1, pp. 172–216, Jan. 2015, [Online]. Available: <http://dx.doi.org/10.3390/en8010172>.
- [69] G. S. Ghfarokhi, M. Arezoomand, and H. Mahmoodian, “Analysis and Simulation of the Single-machine Infinite-bus with Power System Stabilizer and Parameters Variation Effects,” in *2007 International Conference on Intelligent and Advanced Systems*, 2007, pp. 167–171.

- [70] B. Wu and O. Malik, "Multivariable Adaptive Control of Synchronous Machine," 2006.
- [71] C. Zhu, R. Zhou, and Y. Wang, "A New Decentralized Nonlinear Voltage Controller for Multimachine Power Systems," *IEEE Trans. Power Syst.*, pp. 211–216, 1998.
- [72] Y. Wang and G. Guo, "Robust Nonlinear Controller with Voltage Regulation," *Dianli Xitong Zidonghua/Automation Electr. Power Syst.*, pp. 23–29, 2001.
- [73] Y. Wang, Y. L. Tan, and G. Guo, "Robust Nonlinear Coordinated Excitation and SVC Control for Power Systems," 1998, pp. 415–420.
- [74] Y. Wang, L. Xie, and C. E. de Souza, "Robust Control of a Class of Uncertain Nonlinear Systems," *Syst. Control Lett.*, pp. 139–149, 1992, [Online]. Available: [http://dx.doi.org/10.1016/0167-6911\(92\)90097-C](http://dx.doi.org/10.1016/0167-6911(92)90097-C).
- [75] Y. Wang, D. J. Hill, and G. Guo, "Robust Decentralized Control for Multimachine Power Systems," *IEEE Trans. Circuits Syst. I Fundam. Theory Appl.*, pp. 271–279, 1998.
- [76] P. M. Anderson and A. A. Fouad, *Power System Control and Stability*. IEEE Press, 2003.
- [77] Y. Wang, D. J. Hill, and R. H. Middleton, "Adaptive Direct Feedback Linearization of Nonlinear Oscillatory Systems," in *1991 Proceedings of the 30th IEEE Conference on Decision and Control*, 1991, pp. 1106–1107.
- [78] G. Zhang, "Global Control Design and its Applications to Power Systems," Nanyang Technological University, Ph.D. Thesis, 2007.
- [79] Y. Wang, G. Guo, D. J. Hill, and L. Gao, "Nonlinear Decentralized Control for Multimachine Power System Transient Stability Enhancement," 1995, pp. 435–440.

- [80] Y. Wang, G. Guo, and D. J. Hill, "Robust Decentralized Nonlinear Controller Design for Multimachine Power Systems," *Automatica*, pp. 1725–1733, 1997, [Online]. Available: [http://dx.doi.org/10.1016/S0005-1098\(97\)00091-5](http://dx.doi.org/10.1016/S0005-1098(97)00091-5).
- [81] Vishay, "Power Electronic Capacitors-Documents 13017," *Vishay*, 2019. <http://www.vishay.com/docs/13017/gentechinfopec.pdf> (accessed Jan. 03, 2020).
- [82] Electronics TDK, "Disc Type Capacitors with Lead (High Voltage Ceramic Capacitors)," *Electronics TDK*, 2017. <https://product.tdk.com/info/en/products/capacitor/ceramic/lead-disc/catalog.html>. (accessed Jan. 03, 2020).
- [83] H. Jiang and Y. Wang, "Transient Stability Enhancement for Power Systems with Increasing Penetration of Renewable Energy Sources," *IET Gener. Transm. Distrib.*, p. Under Review.
- [84] L. Wu and D. G. Infield, "Towards an Assessment of Power System Frequency Support From Wind Plant-Modeling Aggregate Inertial Response," *IEEE Trans. Power Syst.*, pp. 2283–2291, 2013.
- [85] R. Piwko, N. Miller, J. Sanchez-Gasca, X. Yuan, R. Dai, and J. Lyons, "Integrating Large Wind Farms into Weak Power Grids with Long Transmission Lines," *Gastrointest. Endosc. - GASTROINTEST Endosc.*, pp. 1–7, Feb. 2005.
- [86] S. Sang, C. Zhang, X. Cai, M. Molinas, J. Zhang, and F. Rao, "Control of a Type-IV Wind Turbine With the Capability of Robust Grid-Synchronization and Inertial Response for Weak Grid Stable Operation," *IEEE Access*, pp. 58553–58569, 2019.
- [87] M. Rasmussen and H. K. Jorgensen, "Current Technology for Integrating Wind Farms into Weak Power Grids," in *2005 IEEE/PES*

Transmission & Distribution Conference & Exposition: Asia and Pacific, 2005, pp. 1–4.

- [88] W. Contributors, “Gansu Wind Farm,” *Wikipedia, The Free Encyclopedia*, 2019. https://en.wikipedia.org/w/index.php?title=Gansu_Wind_Farm&oldid=920265706 (accessed Jan. 01, 2020).