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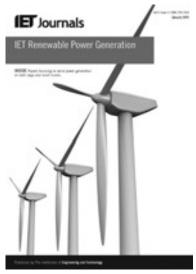

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Renewable energy sources and frequency regulation: survey and new perspectives

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Abstract: As the use of renewable energy sources (RESs) increases worldwide, there is a rising interest on their impacts on power system operation and control. An overview of the key issues and new challenges on frequency regulation concerning the integration of renewable energy units into the power systems is presented. Following a brief survey on the existing challenges and recent developments, the impact of power fluctuation produced by variable renewable sources (such as wind and solar units) on system frequency performance is also presented. An updated LFC model is introduced, and power system frequency response in the presence of RESs and associated issues is analysed. The need for the revising of frequency performance standards is emphasised. Finally, non-linear time-domain simulations on the standard 39-bus and 24-bus test systems show that the simulated results agree with those predicted analytically.

1 Introduction

The increasing need for electrical energy in the 21st century, as well as limited fossil fuel reserves and the increasing concerns with environmental issues for the reduction of carbon dioxide (CO_2) and other greenhouse gasses [1], call for fast development in the area of renewable energy sources (RESs). Renewable energy is derived from natural sources such as the sun, wind, hydro power, biomass, geothermal, and oceans and fuel cells.

Limiting green house gas emissions, avoidance of the construction of new transmission circuits and large generating units, diversification of energy sources to enhance energy security, quality and reliability, and support for competition policy are some important drivers in environmental, commercial and national/regulatory aspects behind the growth of RESs [2].

Recent studies have found that the renewable integration impacts are non-zero and become more significant at higher size of penetrations. Some studies represent a range of estimates based on different system characteristics, penetration levels and study methods. However, a common thread of all methods was the focus on RESs effects on the interconnected power system, rather than in an isolated one.

The RESs affect the dynamic behaviour of the power system in a way that might be different from conventional generators. Conventional power plants mainly use synchronous generators that are able to continue operation during significant transient faults. If a large amount of wind generation is tripped because of a fault, the negative effect of that fault on power system control and operation, including frequency control issue, could be magnified [3]. High renewable energy penetration in power systems may increase uncertainties during abnormal operation and introduces several technical implications and opens important questions, as to whether the traditional power system control approaches to operation in the new environment are still adequate.

Integration of RESs into power system grids have impacts on optimum power flow, power quality, voltage and frequency control, system economics and load dispatch. Regarding the nature of RESs power variation, the impact on the frequency regulation issue has attracted increasing research interest, during the last decade. Significant interconnection frequency deviations can cause under/over frequency relaying and disconnect some loads and generations. Under unfavourable conditions, this may result in a cascading failure and system collapse [4].

This paper covers the issues concerning the integration of new renewable power generation in power systems with the frequency regulation perspective. The paper is organised as follows: An overview on present worldwide RES status and new technical challenges following a high RESs penetration is presented in Section 2. A review on recent developments in frequency regulation area is given in Section 3. Section 4 introduces a generalised load-frequency control (LFC) model, and gives an analytical description of the system frequency response for the new configuration. A discussion on the required supplementary reserve and need to re-examination of existing frequency performance standards is described in Section 5. A simulation study on the IEEE 39-bus and 24-bus test systems is presented in Section 6. Finally, main research needs and a scope for further work are addressed in Section 7.

2 RESs: present status and technical challenges

2.1 Present status and future prediction of RES worldwide

The power system architecture of the future incorporating RESs will look very different from what it is today. The RESs revolution has already commenced in many countries, as evidenced by the growth of RESs in response to the climate change challenge and the need to enhance fuel diversity. Renewable energy currently provides more than 14% of the world's energy supply [5].

Currently, wind is the most widely utilised renewable energy technology in power systems, and its global production is predicted to grow to 300 GW in 2015 [6]. It has been predicted that wind power global penetration will reach 8% by 2020, about 400 GW installed worldwide [7]. In terms of economic value, the global wind market in 2007 was worth about 25 billion EUR or 36 billion US$ in new generating equipment [8].

2.2 Europe

The European Union (EU) has set as a target 12% of electricity supplied by renewable generation by 2010. According to a recent directive of the European parliament [9], this is translated to an electricity production of 22.1% from RESs. It is predicted that 20% of the overall electricity consumption will be supplied from renewable sources by 2020 [7].

Since 2000, the EU has installed 47 000 MW wind energy; 3100 MW hydro; and 1700 MW biomass power capacity during the 8-year period [10]. According to the European Wind Energy Association, European wind power capacity is expected to be more than 180 GW in 2020 [11].

2.3 United States

The US Department of Energy has announced a goal of obtaining 6% of US electricity only from wind by 2020; a goal that is consistent with the current growth rate of wind energy nationwide [12]. Overall US wind power generating capacity grew by 45% in 2007, with total installed capacity now standing at 16.8 GW. It can be expected that the United States will overtake Germany as the leader in wind energy by the end of 2009 [8].

2.4 Asia and pacific region

Numerous works on solar (PV) energy, batteries and energy capacitor units are being performed in Japan [13–15]. The Japan has set an ambitious target of 4.5 GW of electricity to be generated by PV systems by the year 2010 [14]. The growing wind power market in Asian countries is also impressive. Japan installed 1538 MW of wind energy capacity at the end of 2007 [16]. China has added more than 5000 MW of wind energy capacity during 2007. Based on current growth rates, the Chinese Renewable Energy Industry Association forecasts a capacity of around 50 000 MW by 2015 [8]. India also continues to see a steady growth and now has about 8 GW of wind power installations, up from just over 6.2 GW in 2006. In Korea, RES is gradually growing per year and the government plans to replace 5% of the conventional energy source by the year 2011 [7].

After some slow years, the Pacific market gained new impetus in 2007, especially in New Zealand, where 151 MW were installed in 2007. In Australia, the newly elected Labour government has ratified the Kyoto Protocol and pledged to introduce a 20% target for renewable energy by 2020 [8].

2.5 Middle East, North Africa and Latin America

Although Europe, North America, Asia and Pacific region continue having the largest additions to their RES capacity, the Middle East, North Africa and Latin America increased its wind power installations by about 50% at the end of 2007. New capacity was mostly added in Iran, Egypt, Morocco, Tunisia and Brazil [8].

2.6 New technical challenges

The technical issues associated with renewable energy compatibility relate to the ability of renewable energy equipment to function effectively as part of the electricity industry as it exists today. There may also be technical means at the system level to reduce the variability of the aggregated output from RES units. The RES units must meet technical requirements with respect to voltage, frequency, ability to rapidly isolate faulty parts from the rest to the network, and have a reasonable ability to withstand abnormal system operating conditions. With the increasing trend of connecting high penetrations of wind energy conversion systems to the transmission networks comes the challenge of updating the grid code for the connection of high-capacity RESs. However, the novel nature of some RES technologies, such as wind turbines and photovoltaic systems, leads to uncertainties in their technical performance, particularly during abnormal power system operating conditions when power system security may be at risk. It also leads to challenges in developing mathematical models that can adequately predict power system behaviour with high renewable energy penetration.

High RESs penetration increases the risk of tie-line overloading. A large RES such as a wind farm that is located away from major load centres and existing conventional generation units may require network augmentation, and possibly additional interconnections to avoid flow constraints. A sudden reduction in a large RESs power production, not properly forecasted, may also lead to overload problems in interconnection lines, which will be required in the future the development of new control schemes and performance monitoring tools to identify, in advance, the expected behaviour of the system regarding such incidents.

Among all RESs, the progress in wind power development in recent years is impressive. Considerable developments have been recently made on the technological front, and in the above respect, the development of micro-turbines and novel energy storage technologies is potentially the most challenging. However, there are still unresolved issues for wind energy integration, particularly in the area of forecasting and in the general enhancement of frequency regulation. The variable and non-storable nature of key renewable energy forms, such as wind and solar energy, leads to a need for the accurate forecasting of resource availability and consequent electricity production [5].

The important impacts of a large penetration of variable generation in power system operation and control can be summarised in the following directions: regional overloading of transmission lines in normal operation as well as in emergency conditions, reduction of available tie-line capacities due to large load flows, frequency performance, increasing need for balance power and reserve capacity, increasing power system losses, increasing reactive power compensation, and impact on system security and economic issues [11]. Of course, well-designed wind plants do not have all of above negative impacts on the power system.

Here, the issues concerning the integration of new renewable power generation (particularly from wind power) in power systems with the frequency regulation problem are discussed. The recent investigation studies indicate that relatively large-scale wind generation will have an impact on power system frequency regulation as well as other operation issues and costs; however, these impacts in many countries are relatively low at penetration rates that are expected over the next several years [17]. Increasing wind power generation may in the future leads to a higher frequency deviation. With increasing wind power the frequency deviation rate following a disturbance will be increased [18, 19].

3 Recent developments on the RES and frequency regulation

This section presents a brief critical literature review and an up-to-date bibliography for the proposed studies on the frequency regulation in the presence of RESs and associated issues. A considerable part of attempts has focused on wind power generation units.

3.1 Impact analysis and primary frequency control

Integrating energy storage systems (ESSs) or energy capacitor systems (ECSs) into the wind energy system to diminish the wind power impact on power system frequency has been addressed in several reported works [20–24]. In [20], an ESS-based wind power filtering algorithm is proposed. It is shown that power systems are more sensitive to the power fluctuations in the medium frequency region (between 0.01 and 1 Hz), in which the majority of wind power fluctuations are located and below. In [22–24], different ESSs by means of an electric double-layer capacitor and superconducting magnetic energy storage and energy saving are proposed for wind power levelling.

The impact of wind generation on the operation and development of the UK electricity systems is described in [25]. Impacts of wind power components and variations on power system frequency control are described in [26, 27]. Using the kinetic ESS (blade and machine inertia) to participate in primary frequency control is addressed in [28]. Frequency regulation impacts are defined to be those impacts that occur on the basis of a few seconds to minutes. Therefore, when comparing different wind integration studies, it is important to adopt a clear definition of the time scales involved.

The technology to filter out the power fluctuations (in result frequency deviation) by wind turbine generators for the increasing amount of wind power penetration is growing. The new generation of variable-speed, large wind turbine generators with high moments of inertia from their long turbine blades can filter power fluctuations in the wind farms. A method is presented in [28] to let variable-speed wind turbines emulate inertia and support primary frequency control.

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A method of quantifying wind penetration based on the amount of fluctuating power that can be filtered by wind turbine generation and thermal plants is addressed in [29]. A small power system including three thermal units (equipped with LFC system) and a wind farm is considered as a test example. Using the Bode diagram of system transfer function between frequency deviation and real power fluctuation signals, the permitted power fluctuation for 1% frequency deviation is approximated.

To ensure a regular primary reserve even when the wind generator works under rated power, without any wind speed measurement, a fuzzy logic supervisor is proposed in [30]. This supervisor is used to simultaneously control the generator torque and the pitch angle to keep a primary reserve.

Using modal techniques, the dynamic influence of wind power on the primary frequency control is studied in [31]. This study shows that the wind turbines excite the power system in the electromechanical modes. An increase in the wind power leads to an increase in the frequency because the load on synchronous machines is reduced and the speed drop characteristics of the speed governors lead to an operational frequency slightly above the rated. Similarly, a reduction in the wind power leads to a decrease in the frequency.

Some preliminary studies showed that the kinetic energy stored in the rotating mass of a wind turbine can be used to support primary frequency control for a short period of time [28]. The capability of providing a short-term active power support of a wind farm to improve the primary frequency control performance is discussed in [32]. To support primary frequency control for a longer period, some techniques such as using a combination of wind and fuel cell energies are suggested [33, 34]. The amount of installed fuel cell energy capacity needed to compensate frequency deviation is discussed in [33].

3.2 Supplementary frequency control and required reserve

Some recent studies analyse the impacts of RESs on power market operation and supplementary frequency control [5, 17, 20–23, 27, 35–40]. Some of those are reviewed in [17]. A study is conducted in [38] to help determine how wind generation might interact in the competitive wholesale market for regulation services and a real-time balancing market. This study recognised that wind integration does not require that each deviation in wind power output be matched by a corresponding and opposite deviation in other resources, and the frequency performance requirement must apply to the aggregated system, not to each individual generator. Several works are reported on considering the effect of wind power fluctuation on LFC structure [20–24, 27]. An automatic generation control system for a wind farm with variable speed turbines is addressed in [36]. The proposed integrated control system includes two control levels (supervisory system and machine control system). A distributed control system for frequency control in an isolated wind system is given in [37].

A year of actual wind speed data and hourly load data for a region is used to determine the optimal sizes and locations of local power plants in [39]. This analysis has focused on the impact of wind plants on hourly system imbalance, and physical requirements that wind would impose on the electrical supply. An electrolyser system with a fuzzy PI control is used in [41] to solve power quality issues resulting from micro-grid frequency fluctuations.

The impacts of wind power on tie-line power flow in the form of low frequency oscillations due to insufficient system damping are studied in [42, 43]. A control scheme based on controllable distributed generators is addressed in [44] to attenuate the mentioned tie-line flow deviation.

While the amount of generation to participate in the LFC task to compensate the additional variation will grow, the rising RES market share will reduce the amount of generation that is actually capable of providing frequency support. To overcome the above problem, several approaches have been proposed. A demand-based frequency control idea is presented in [45] to provide frequency control support where conventional LFC reserve is not enough or unavailable.

The influence of PV system on power system frequency control is discussed in [15]. Using redox flow (RF) batteries for supplementary control and maintenance of power quality in the presence of distributed power resources is suggested in [13]. It is shown that the LFC capacity of RF battery systems is ten times that of fossil power systems, due to quick response characteristics.

Owing to the unpredictable amount of RES power available at any instant, such as solar and wind units, these powers cannot be regarded as a main power reserve for frequency regulation purposes. The function of the kinetic energy storage of wind turbine generators is only to make up for the deficient power in the few seconds when the existing generator units in the supplementary frequency control loop are too slow to provide.

Recent studies show that the operational impacts of individual fast fluctuations are largely absorbed by the large mechanical and thermal time constants as well as control dead bands of conventional thermal units [26]. In steady-state operation, assuming that the total RES production level can be defined as P_{RES} and total consumption level in P_L, the amount of power to be produced by the conventional units (P_G) is

$$P_G = P_L + P_{Losses} - P_{RES} \quad (1)$$

This means that the steady-state impacts are largely dependent on the final dispatch solution to be adopted. However, the variable renewable electricity output may or may not be available during peak demand and abnormal periods. It might be that intermittent resources cannot contribute to the overall system frequency regulation and reliability. For power systems with small amounts of RESs, the additional variation from RESs is small. However, for a large RESs penetration, the conventional LFC reserve may be insufficient to maintain frequency within the bounds for service quality.

Recently, several studies have been conducted on the required LFC reserve estimation in the presence of various RES units. A mathematical model to evaluate the impact of small PV power generating stations on economic and performance factors for a large-scale power system is developed in [14]. Using multi-point observation data, the required LFC capacity for the output fluctuation of PV systems is estimated in [15].

It was found that wind power, combined with the varying load, does not impose major extra variations on the system until a substantial penetration is reached [46]. Large geographical spreading of wind power will reduce variability, increase predictability and decrease the occasions with near zero or peak output. It is investigated in [46] that the power fluctuation from geographically dispersed wind farms will be uncorrelated with each other, hence for smoothing the total power, too large additional frequency regulation reserve is not required.

It is estimated in [25] that for a 10 GW installed wind capacity (in UK power system), 126–192 MW additional continuous conventional LFC power is required. According to a study for Denmark and Germany [47], the supplementary control must provide 6.6 MW per minute of additional capacity per 1000 MW of installed wind power to keep the nominal frequency. Usually, the demand on supplementary control is specified by the wind power production forecast error. That is, the difference between the forecast and the actual power productions.

The fluctuation of the aggregated wind power output in a short term (e.g. tens of seconds) for a larger number of wind turbines are much smoothed. It is investigated that the wind turbines aggregation has positive effects on the regulation requirement. Relative regulation requirement decreases whenever larger aggregations are considered. Based on a record [48], a 202 MW wind plant would have required 18.2 MW of regulation, if it had to compensate for its variability independently, but would require only 9.4 MWh when integrated into the control area (48% reduction).

3.3 Emergency frequency control

There are few reports on the role of distributed RESs in emergency conditions. The impact of distributed utilities on transmission stability is addressed in [49], and an optimal load shedding strategy for power systems with distributed sources is introduced in [50]. The need for re-tuning of automatic under frequency load shedding df/dt relays is emphasised in [51, 52]. The system performance and frequency stability during a severe short-circuit and after a sudden loss of generation is discussed in [53].

IEEE 1547 [54] considers small RES unit having less impact on system operation, but large RES unit can have an impact on distribution system safety. This requirement is taken into account by allowing the network operator to specify the frequency setting and time delay for under frequency trips. When frequency is out of the given protection range [55], the RES unit shall cease to energise the area power system within the clearing time as indicated. The clearing time is the period elapsed between the start of the abnormal condition and the RES ceasing to energise the power system.

Curtailing the megawatt (MW) output of wind generation is another method to restore the system frequency in emergency conditions. As wind penetration levels increase, the amount of curtailment and frequency of curtailment will increase. When wind generation levels are a high percentage of system demand, when the output from wind generators will differ significantly from the forecast output because of sudden unpredicted changes in weather patterns and in case of simultaneous losing of a number of transmission lines, it may be necessary to curtail wind generation in order to manage the power system [56].

3.4 On electronically coupled distributed RES systems

Many of the RESs such as PV and fuel cells use a power electronic converter (inverter) for grid interfacing. Some wind applications as well as some synchronous machines and micro-turbines are utilising power electronic devices for grid interface as the benefits of the electronic interface justifies the additional cost and complexity [57].

Power electronic inverters are capable of converting the energy from a variety of sources such as variable frequency (wind), high frequency (turbines) and direct energy (PV and fuel cells) [58]. Inverter-based distributed RESs are generally considered low power by utility standards from 1 kW up to a few MW. Generators connected to renewable sources are not reliable and thus are not considered dispatchable by the utility and thus are not tightly integrated into the power supply system. The inverter interface decouples the generation source from the distribution network.

Since inverters monitor the frequency at their output terminals for control purposes, it is easy to detect when the inverter frequency shifts outside a window centred around the nominal frequency set point. Consideration still needs

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to be given to the case when a balanced load condition exists and frequency shift may be small or non-existent after the utility is no longer present. Since the inertia of the electronically coupled RESs is typically small to maintain the frequency of the system in the case of large load fluctuations, fluctuations will be damped at a high speed by other control units such as the battery inverter control system [59].

Nowadays, many researchers are actively working on the existing challenges on the use of electronically coupled distributed RESs, specifically on the frequency (and voltage) control of an islanded microgrid under balanced and unbalanced conditions. Several valuable research works on modelling, analysis and control of electronically coupled distributed RESs have been reported [60–65]. In some reports, in order to enhance the dynamic response against the large and/or fast load changes, the load dynamics are directly incorporated in the designed control loop [63].

3.5 Inertia response

The variable speed wind turbines such as doubly fed induction generators (DFIG) effectively decouple the rotor of the turbine blades from the rotor of the electric generator through the use of a power electronics converter. It has the significant disadvantage of not being able to utilise the inertia of the blades; thus, limiting the ability of the speed wind turbines to provide active frequency support in a power system during a loss of generation event. It has been shown that through the use of a supplementary controller, inertia can be emulated from the DFIG wind turbine [27, 66–68]. It is also found that the inertia response of a DFIG employing field-oriented control is strongly influenced by the rotor current-control bandwidth [67]. Therefore the increasing penetration of electronically coupled distributed RESs such as variable speed wind turbines leads to a reduction of inertia in the grid [66].

On the other hand, in the fixed speed generators (FSGs), the rotor of the turbine blades is coupled to the rotor of the electric machine through a gearbox. This design allows the turbine to utilise the kinetic energy stored in the turbine blade, and contribute to system frequency stability by providing a level of spinning inertia.

Variable speed wind turbines can provide the necessary voltage support and FSGs can provide frequency support to maintain system stability. It is found that by controlling the ratio of penetration between the two types of turbines, the voltage and frequency characteristics can be improved [69].

4 Generalised LFC model considering RES impacts

4.1 Generalised LFC model

When renewable power plants are introduced into the power system, an additional source of variation is added to the already variable nature of the system. To analyse the additional variation caused by RES units, the total effect is important, and every change in RES power output does not need to be matched one for one by a change in another generating unit moving in the opposite direction. Instantaneous fluctuations in load and RES power output might amplify each other, might be completely unrelated to each other, or may cancel each other out [70]. However, the slow RES power fluctuation dynamics and total average power variation negatively contribute to the power imbalance and frequency deviation, which should be taken into account in the LFC control scheme. This power fluctuation must be included in the conventional LFC structure.

A generalised LFC model in the presence of RES is shown in Fig. 1 [51]. Here, to cover the variety of generation types in the control area, different values for turbine governor

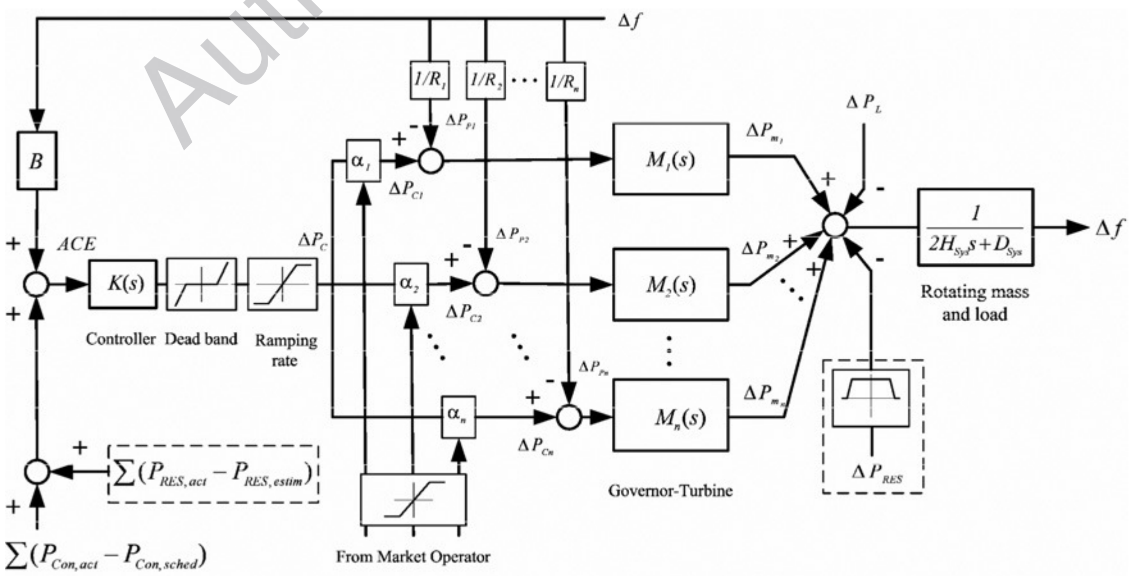

Figure 1 *LFC model with considering RES power fluctuation*

parameters and the generator regulation parameters are considered. Fig. 1 shows the block diagram of typical control area with n generator units. The shown blocks and parameters are defined as follows: Δf is the frequency deviation, ΔP_{m} is the mechanical power, ΔP_{C} is the supplementary control action, ΔP_{L} is the load disturbance, H_{Sys} is the equivalent inertia constant, D_{Sys} is the equivalent damping coefficient, B is the frequency bias, R_i is the drooping characteristic, ΔP_{P} is the primary control, α_i is the participation factors, ΔP_{RES} is the RES power fluctuation, $K(s)$ is the LFC controller and $M_i(s)$ is the governor-turbine model.

Following a load disturbance within the control area, the frequency of the area experiences a transient change and the feedback mechanism generates appropriate rise or lower signal to the participating generator units according to their participation factors α_i to make generation follow the load. In the steady state, the generation is matched with the load, driving the tie-line power and frequency deviations to zero. As there are many conventional generators in each area, the control signal has to be distributed among them in proportion to their participation.

As shown in Fig. 1, the frequency performance of a control area is represented approximately by a lumped load generation model using equivalent frequency, inertia and damping factors [71]. Because of range of use and specific dynamic characteristics such as a considerable amount of kinetic energy, the wind units are more important than the other RESs. The equivalent system inertia can be defined as

$$H_{\mathrm{sys}} = H_{\mathrm{C}} + H_{\mathrm{W}} = \sum_{i=1}^{N1} H_{\mathrm{C}i} + \sum_{i=1}^{N2} H_{\mathrm{W}i} \tag{2}$$

The H_{C} and H_{W} are the total inertia constants due to conventional and wind turbine generators, respectively. The inertia constant for wind power is time dependent. The typical inertia constant for the wind turbines is about two to six seconds [72].

As mentioned, wind turbines have a significant amount of kinetic energy stored in the rotating mass of their blades. It is noteworthy that modern wind plants can have active control that presents as much inertia to the power system as desired if this is specified in the design. Depending on the type of generator units, typical inertia constants for the grid power generators are in the range of 2–9 s [73].

In Fig. 1, the filtered total effect of power fluctuation ΔP_{RES} is considered. For a large RESs penetration, the resulting ACE signal must reflect the total RESs power generation changes that is usually smoothed compared to variations from the individual RES units.

$$\begin{aligned} \mathrm{ACE} = \beta\Delta f &+ \sum (P_{\mathrm{Con,act}} - P_{\mathrm{Con,sched}}) \\ &+ \sum (P_{\mathrm{RES,act}} - P_{\mathrm{RES,estim}}) \end{aligned} \tag{3}$$

where $P_{\mathrm{Con,act}}$, $P_{\mathrm{Con,sched}}$, $P_{\mathrm{RES,act}}$ and $P_{\mathrm{RES,estim}}$ are actual conventional power, scheduled conventional power, actual RESs power and estimated RESs power, respectively.

In typical LFC implementations, the system frequency gradient and ACE signal must be filtered to remove noise effects before use. The ACE signal then is often applied to a proportional integral (PI) control block [74, 75]. Control dead band and ramping rate are different for various systems [51, 76]. The control can send higher/lower pulses to generating plants if its ACE signal exceeds a standard limit.

4.2 Frequency response analysis

Considering the effect of primary and supplementary controls in Fig. 1, the system frequency can be obtained as [51]

$$\Delta f(s) = \frac{1}{2H_{\mathrm{Sys}}s + D_{\mathrm{Sys}}} \left[\sum_{k=1}^{n} \Delta P_{\mathrm{m}_k}(s) - \Delta P_{\mathrm{RES}}(s) - \Delta P_{\mathrm{L}}(s) \right] \tag{4}$$

where

$$\Delta P_{\mathrm{m}_k}(s) = M_k(s)[\Delta P_{\mathrm{C}_k}(s) - \Delta P_{\mathrm{P}_k}(s)] \tag{5}$$

and

$$\Delta P_{\mathrm{P}_k}(s) = \frac{\Delta f(s)}{R_k} \tag{6}$$

Here, it is assumed that the ΔP_{L} in addition to the area load disturbance includes the impacts of tie-line power deviation. The ΔP_{P} and ΔP_{C} are primary (governor natural response) and supplementary (LFC) control actions. Expressions (5) and (6) can be substituted into (4) with the result

$$\begin{aligned} \Delta f(s) = \frac{1}{2H_{\mathrm{Sys}}s + D_{\mathrm{Sys}}} \Bigg(&\sum_{k=1}^{n} M_k(s)\left[\Delta P_{\mathrm{C}_k}(s) - \frac{1}{R_k}\Delta f(s)\right] \\ &- \Delta P_{\mathrm{RES}}(s) - \Delta P_{\mathrm{L}}(s) \Bigg) \end{aligned} \tag{7}$$

For the sake of load disturbance analysis we are usually interested in $\Delta P_{\mathrm{L}}(s)$ in the form of a step function, that is

$$\Delta P_{\mathrm{L}}(s) = \frac{\Delta P_{\mathrm{L}}}{s} \tag{8}$$

Substituting $\Delta P_{\mathrm{L}}(s)$ into (8) and summarising the result yields

$$\Delta f(s) = \frac{1}{g(s)} \left[\sum_{k=1}^{n} M_k(s)\Delta P_{\mathrm{C}_k}(s) - \Delta P_{\mathrm{RES}}(s) \right] - \frac{1}{sg(s)}\Delta P_{\mathrm{L}} \tag{9}$$

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where

$$g(s) = 2H_{\mathrm{Sys}}s + D_{\mathrm{Sys}} + \sum_{k=1}^{n} \frac{M_k(s)}{R_k} \tag{10}$$

Several low-order models for representing turbine-governor dynamics $M_i(s)$ to use in power system frequency analysis and control design have been proposed. In these models, the slow system dynamics of the boiler and the fast generator dynamics are ignored. A second-order model was first introduced in [77]. Also, a simplified first-order turbine-governor model was proposed in [78].

Substituting this model and using the final value theorem, the frequency deviation in steady state can be obtained as follows (Appendix)

$$\Delta f_{\mathrm{ss}} = \frac{R_{\mathrm{Sys}}(\Delta P_{\mathrm{C}} - \Delta P_{\mathrm{RES}} - \Delta P_{\mathrm{L}})}{(D_{\mathrm{Sys}}R_{\mathrm{Sys}} + 1)} \tag{11}$$

The inverse Laplace transformation of (4) gives

$$2H_{\mathrm{Sys}} \frac{\mathrm{d}\Delta f(t)}{\mathrm{d}t} + D_{\mathrm{Sys}}\Delta f(t) = \sum_{k=1}^{n} \Delta P_{\mathrm{m}_k}(s) - \Delta P_{\mathrm{RES}}(s) - \Delta P_{\mathrm{L}}(s) = \Delta P_{\mathrm{D}}(t) \tag{12}$$

Neglecting the network power losses, $\Delta P_{\mathrm{D}}(t)$ shows the load-generation imbalance proportional to the total load change and RES power fluctuation. The magnitude of total load-generation imbalance immediately after the occurrence of disturbance at $t = 0^+$ s can be expressed as follows

$$\Delta P_{\mathrm{D}} = 2H_{\mathrm{Sys}} \frac{\mathrm{d}\Delta f}{\mathrm{d}t} \tag{13}$$

The Δf is the frequency of the equivalent system. To express the result into a form suitable for sampled data, (13) can be represented in the following difference equation

$$\Delta P_{\mathrm{D}}(T_{\mathrm{S}}) = \frac{2H_{\mathrm{Sys}}}{T_{\mathrm{S}}}[\Delta f_1 - \Delta f_0] \tag{14}$$

where T_{S} is the sampling period. Δf_1 and Δf_0 are the system equivalent frequencies at t_0 and t_1 (the boundary samples within the assumed interval).

Equations (13) and (14) show that the frequency gradient in a power system is proportional to the magnitude of total load-generation imbalance. The factor of proportionality is the system inertia. In fact, the inertia constant is loosely defined by the mass of all the synchronous rotating generators and motors connected to the system. For a specific load decrease, if H is high, then the frequency will fall slowly and if H is low, then the frequency will fall faster.

5 Need for revising of performance standards

Power system frequency control is an issue that may evolve into new guidelines. The increasing share of renewable energy, which is difficult to predict accurately, may have an adverse impact on frequency quality. The existing frequency operating standards [51] need to change to allow for the introduction of renewable power generation, and allow for modern distributed generator technologies. It is investigated that the slow component of renewable power fluctuation negatively affects the performance standards such as policy P1 of Union for the Coordination of Transmission of Electricity (UCTE) performance standard [79], or the control performance standards CPS1 and CPS2 introduced by North American Electric Reliability Council (NERC) [26].

Up to now, wind turbine compatibility to the various standard requirements is established only through specific tests or simulations that are performed by the manufacturers or other independent laboratories, upon demand of system operators. Standardised-type tests have not been developed yet, due to the diversity of requirements appearing in grid codes [80], performance standards and the relatively limited time they have been in force. Moreover, testing the actual behaviour of wind turbines during system faults presents significant difficulties, since on-site tests on installed machines are necessary, which would involve power system frequency and power fluctuations.

The standards redesign must be done in both normal and abnormal conditions, and should take account of operational experience on the initial frequency control schemes and again used measurement signals including tie-line power, frequency and rate of frequency change settings. The new set of frequency performance standards are under development in many countries [81, 82]. The new standards introduce the update high and low trigger, abnormal, and relay limits applied on the interconnection frequency excursions.

The revised standards may bring an element of a more centralised frequency control through a better coordination among control areas, delegating more authority to the control areas performing frequency monitoring functions, and perhaps creating distributed or inter-area control centres to decentralised frequency control through the creation of corresponding ancillary service markets [83, 84].

For high wind penetration, frequency relay settings not only need revision, but current and voltage relays also need to be coordinated [85, 86]. Protection schemes for distribution and transmission networks are one of the main problems posed by RESs in power systems. Change of operational conditions and dynamic characteristics influence the requirements to protection parameters.

The performance standards revision has already commenced in many countries [11, 35, 82, 83]. In Australia, the Australian Electricity Market Commission is proposing revised technical rules for generator connection, including wind generators. As well as meeting technical standards, generators are required to provide information on energy production via the system operator's SCADA system [35]. National Electricity Market Management Company sets out functional requirement for an Australian Wind Energy Forecasting System for wind farms in market regions. In the USA, NERC is working to revise the conventional control performance standards [82]. The existing market rules and priority rules for the transport of RES electricity is also under re-examination by UCTE in Europe [11].

Grid connection guidelines are still a major controversial subject with regard to distributed RESs. The connection rules and technical requirements that differ from region to region make it all even more complicated. In order to allow a flexible and efficient introduction of RESs, there is a need for a single document being a consensus standard on technical requirements for RESs interconnection rather than having the manufacturers and the operators to conform to numerous local practices and guidelines [55].

6 Simulation study

6.1 39-bus test system

The power outputs of some RESs such as solar and wind power generation systems are dependent on weather conditions, seasons and geographical location. Therefore they can significantly influence the system frequency regulation performance.

This section provides a simulation study on the impacts of solar and wind power units on the power system frequency. For this purpose, as shown in Fig. 2, a network with the same topology as the well-known IEEE 39-bus test system, is considered as a study system to simulate the impact of existing RESs (PV and wind turbine units) on the system frequency performance. The test system has 10 generators, 19 loads, 34 transmission lines and 12 transformers. Here, the test system is updated by two wind farms in areas 1 and 3, and a photovoltaic (PV) unit in area 2. The total generation includes 842 MW conventional power, 2000 kW solar power and 46 MW wind power. The test system is organised into three areas. The amount of load in Area 1, Area 2 and Area 3 are 265.5, 233 and 125 MW, respectively.

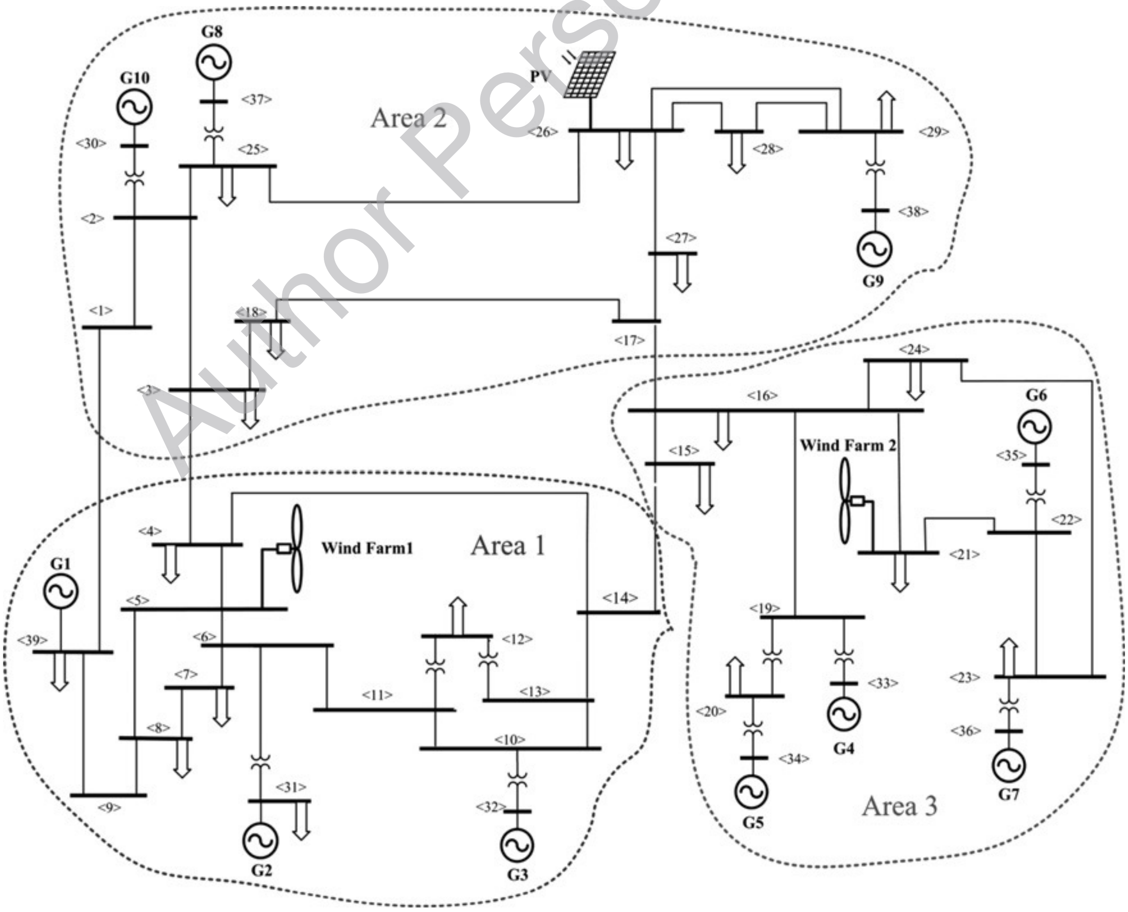

Figure 2 *Single-line diagram of 39-bus test system*

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All power plants in the power system are equipped with speed governor and power system stabiliser. However, only one generator in each area is responsible for the LFC task using a PI controller: G1 in Area 1, G9 in Area 2 and G4 in Area 3. The simulation parameters for the generators, loads, lines and transformers of the test system are assumed the same as given in [87]. Dynamics of WTGs including the pitch angle control of the blades are also considered. The start up and rated wind velocity for the wind farms are specified as about 8.16 (m/s) and 14 (m/s), respectively. Furthermore, the pitch angle controls for the wind blades are activated only beyond the rated wind velocity. The pitch angles are fixed to zero degree at the lower wind velocity below the rated one.

For the sake of simulation, random variations of solar isolation and wind velocity have been taken into account. A combination of variable and fixed wind turbines have been used in the wind farms. The variation of produced powers by wind farms and PV sources perform the source of frequency variation in the study system. The wind velocity V_{Wind} (m/s), the total output power of wind farms P_{WT} (MW) and the output power of PV unit P_{PV} (MW) are shown in Fig. 3.

The corresponding frequency deviation because of wind power fluctuations for each area is shown in Fig. 4. When the power of RESs is introduced into the power system, an imbalance is created when the actual RES output deviates from its forecast. This power imbalance may lead to frequency deviations from nominal value (60 Hz in the present example). From the power quality point of view, frequency deviations should be limited in a specified standard band. As shown in the simulation results, in the presence of wind power generation, the frequency regulation performance is significantly decreased.

As discussed in Section 4, adding of RES units (specifically wind generators) to a power system leads to increase in total system inertia. The most pronounced effect of high values of inertia is to reduce the initial rate of frequency decline, and to reduce the maximum deviation. To investigate above issue, system response following a step load disturbance is investigated. A step load increase is considered at 10 s in each area as follows: 3.8% of area load at bus 8 in Area 1, 4.3% of area load at bus 3 in Area 2 and 6.4% of area load at bus 16 in Area 3 have been changed. The applied step load disturbances, overall frequency and the frequency gradient of system with and without RESs are shown in Fig. 5. For having a clear comparison, a zoomed view of the rate of frequency changes of around 10 s is redrawn in Fig. 6.

It can be seen that the frequency drop has reduced. It is justifiable by considering the larger inertia because of the addition of large wind farms to the system. The higher inertia value results in a lower drop in frequency. Since the system inertia determines the sensitivity of overall system frequency, it plays an important role in the frequency regulation issue. A large interconnected power system generally has sizeable system inertia, and frequency deviation in the presence of wind and solar power variations is small. In other words, larger electricity industry may be more capable of absorbing variations in electricity output from RESs.

However, the combination of RES systems to system inertia of a small power system must be considered, and the

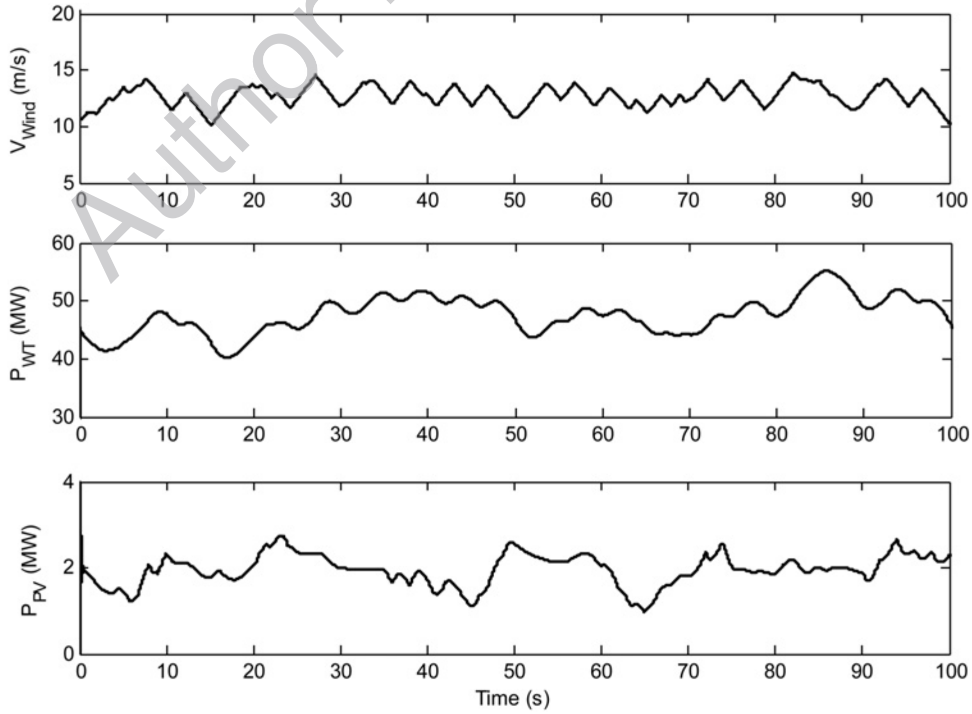

Figure 3 *Wind velocity and the output power of RES units*

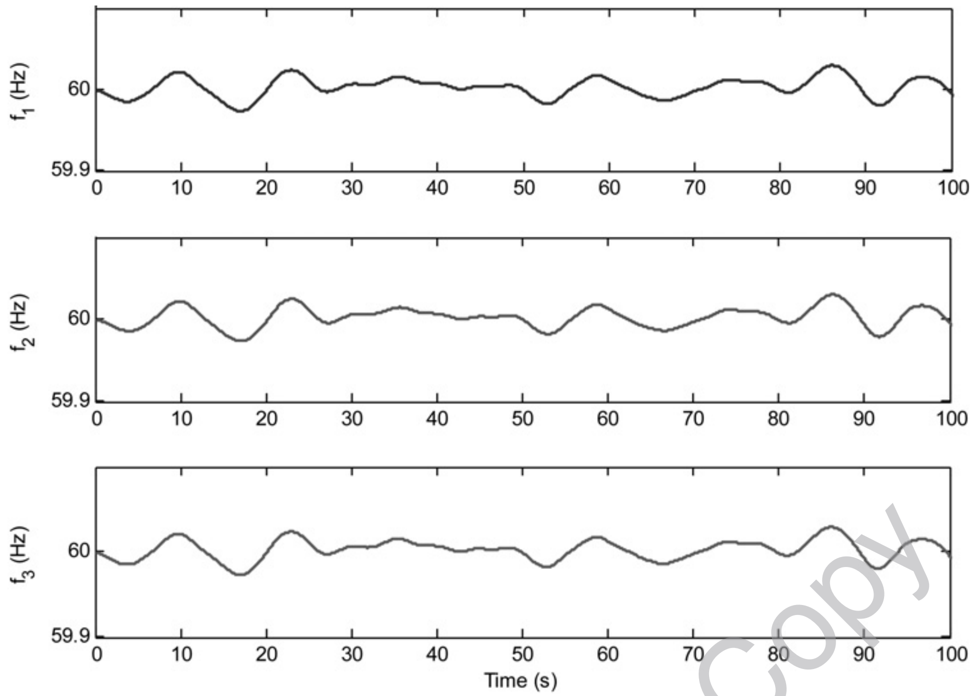

Figure 4 *Area frequency response to RES power fluctuations*

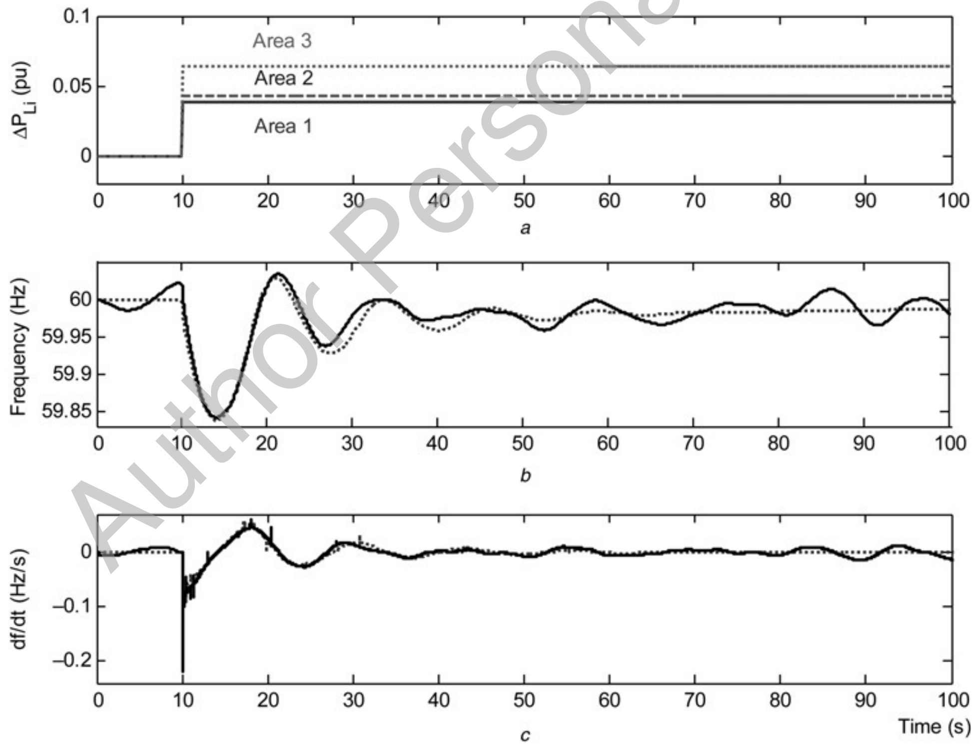

Figure 5 *System response following simultaneous load disturbances with (solid) and without (dotted) RESs*

a Load disturbances
b System frequency
c Rate of frequency change

LFC designs need to consider altering their frequency control strategies to avoid long rates of change of the system frequency. For a power system, increasing amount of RES power may increase variation in system frequency. As a simulation scenario, in the 39-bus test system, the renewable power penetration is increased to about 10%. The frequency deviation in each area following the simultaneous disturbances (Fig. 5*a*) is shown in Fig. 7

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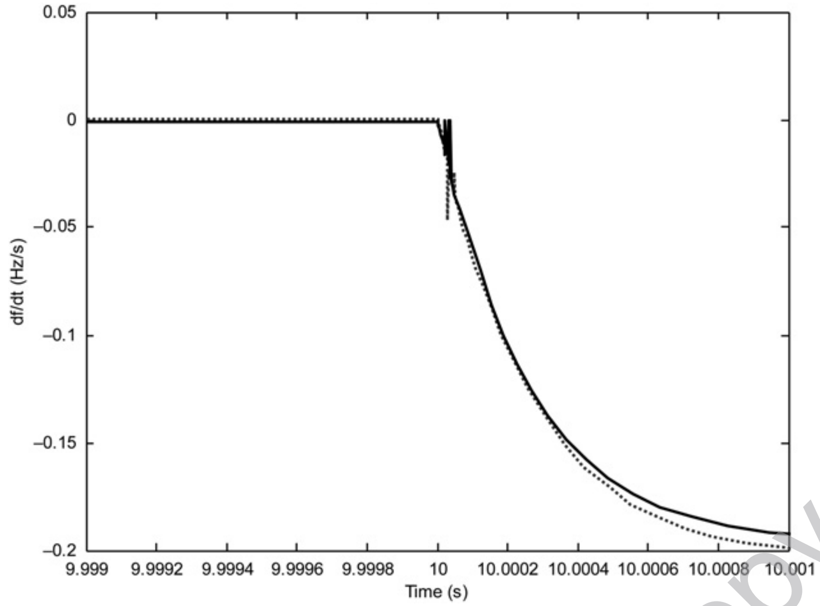

Figure 6 *Zoomed view of the rate of frequency changes following simultaneous load disturbances at 10 s, with (solid) and without (dotted) RESs*

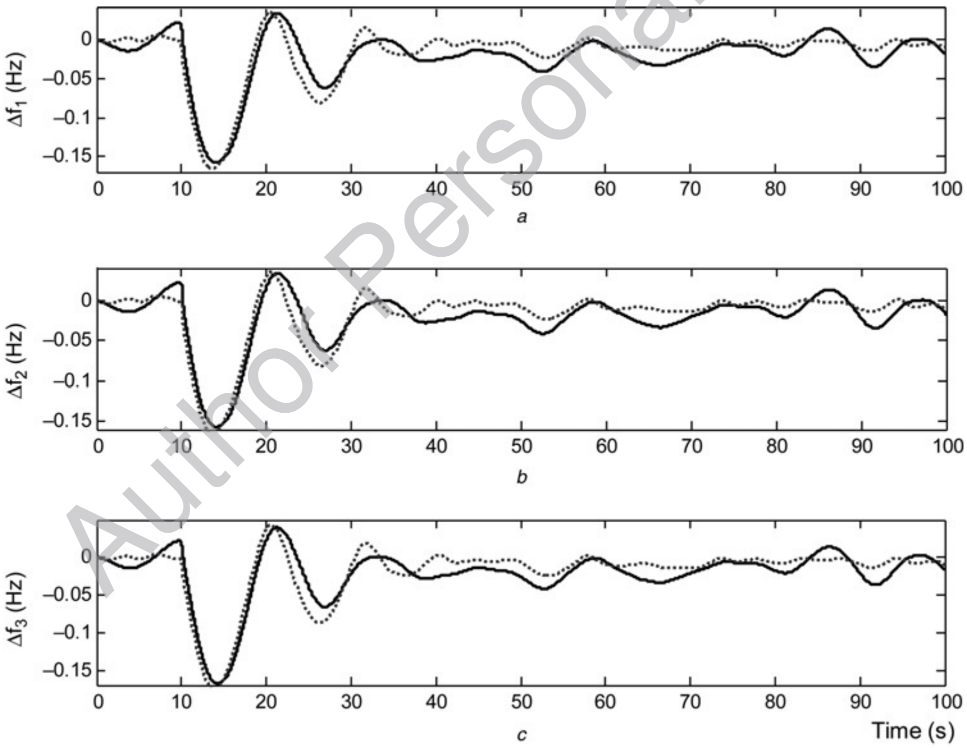

Figure 7 *Frequency deviation in three areas following simultaneous load disturbances with (solid) and without (dotted) RESs; wind power penetration is increased to 12%*

6.2 Using $\Delta f/\Delta t$ rather than df/dt

Recalling (2), since large wind farms can considerably increase the overall system inertia, the df/dt will be significantly changed. From an operational point of view, a larger variable renewable power in the power system causes a smaller frequency rate change following a sudden loss of generation or load disturbance. This issue is important for those networks that use the protective df/dt relays to re-evaluate their tuning strategies.

The local and inter-modal oscillations during large disturbances can cause df/dt relays to measure a quantity at a location that is different to the actual underlying system df/dt. Recent investigations have shown that power systems are prone to inter-modal oscillations during large disturbances [51, 81, 88, 89]. Using $\Delta f/\Delta t$ setting, which is derived over an appropriate time interval, gave values closer to the real rate of system frequency change and not influenced by other oscillations and disturbances. Fig. 8 shows the df/dt and $\Delta f/\Delta t$ signals for the described power system example (Section 6) following a load disturbance. The $\Delta f/\Delta t$ measurement period (sampling time) is considered about 200 ms. This figure illustrates the above statement clearly. The high-frequency oscillations are not appeared in the $\Delta f/\Delta t$ measured signal. Therefore the frequency relays operating based on $\Delta f/\Delta t$ are more likely to operate appropriately to the underlying changes rather than any local measurement that could be the result of a lesser inherent mixed change of frequency and local oscillation.

6.3 24-bus test system

Another simulation is performed on the 24-bus IEEE reliability test system in the presence of a high penetration of DFIG-type WTGs with a variable wind speed, which affects power system frequency, significantly. Single-line diagram of the updated 24-bus reliability test system is illustrated in Fig. 9. The system with simulation data is described in [90]. Here, the generators data are selected the same as given in [91]. Similar to the 39-bus example, this test system is also divided into three areas. Total generation and load (Generation, Load) in areas 1, 2 and 3 are considered as (1470, 750 MW), (945.3, 768 MW) and (584, 1332 MW), respectively. Most of the generation loads are located in Area 1 and Area 3. In Area 2, there is almost the same amount of load and generation. Area 1 delivers a part of its generation into Area 2 and Area 3 through three tie-lines 16-19, 16-14 and 24-3. Four wind farms are connected with the system to provide a high wind power penetration example. The wind farms supply about 15% of overall system demand.

To show the impacts of renewable (wind) power on power system frequency, the system is examined in the presence of a disturbance, with and without renewable power produced by WTGs. To have an obvious simulation results, the disturbance is applied by cutting of line 16–19 at 10 s. Frequency response for both cases is shown in Fig. 10. Since Area 1 is a supplier area, the direction of frequency change in this area, immediately after losing line of 16–19, is different from other two areas. It is clearly shown that in the presence of a considerable amount wind power, frequency deviations in all interconnected areas are significantly increased.

In these cases, using compensation devices such as ECS and batteries [13, 92], and optimal/robust tuning techniques such as those described in [74, 75], can be useful to improve the system frequency control performance. A controllable battery system in order to suppress the fluctuation of the total power output of distributed generation and area frequency control is introduced in [92]. In [92], battery output is controlled by the LFC signal and it is shown that installation of battery with a sufficient capacity makes it possible to decrease the LFC capacity of conventional generators units. Installing batteries and dump loads can absorb the fluctuating solar and wind powers. However, these methods have the disadvantages of high cost and low efficiency.

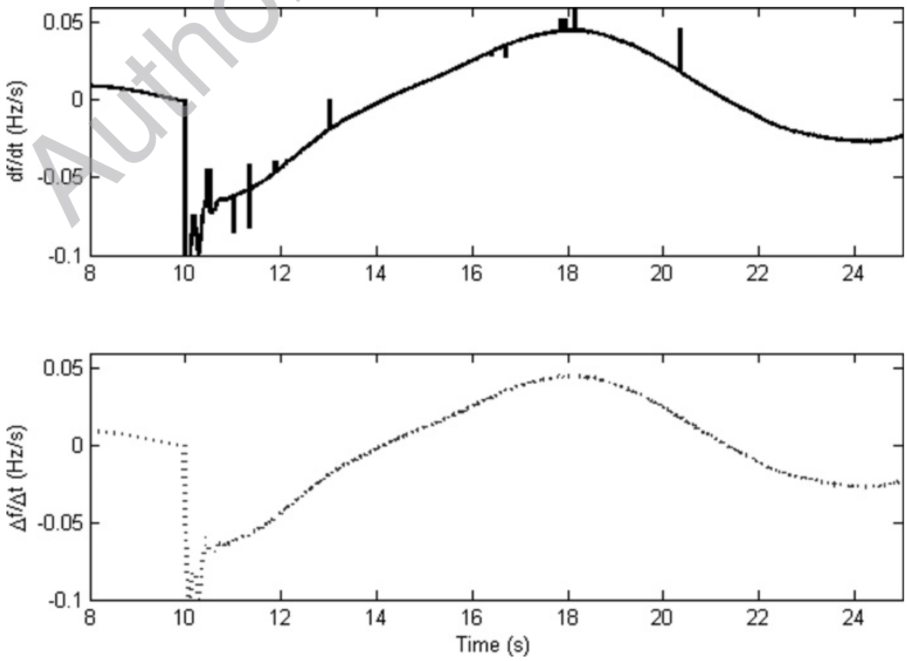

Figure 8 *df/dt and Δf/Δt signals*

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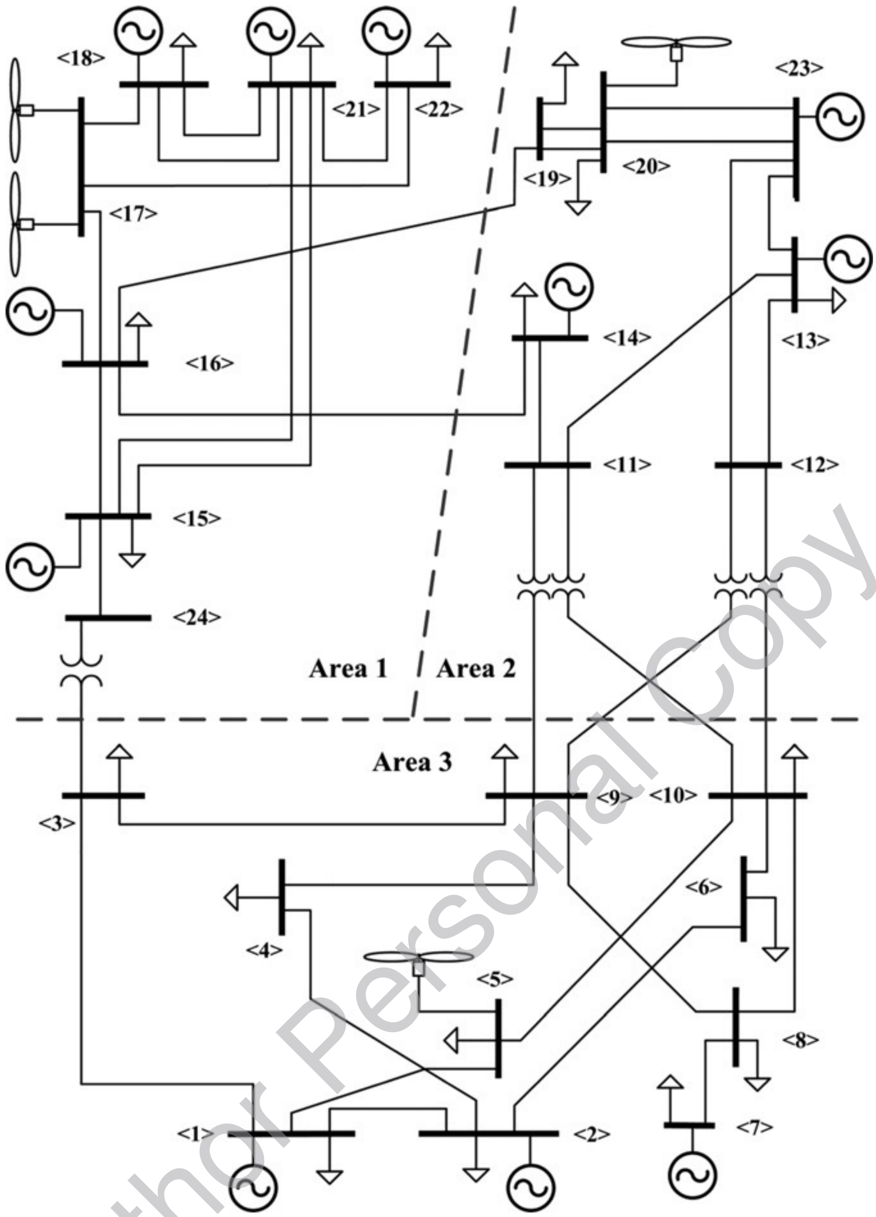

Figure 9 *Three-area 24-bus test power system*

7 Scope for further work

Introducing a significant number of RESs into power systems adds new societal, economical, environmental and technical challenges associated with RESs. Research on this area has already received increasing attention. However, the impact analysis techniques and the appropriate modelling and control synthesis are in the early stages of development. Continued work is needed to identify the key distributed RESs and grid characteristics that determine the technical/economical impact dynamics and to design effective compensation methods. Additional research is required in understanding how future power systems should be designed to simplify the integration of RESs (towards a plug-and-play system). Also the infrastructure requirements to allow RESs to be dispatched centrally (if desired) should be considered. Some important research needs in future (on the subject of RESs and frequency regulation) can be summarised as follows:

1. *Improvement of modelling techniques:* The increase in the share of RESs production in power system network is increasingly requiring an analysis of the system dynamic behaviour of some incidents that may occur through an effective modelling. A proper dynamic modelling of the RES units, for dynamic behaviour studies, is a key issue to gain an adequate idea of the impact in the network resulting from the presence of these generation units following some disturbances.

A more complete dynamic frequency response model is needed in order to frequency control analysis and synthesis in interconnected power systems with a high degree of RES penetration. Although any model that involves the complete

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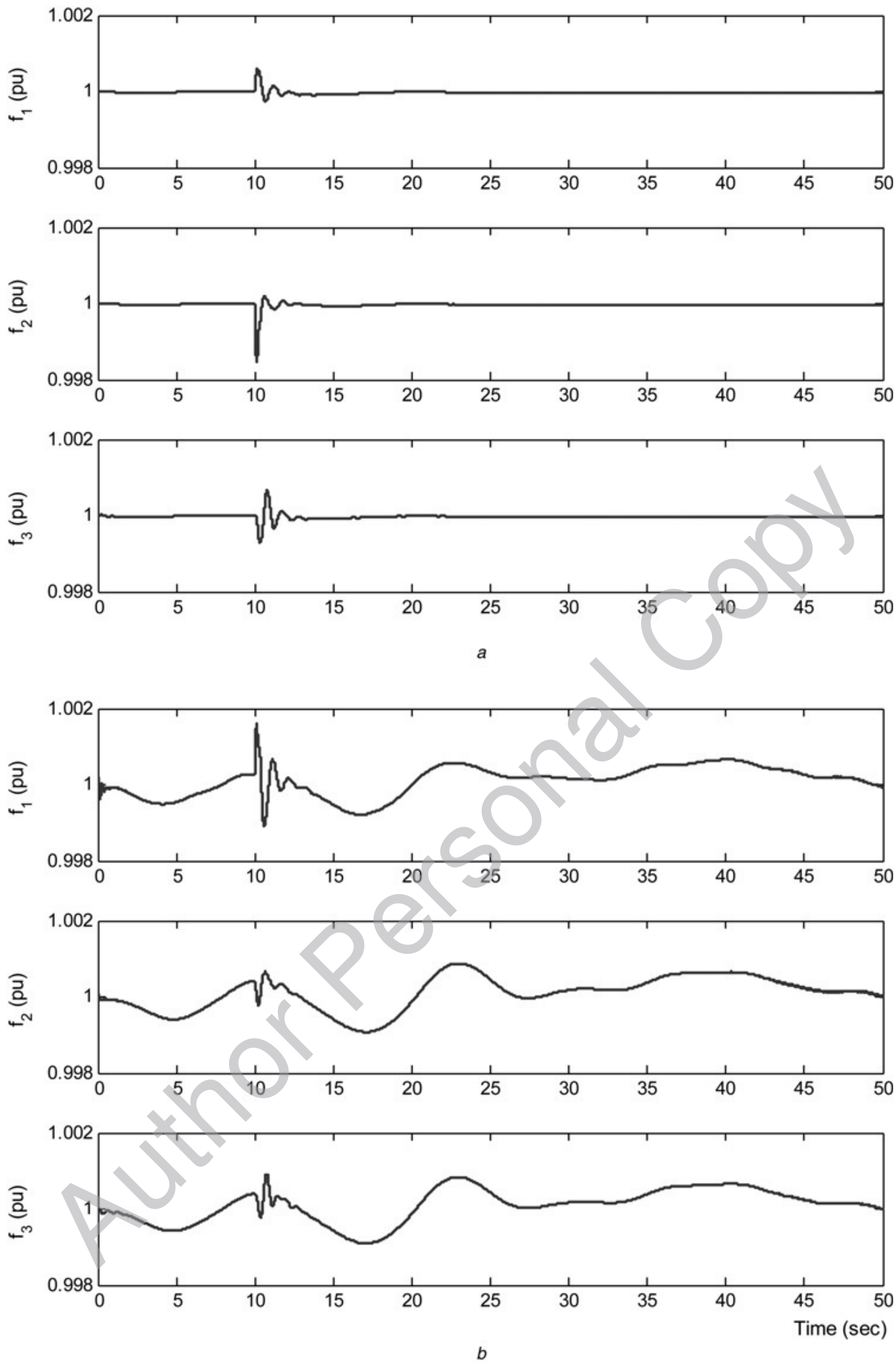

Figure 10 *Frequency deviation in three areas following loss of line 16–19*
a without RESs
b with RESs

interactions of wind power with conventional power system operation requires a number of simplifying assumptions, most proposed models do not account the uncertainty of wind generation in a frequency regulation time scale.

2. *Develop effective control schemes for contribution of RESs in frequency regulation issue:* The contribution of RESs in active power and frequency regulation refers to the ability of these units to regulate their power output, either by disconnecting a part of generation or by an appropriate control action. More effective practical algorithms and control methodologies are needed to do these issues, properly. Improvement in the response of the wind turbine aerodynamic and pitch control systems, in order to perform

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fast limitation of the accelerating mechanical torque, to prevent rotor over speed and smoothly participate in frequency regulation task can be considered in the direction of mentioned ability. Physical limitations of the blades and the pitch regulation mechanism impose a limit on the effectiveness of such an approach [80].

Since the RES power is stochastic, still it is difficult to use RES kinetic energy storage in frequency control, straightly. Some recent studies have addressed how to recover the wind turbines kinetic energy after discharge without causing a negative power spike in the power system [93]. However, further studies are needed to coordinate the timing and the size of the kinetic energy discharge with the characteristics of conventional plants.

3. *Coordination between regulation powers of RES units and conventional generators:* In case of supporting frequency regulation, an important feature of some RES units is the possibility of their fast active power injection. Following a power imbalance, the active power generated by RES units quickly changes to recover the system frequency. As this increased/decreased power can last just for a few seconds, conventional generators should eventually take charge of the huge changed demand by shifting their generation to compensate power imbalance [94]. But the fast power injection by RES units may slow down to a certain extent the response of conventional generators. To avoid this undesirable effect, a coordination between RES and conventional LFC generators is needed.

4. *Improvement of computing techniques and measurement technologies:* The design of a definitive frequency threshold detector and trigger, which discharge the kinetic energy from the inertias of wind turbine generators, will require extensive research to incorporate signal processing, adaptive strategies, pattern recognition and intelligent features to achieve the same primary reserve capability of conventional plants [93]. Advanced computing algorithm and fast hardware measurement devices are also needed to realise optimal/adaptive frequency control schemes for the power systems with a high penetration of RESs.

5. *Define new grid codes:* Further study is needed to define new grid codes for contribution of large RES units (connected to the transmission system) to power system frequency control much as the conventional power plants and investigation of their behaviour in case of abnormal operating conditions of network. The grid codes require high capacity RESs to provide frequency response, that is to contribute to the regulation of system frequency. The active power ramp rate must comply with the respective rates applicable to conventional power units [80]. The new grid codes should clearly impose the requirements on the regulation capabilities of the active power of RES units.

6. *Revising of existing frequency standards:* There exist some principles to be taken into account in the future standards development in area of frequency regulation in the presence of RESs. Standards should be comprehensive, transparent and explicit to avoid misinterpretation. The requirements imposed should reflect an optimum balance between cost and technical performance. A reasonable amount of development time is also needed, by planning standards requirements in advance. Proper consideration should also be given to coordinate the large-scale interconnected systems, via their responsible control centres and organisations, such as the collaboration among neighbouring transmission system operators and UCTE in European networks. Finally, frequency performance standards compliance verification remains a major open issue for RES units. This concerns specific RES unit capabilities and will require the development of additional standards for testing, from the level of the component up to the entire RES.

7. *Other research needs:* To allow for increased penetration of RESs, a change in regulation reserve policy may be required. In this direction, in addition to deregulation policies, the amount and location of RES units, renewable generation technology, and the size and characteristics of the electricity system must be considered as important technical aspects. Moreover, some important research needs in future are: the updating of existing emergency frequency control schemes for N-1 contingency, economic assessment/analysis the frequency regulation prices (considering various control strategies, penetration level, and installation location of RES units), further study on frequency stability using dynamic demand control and ratios of RES technologies, and quantification of reserve margin due to increasing RES penetration.

8 Conclusion

This paper presents an overview of the key issues concerning the integration of RESs into the power system frequency regulation, that are of most interest today. The most important issues with the recent achievements in this literature are briefly reviewed. The impact of RESs on frequency control problem is described. An updated LFC model is introduced. Power system frequency response in the presence of RESs and associated issues is analysed, and the need for the revising of frequency performance standards is emphasised. Finally, a non-linear time-domain simulation study and a remark on the use of df/dt protective relays and future work are presented.

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10 References

[1] The United Nations Framework Convention on Climate Change: 'The Kyoto Protocol', [Online] available at: http://unfccc.int/resource/docs/convkp/kpeng.pdf, 1997

[2] PECAS LOPES J.A., HATZIARGYRIOU N., MUTALE J., ET AL.: 'Integrating distributed generation into electric power systems: a review of drivers, challenges and opportunities', *Electric Power Syst. Res.*, 2007, **77**, pp. 1189–1203

[3] GARDNER P., SNODIN H., HIGGINS A., ET AL.: 'The impacts of increased levels of wind penetration on the electricity systems of the republic of Ireland and Northern Ireland (final report)' (Garrad Hassan and Partners Ltd., 2003), [Online] available at: http://www.cer.ie/cerdocs/cer03024.pdf

[4] MAKAROV Y.V., RESHETOV V.I., STROEV V.A., ET AL.: 'Blackout prevention in the United States, Europe and Russia', *Proc. IEEE*, 2005, **93**, (11), pp. 1942–1955

[5] OUTHRED H., BULL S.R., KELLY S.: 'Meeting the challenges of integrating renewable energy into competitive electricity industries', [Online] available at: http://www.reilproject.org/documents/GridIntegrationFINAL.pdf, 2007

[6] BTM Consult APS: 'International wind energy development world market update 2005'. Forecast 2006–2010, [Online] available at: http://www.btm.dk/Documents/Pressrelease.pdf, 2006

[7] Department of Trade and Industry: 'The energy challenge energy review report' (DTI, London, 2006)

[8] GWEC Latest News: 'US, China & Spain lead world wind power market in 2007'. The Global Wind Energy Council, [Online] available at : http://www.gwec.net/. Cited 28 February 2008

[9] European Commission: 'Directive of the European Parliament and the council on the promotion of electricity from renewable energy sources in the internal electricity market', 2000

[10] EWEA Publications: 'Wind energy leads EU power installations in 2007, but national growth is inconsistent'. The European Wind Energy Association, [Online] available at: http://www.ewea.org, 2008

[11] EWIS: 'Towards a successful integration of wind power into European electricity grids (final report)', [Online] available at: http://www.ornl.gov/~webworks/cppr/y2001/rpt/122302.pdf, 2007

[12] AWEA Resources: U.S. Wind Energy Projects. The American Wind Energy Association, [Online] available at: http://www.awea.org, 2008

[13] SASAKI T., KADOYA T., ENOMOTO K.: 'Study on load frequency control using redox flow batteries', *IEEE Trans. Power Syst.*, 2004, **19**, (1), pp. 660–667

[14] ASANO H., YAJIMA K., KAYA Y.: 'Influence of photovoltaic power generation on required capacity for load frequency control', *IEEE Trans Energy Convers.*, 1996, **11**, (1), pp. 188–193

[15] YANAGAWA S., KATO T., WU K., ET AL.: 'Evaluation of LFC capacity for output fluctuation of photovoltaic power generation systems based on multi-point observation of insolation'. Proc. Conf. Energy, Economy and Environment, 2001, vol. 17, pp. 271–276

[16] MUYEEN S.M., TAMURA J., MURATA T.: 'Stability augmentation of a grid-connected wind farm' (Springer, London, 2009)

[17] PARSONS B., MILLIGAN M., ZAVADIL B.: 'Grid impacts of wind power: a summary of recent studies in the United States'. Presented at the European Wind Energy Conf. and Exhibition, Madrid, Spain, 2003

[18] KOCH F., ERLICH I., SHEWAREGA F.: 'Dynamic simulation of large wind farms integrated in a multimachine network'. Presented at the IEEE PES General Meeting, Ontario, Canada, 2003

[19] ERLICH I., RENSCH K., SHEWAREGA F.: 'Impact of large wind power generation on frequency stability'. Proc. PES General Meeting, 2006

[20] LI W., JOOS G., ABBEY C.: 'Wind power impact on system frequency deviation and an ESS based power filtering algorithm solution'. Proc. IEEE PSCE 2006, 2006, pp. 2077–2084

[21] ABE K., OHBA S., IWAMOTO S.: 'New load frequency control method suitable for large penetration of wind power generations'. Proc. PES General Meeting, 2006, 2006

[22] KINJO T., SENJYU T., URASAKI N., ET AL.: 'Output leveling of wind power generation system by EDLC energy storage'. Proc. 40th Annual Conf of IEEE IECON 2004, 2004, vol. 3, pp. 3088–3093

[23] NOMURA S., OHATA Y., HAGITA T., ET AL.: 'Wind farms linked by SMES systems', *IEEE Trans. Appl. Superconduct.*, 2005, **15**, (2), pp. 1951–1954

[24] BARTON J.P., INFIELD D.G.: 'Energy storage and its use with intermittent renewable energy', *IEEE Trans. Energy Convers.*, 2004, **19**, (2), pp. 441–448

[25] STRBAC G., SHAKOOR A., BLACK M., ET AL.: 'Impact of wind generation on the operation and development of the UK

doi: 10.1049/iet-rpg.2009.0049

electricity systems', *Electric Power Syst. Res.*, 2007, **77**, pp. 1214–1227

[26] BANAKAR H., LUO C., OOI B.T.: 'Impacts of wind power minute to minute variation on power system operation', *IEEE Trans. Power Syst.*, 2008, **23**, (1), pp. 150–160

[27] LALOR G., MULLANE A., O'MALLEY M.: 'Frequency control and wind turbine technology', *IEEE Trans. Power Syst.*, 2005, **20**, (4), pp. 1905–1913

[28] MORREN J., DE HAAN S.W.H., KLING W.L., *ET AL.*: 'Wind turbine emulating inertia and supporting primary frequency control', *IEEE Trans. Power Syst.*, 2006, **21**, (1), pp. 433–434

[29] LUO C., GOLESTANI FAR H., BANAKAR H., *ET AL.*: 'Estimation of wind penetration as limited by frequency deviation', *IEEE Trans. Energy Convers.*, 2007, **22**, (2), pp. 783–791

[30] COURTECUISSE V., MOKADEM M.E., SAUDEMONT C., *ET AL.*: 'Experiment of a wind generator participation to frequency control'. Presented at the 1st EPE-Wind Energy Chapter, Delft, 2008

[31] ROSAS P.: 'Dynamic influences of wind power on the power system'. PhD dissertation, Technical University of Denmark, 2003

[32] ULLAH N.R., THIRINGER T., KARLSSON D.: 'Temporary primary frequency control support by variable speed wind turbines: potential and applications', *IEEE Trans. Power Syst.*, 2008, **23**, (2), pp. 601–612

[33] MORREN J., DE HAAN S.W.H., FERREIRA J.A.: 'Primary power/frequency control with wind turbines and fuel cells'. Proc. PES General Meeting 2006, 2006

[34] RAJASHEKARA K.: 'Hybrid fuel-cell strategies for clean power generation', *IEEE Trans. Ind. Appl.*, 2005, **41**, (3), pp. 682–689

[35] AEMC: 'Draft national electricity amendment (technical standards for wind generation and other generator connections) Rule 2006', [Online] available at: http://www.aemc.gov.au, 2006

[36] AMENEDO J.L.R., ARNALTE S., BURGOS J.C.: 'Automatic generation control of a wind farm with variable speed wind turbines', *IEEE Trans. Energy Convers.*, 2002, **17**, (2), pp. 279–284

[37] SEBASTIAN R., QUUESADA J.: 'Distributed control system for frequency control in a isolated wind system', *Renew. Energy*, 2006, **31**, pp. 285–305

[38] HIRST E.: 'Integrating wind output with bulk power operations and wholesale electricity markets', *Wind Energy*, 2002, **5**, (1), pp. 19–36

[39] MILLIGAN M.: 'Wind power plants and system operation in the hourly time domain'. Windpower 2003 (AWEA, Austin, TX, 2003)

[40] DOHERTY R., OUTHRED H., O'MALLEY M.: 'Establishing the role that wind generation may have in future generation portfolios', *IEEE Trans. Power Syst.*, 2006, **21**, pp. 1415–1422

[41] LI X., SONG Y.J., HAN S.B.: 'Frequency control in micro-grid power system combined with electrolyzer system and fuzzy PI controller', *J Power Sources*, 2008, **180**, pp. 468–475

[42] SLOOTWEG J.G., KLING W.L.: 'The impact of large scale wind power generation on power system oscillations', *Electric Power Syst. Res.*, 2003, **67**, pp. 9–20

[43] CHOMPOO-INWAI C., LEE W., FUANGFOO P., *ET AL.*: 'System impact study for the interconnection of wind generation and utility system', *IEEE Trans. Ind. Appl.*, 2005, **41**, pp. 163–168

[44] DECHANUPAPRITTHA S., HONGESOMBUT K., MITANI Y., *ET AL.*: 'Frequency stabilization of interconnected power system with wind farms by controllable distributed generator'. Proc. Power Engineering Conf. (IPEC), 2005, 2, pp. 679–683

[45] BLACK J.W., ILIC M.: 'Demand-based frequency control for distributed generation'. Proc. IEEE PES Summer Meeting, 2002, vol. 1, pp. 427–432

[46] HOLTTINEN H.: 'Impact of hourly wind power variation on the system operation in the Nordic Countries', *Wind Energy*, 2005, **8**, (2), pp. 197–218

[47] ACKERMANN T., MORTHORST P.E.: 'Economic aspects of wind power in power systems', in ACKERMANN T. (ED.): 'Wind power in power systems' (Wiley, England, 2005)

[48] KIRBY B.: 'Frequency regulation basics and trends' (Oak Ridge National Lab., 2004), [Online] available at: http://www.ornl.gov/~webworks/cppr/y2001/rpt/122302.pdf

[49] DONNELLY M.K., DAGLE J.E., TRUDNOWSKI D.J., *ET AL.*: 'Impacts of the distributed utility on transmission system stability', *IEEE Trans. Power Syst.*, 1996, **11**, (2), pp. 741–747

[50] XU D., GIRGIS A.A.: 'Optimal load shedding strategy in power systems with distributed generation'. Proc. IEEE PES Winter Meeting, 2001, vol. 2, pp. 788–793

[51] BEVRANI H.: 'Robust power system frequency control' (Springer, New York, 2009)

[52] BEVRANI H., LEDWICH G., FORD J.J.: 'On the use of df/dt in power system emergency control'. Proc. IEEE Power Systems Conf. & Exposition, Seattle, Washington, USA, 2009

[53] ERLICH I., SHEWAREGA F.: 'Insert impact of large-scale wind power generation on the dynamic behaviour of interconnected systems'. Proc. iREP Symp.-Bulk Power System Dynamics and Control, Charleston, SC, USA, 2007

[54] IEEE 1547, Standard for interconnection distributed resources with electric power system, 2003

[55] THONG V.V., DRIESEN J., BELMANS R.: 'Overview and comparisons of existing DG interconnection standards and technical guidelines'. Proc. Int. Conf. Clean Electrical Power-ICCEP, 2007, pp. 51–54

[56] ESB National Grid: 'Options for operational rules to curtail wind generation', 2009 [Online] available at: www.cer.ie/cerdocs/cer04247.doc

[57] MOORE A.T.: 'Distributed generation (DG) protection overview'. Technical report (University of Western Ontario, 2008 [Online] available at: http://www.eng.uwo.ca/people/tsidhu/Documents/DG%20Protection%20V4.pdf

[58] DOUMBIA M., AGBOSSOU K., BOSE T.: 'Islanding protection evaluation of inverter-based grid-connected hybrid renewable energy system'. Proc. IEEE Conf. Electrical and Computer Engineering, 2004, vol. 2, pp. 1081–1084

[59] MAEJIMA H., FUJIOKA Y., KOSIMA Y., *ET AL.*: 'Structures of small power supply networks and a practical example with renewable energy resources'. Proc. IEEE PES General Meeting, 2007

[60] KATIRAEI F., IRAVANI M.R., LEHN P.W.: 'Micro-grid autonomous operation during and subsequent to islanding process', *IEEE Trans. Power Del.*, 2005, **20**, (1), pp. 248–257

[61] KATIRAEI F., IRAVANI M.R.: 'Power management strategies for a microgrid with multiple distributed generation units', *IEEE Trans. Power Syst.*, 2006, **21**, (4), pp. 1821–1831

[62] YAZDANI A., IRAVANI R.: 'A unified dynamic model and control for the voltage-sourced converter under unbalanced grid conditions', *IEEE Trans. Power Del.*, 2006, **21**, (3), pp. 1620–1629

[63] KARIMI H., NIKKHAJOEI H., IRAVANI R.: 'Control of an electronically-coupled distributed resource unit subsequent to an islanding event', *IEEE Trans. Power Del.*, 2008, **23**, (1), pp. 493–501

[64] NIKKHAJOEI H., IRAVANI R.: 'Steady-state model and power flow analysis of electronically-coupled distributed resource units', *IEEE Trans. Power Del.*, 2007, **22**, (1), pp. 721–728

[65] NIKKHAJOEI H., IRAVANI R.: 'Dynamic model and control of AC–DC–AC voltage-sourced converter system for distributed resources', *IEEE Trans. Power Del.*, 2007, **22**, (2), pp. 1169–1178

[66] MORREN J., PIERIK J., DE HAAN S.W.H.: 'Inertial response of variable speed wind turbines', *Electric Power Syst. Res.*, 2006, **76**, (11), pp. 980–987

[67] MULLANE A., OAPOS MALLEY M.: 'The inertial response of induction-machine-based wind turbine', *IEEE Trans Power Syst.*, 2005, **20**, (3), pp. 1496–1503

[68] RAMTHARAN G., EKANAYAKE J.B., JENKINS N.: 'Frequency support from doubly fed induction generator wind turbines', *IET Renew. Power Gener.*, 2007, **1**, (1), pp. 3–9

[69] VITAL E., KEANE A., O'MALLEY M.: 'Varying penetration ratios of wind turbine technologies for voltage and frequency stability'. Proc. IEEE PES General Meeting, Pittsburgh, PA, 2008

[70] GROSS R., HEPTONSTALL P., LEACH M., *ET AL.*: 'Renewable and the grid: understanding intermittency', *Energy*, 2007, **160**, pp. 31–41

[71] KUNDUR P.: 'Power system stability and control' (McGraw-Hill, Englewood Cliffs, NJ, 1994)

[72] KNUDSEN H., NIELSEN J.N.: 'Introduction to the modelling of wind turbines', in ACKERMANN T. (ED.): 'Wind power in power systems' (Wiley, England, 2005)

[73] GRAINGER J.J., STEVENSON W.D.: 'Power system analysis' (McGraw-Hill, New York, 1994)

[74] BEVRANI H., MITANI Y., TSUJI K.: 'Robust decentralized load-frequency control using an iterative linear matrix inequalities algorithm', *IEE Proc. Gener. Transm. Distrib.*, 2004, **150**, (3), pp. 347–354

[75] BEVRANI H., HIYAMA T.: 'On load-frequency regulation with time delays: design and real-time implementation', *IEEE Trans Energy Convers.*, 2009, **24**, (1), pp. 292–300

[76] BEVRANI H.: 'Decentralized robust load-frequency control synthesis in restructured power systems'. PhD dissertation, Osaka University, 2004

[77] ELGERD O.I., FOSHA C.: 'Optimum megawatt-frequency control of multiarea electric energy systems', *IEEE Trans. Power Appar. Syst.*, 1970, **PAS-89**, (4), pp. 556–563

[78] ANDERSON P.M., MIRHEYDAR M.: 'A low-order system frequency response model', *IEEE Trans. Power Syst.*, 1990, **5**, (3), pp. 720–729

[79] UCTE: 'UCTE appendix to policy P1: load-frequency control and performance'. UCTE Operation Handbook, 2004

doi: 10.1049/iet-rpg.2009.0049

[80] TSILI M., PAPATHANASSIOU S.: 'A review of grid code technical requirements for wind farms', *IET Renew. Power Gener.*, 2009, **3**, (3), pp. 308–332

[81] CLARKE D.E.: 'Tasmanian experience with the use of df/dt triggering of UFLSS'. Final Report (Transend Networks PTY LTD, no. D08/22185, 2008

[82] NERC: 'Balance resources and demand standard ver. 2', 2007 [Online] available at: http://www.nerc.com/~filez/standards/Balance-Resources-Demand.html

[83] MAKAROV Y.V., RESHETOV V.I., STROEV V.A., *ET AL.*: 'Blackout prevention in the United States, Europe and Russia', *Proc. IEEE*, 2005, **93**, (11), pp. 1942–1955

[84] ILIC M., SKANTZE P., YU C.N., *ET AL.*: 'Power exchange for frequency control'. Proc. IEEE PES Winter Meeting, 1999, vol. 2, pp. 809–819

[85] MOMOH J.A.: 'Electric power distribution, automation, protection, and control' (CRC Press, NW, 2008)

[86] HEIER S.: 'Grid integration of wind energy conversion systems' (Wiley, England, 2006, 2nd edn.)

[87] DANESHFAR F.: 'Automatic generation control using multi-agent systems'. Master dissertation, University of Kurdistan, 2009 [Online] available at: www.bevrani.com/Supervision.htm

[88] ANDERSON P.M.: 'Power system protection' (IEEE Press/Wiley, New York, 1999)

[89] IEEE guide for the application of protective relays used for abnormal frequency load shedding and restoration, Power Systems relaying Committee, IEEE Std C37.117, 2007

[90] IEEE RTS Task Force of APM Subcommittee: 'The IEEE reliability test system-1996', *IEEE Trans. Power Syst.*, 1999, **14**, (3), pp. 1010–1020

[91] ANDERSON P.M., FOUAD A.A.: 'Power system control and stability' (IEEE Press, New York, 1994)

[92] ARITA M., YOKOYAMA A., TADA Y.: 'Evaluation of battery system for frequency control in interconnected power system with a large penetration of wind power generation'. Presented at the Int. Conf. Power System Technology, 2006

[93] KEUNG P.K., LI P., BANAKAR H., OOI B.T.: 'Kinetic energy of wind-turbine generators for system frequency support', *IEEE Trans. Power Syst.*, 2009, **24**, (1), pp. 279–287

[94] MANUEL J.M., MAURICO J.M., MARANO A., *ET AL.*: 'Frequency regulation contribution through variable-speed wind energy conversion systems', *IEEE Trans. Power Syst.*, 2009, **24**, (1), pp. 173–180

11 Appendix

Substituting $M_i(s)$ from [77] or [78] into (9) and (10), and using the final value theorem, the frequency deviation in steady state can be obtained from (9) as follows [51]

$$\Delta f_{ss} = \lim_{s\to 0} s\Delta f(s) = \frac{1}{g(0)}[\Delta P_C - \Delta P_{RES}] - \frac{1}{g(0)}\Delta P_L \tag{15}$$

where

$$\Delta P_C = \lim_{s\to 0} s\sum_{k=1}^{n} M_k(s)\Delta P_{C_k}(s) \tag{16}$$

$$\Delta P_{RES} = \lim_{s\to 0} s\Delta P_{RES}(s) \tag{17}$$

$$g(0) = D_{Sys} + \sum_{k=1}^{n}\frac{1}{R_k} = D_{Sys} + \frac{1}{R_{Sys}} \tag{18}$$

Here, R_{Sys} is the equivalent system droop characteristic, and

$$\frac{1}{R_{Sys}} = \sum_{k=1}^{n}\frac{1}{R_k} \tag{19}$$

By definition [71], $g(0)$ is equivalent to the system's frequency response characteristic (β)

$$\beta = D_{Sys} + \frac{1}{R_{Sys}} \tag{20}$$

Using (18), (15) can be rewritten into the following form

$$\Delta f_{ss} = \frac{\Delta P_C - \Delta P_{RES} - \Delta P_L}{D_{Sys} + 1/R_{Sys}} \tag{21}$$

Equation (21) shows that if the disturbance magnitude matches with the available power reserve (supplementary control) $\Delta P_C = \Delta P_{RES} + \Delta P_L$, the frequency deviation converges to zero in steady state. Since the value of a droop characteristic R_k is bounded between about 0.05 and 0.1 for most generator units ($0.05 \le R_k \le 0.1$) [78], for a given control system according to (19) we can write $R_{Sys} \le R_{min}$. For a small enough $D_{Sys}R_{Sys}$, (21) can be reduced to

$$\Delta f_{ss} = \frac{R_{Sys}(\Delta P_C - \Delta P_{RES} - \Delta P_L)}{(D_{Sys}R_{Sys} + 1)} \cong R_{Sys}(\Delta P_C - \Delta P_{RES} - \Delta P_L) \tag{22}$$

Without a supplementary control signal ($\Delta P_C = 0$), the steady-state frequency deviation will be proportional to disturbance magnitude as follows

$$\Delta f_{ss} = -\frac{R_{Sys}(\Delta P_{RES} + \Delta P_L)}{(D_{Sys}R_{Sys} + 1)} \tag{23}$$

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