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Load Frequency Control
In the Presense of Wind Farms

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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. This report presents an overview of the key issues and new challenges on frequency regulation concerning the integration of renewable energy units (especially wind turbine generators) into the power systems. 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 presented. An updated LFC model is introduced, and power system frequency response in the presence of RESs and associated issues is analyzed. The need for the revising of frequency performance standards is emphasized. Finally, nonlinear time-domain simulations on a nine-bus test system show that the simulated results agree with those predicted analytically.

Key Words: Renewable energy sources, Frequency regulation, LFC, Frequency response model, Power fluctuation.

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, 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 behavior 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 transmission congestion, optimum power flow, power quality, voltage and frequency control, system economics and load dispatch. Regarding to 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 unfavorable conditions, this may result in a cascading failure and system collapse [4].

This work covers the issues concerning the integration of new renewable power generation in power systems with the frequency regulation perspective. The report is organized 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 generalized 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. Finally, a simulation study on IEEE nine-bus test system is presented in Section 6.

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 utilized 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 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; 3,100 MW hydro; and 1,700 MW biomass power capacity during the eight year period [10]. According to the European Wind Energy Association (EWEA), European wind power capacity is expected to be more than 180 GW in 2020 [11].

2.3 United States

The U.S. Department of Energy has announced a goal of obtaining 6% of U.S. electricity only from wind by 2020; a goal that is consistent with the current growth rate of wind energy nationwide [12]. Overall U.S. 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 U.S. 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 5,000 MW of wind energy capacity during 2007. Based on current growth rates, the Chinese Renewable Energy Industry Association (CREIA) 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. 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 behavior with high renewable energy penetration.

High RESs penetration increases the risk of tie-line overloading. A large renewable energy source such as a wind farm that is located away from major load centers 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 behavior 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 summarized 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, grid congestions, 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 [18]. 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 increase [19, 20].

3 Recent Developments on 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 [21-25]. In [21], 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 [23-25], different ESSs by means of an electric double-layer capacitor (EDLC) and superconducting magnetic energy storage (SMES) and energy saving are proposed for wind power leveling.

The impact of wind generation on the operation and development of the UK electricity systems is described in [26]. Impacts of wind power components and variations on power system frequency control are described in [27, 28]. Using the kinetic energy storage system (blade and machine inertia) to participate in primary frequency control is addressed in [29]. 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 [29] to let variable-speed wind turbines emulate inertia and support primary frequency control.

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 [30]. 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 [31]. 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 [32]. 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 [29]. The capability of providing a short term active power support of a wind farm to improve the primary frequency control performance is discussed in [33]. To support primary frequency control for a longer period, some techniques such as using a combination of wind and fuel cell energies are suggested [34, 35]. The amount of installed fuel cell energy capacity needed to compensate frequency deviation is discussed in [34].

3.2 Supplementary Frequency Control and Required Reserve

Some recent studies analyze the impacts of RESs on power market operation and supplementary frequency control [5, 18, 21-24, 28, 36-41]. Some of those are reviewed in [18]. A study is conducted in [39] to help determine how wind generation might interact in the competitive wholesale market for regulation services and a real time balancing market. This study recognized 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 [21-24,28]. An automatic generation control system for a wind farm with variable speed turbines is addressed in [37]. 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 [38].

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 [40]. 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 electrolyzer system with a fuzzy PI control is used in [42] 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 [43, 44]. A control scheme based on controllable distributed generators is addressed in [45] 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 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 [46] 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.

Due 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. 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 [27].

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:

$$P_G = P_L + P_{Losses} - P_{RES} \tag{1}$$

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 [47]. 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 [47] that the power fluctuation from geographically dispersed wind farms will be uncorrelated with each other, hence smoothing the sum power and not imposing any significant requirement for additional frequency regulation reserve, and required extra balancing is small.

It is estimated in [26] that for a 10 GW installed wind capacity (in UK power system), 126 MW to 192 MW additional continues conventional LFC power is required. According to a study for Denmark and Germany [48], 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 [49], 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 [50], and an optimal load shedding strategy for power systems with distributed sources is introduced in [51]. The need for re-tuning of automatic under frequency load shedding (UFLS) df/dt relays is emphasized in [52, 53]. The system performance and frequency stability during a severe short-circuit and after a sudden loss of generation is discussed in [54].

IEEE 1547 [55] 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 underfrequency trips. When frequency is out of the given protection range [56], the RES unit shall cease to energize 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 energize the power system.

A variety of studies are recommended to analyze the protection-based penetration limits with consideration of the RESs capacity, location and technology. The studies aid in determining mitigation strategies to increase the protection based penetration limit. The loss of coordination, de-sensitization, nuisance fuse blowing, bidirectional relay requirements and overvoltage, should be studied in order to arrive at the penetration limits of RESs in an existing distribution system [57, 58].

The effect of adding RES units to distribution feeder can produce blind zones for protection devices or upset the coordination between two (or more) protective devices and should be studied carefully [59]. In normal operation, protection devices are coordinated such that the primary protection operates before the backup can take action. Interconnecting distributed RESs increases the short circuit level. Depending on the original protection coordination settings along with the size, location and type of the RESs, uncoordinated situations may be found. In these situations, the backup operates before the primary, which results in nuisance tripping to some of the loads.

The introduction of distributed RESs that can operate in islanding mode results in a complex problem that requires study to determine the necessary settings and changes needed for proper island operation. When parallel operation is lost, the RESs must separate itself from the utility system quickly to support the substation reclose attempt. Detecting the loss of parallel operation (unintentional island formation) is done by establishing an over/under frequency (and over/under voltage) within which the distributed RES is allowed to operate. Under most circumstances the frequency will quickly move outside of normal operation when parallel operation is lost.

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 [60].

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 utilizing 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) [61]. 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 so are not considered dispatchable by the utility and so are not tightly integrated into the power supply system. The inverter interface decouples the generation source from the distribution network and the islanding characteristics of the distributed generator are primarily determined by the inverter.

Since inverters monitor the frequency at their output terminals for control purposes, it is relative easy to implement a passive islanding detection technique based on detecting when the inverter frequency shifts outside a window centred around the nominal frequency set point. Consideration still needs to be given to the case when a balanced load condition exists and frequency shift may be small or nonexistent after the utility is no longer present.

RESs with the electronic power interfaces have islanding capabilities. Frequency control is an important issue in islanding operation when the distributed RESs network is disconnected from the utility grid. During the islanding operation, it is necessary to maintain the balance between electricity supply and demand instantaneously. 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 [62].

Both the probability of islanding and the risks associated with the formation of an island are typically less for electronically-coupled distributed RESs than for synchronous generator based distributed units [63]. A study also showed that the risk of electric shock due to islanding of PV systems under worst-case PV penetration scenarios to both operators and customers does not increase the risk that already exists [64].

Nowadays, many researchers are actively working on the existing challenges on the use of electronically-coupled distributed RESs, e.g., islanding prevention, fast detection of islanding phenomenon, and frequency (and voltage) control of an islanded microgrid under balanced and unbalanced conditions. Several valuable research works on modeling, analysis and control of electronically-coupled distributed RESs have been reported [65-70]. In these works, control challenges and design techniques for islanded operation of distributed RESs and its local load are mainly addressed. 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 [68].

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 utilize 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 [28, 71-73]. It is also found that the inertia response of a DFIG employing field-oriented control is strongly influenced by the rotor current-control bandwidth [72]. Therefore, the increasing penetration of electronically-coupled distributed RESs such as variable speed wind turbines lead to a reduction of inertia in the grid [71].

On the other hand, in the fixed speed generators (FSG), the rotor of the turbine blades is coupled to the rotor of the electric machine through a gearbox. This design allows the turbine to utilize 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 [74].

4. A Generalized LFC Model Considering RES Impacts

4.1 Generalized 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 analyze 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, be completely unrelated to each other, or they may cancel each other out [75]. 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 generalized LFC model in the presence of RES is shown in Fig. 1. Here, to cover the variety of generation types in the control area, different values for turbine-governor 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 frequency deviation, ΔP_m is mechanical power, ΔP_C is supplementary control action, ΔP_L is load disturbance, H_{Sys} is equivalent inertia constant, D_{Sys} is equivalent damping coefficient, B is frequency bias, R_i is drooping characteristic, ΔP_P is primary control, α_i is participation factors, ΔP_{RES} is RES power fluctuation, $K(s)$ is LFC controller, and $M_i(s)$ is 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 [76]. 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:

$$H_{sys} = H_C + H_W = \sum_{i=1}^{N1} H_{Ci} + \sum_{i=1}^{N2} H_{Wi} \tag{2}$$

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 dependant. The typical inertia constant for the wind turbines is about two to six seconds [77].

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 which 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 two to nine seconds [78].

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 which is usually smoothed compared to variations from the individual RES units.

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

where $P_{Con,act}$, $P_{Con,sched}$, $P_{RES,act}$, and $P_{RES,estim}$ 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 [79, 80]. Control dead band and ramping rate are different for various systems [52, 81]. The control can send higher/lower pulses to generating plants if its ACE signal exceeds a standard limits.

4.2 Frequency Response analysis

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

$$\Delta f(s) = \frac{1}{2H_{Sys}s + D_{Sys}}[\sum_{k=1}^{n} \Delta P_{m_k}(s) - \Delta P_{RES}(s) - \Delta P_L(s)] \qquad (4)$$

Where

$$\Delta P_{m_k}(s) = M_k(s)[\Delta P_{C_k}(s) - \Delta P_{P_k}(s)] \qquad (5)$$

and

$$\Delta P_{P_k}(s) = \frac{\Delta f(s)}{R_k} \qquad (6)$$

Here ΔP_P and ΔP_C are primary (governor natural response) and supplementary (LFC) control actions. The expressions (5) and (6) can be substituted into (4) with the result

$$\Delta f(s) = \frac{1}{2H_{Sys}s + D_{Sys}} . \left(\sum_{k=1}^{n} M_k(s)[\Delta P_{C_k}(s) - \frac{1}{R_k}\Delta f(s)] - \Delta P_{RES}(s) - \Delta P_L(s) \right) \qquad (7)$$

For the sake of load disturbance analysis we are usually interested in $\Delta P_L(s)$ in the form of a step function, i.e.,

$$\Delta P_L(s) = \frac{\Delta P_L}{s} \qquad (8)$$

Substituting $\Delta P_L(s)$ in (8) and summarizing the result yields

$$\Delta f(s) = \frac{1}{g(s)}[\sum_{k=1}^{n} M_k(s)\Delta P_{C_k}(s) - \Delta P_{RES}(s)] - \frac{1}{sg(s)}\Delta P_L \qquad (9)$$

where

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

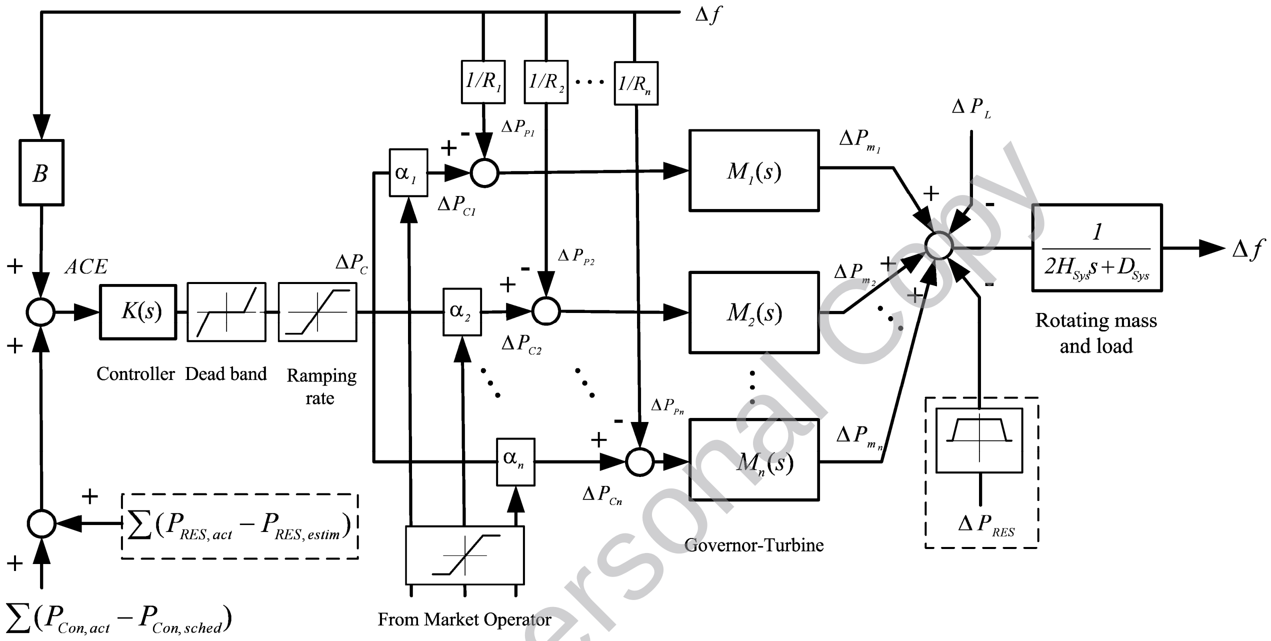

Fig. 1. LFC model with considering RES power fluctuation.

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 [82]. Also, a simplified first order turbine-governor model was proposed in [83].

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

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

The inverse Laplace transformation of (4) gives

$$2H_{Sys}\frac{d\Delta f(t)}{dt} + D_{Sys}\Delta f(t) = \sum_{k=1}^{n}\Delta P_{m_k}(s) - \Delta P_{RES}(s) - \Delta P_L(s) = \Delta P_D(t) \tag{12}$$

Neglecting the network power losses, $\Delta P_D(t)$ 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:

$$\Delta P_D = 2H_{Sys}\frac{d\Delta f}{dt} \tag{13}$$

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:

$$\Delta P_D(T_S) = \frac{2H_{Sys}}{T_S}[\Delta f_1 - \Delta f_0] \tag{14}$$

where, the T_S is the sampling period. The 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. RESs and Frequency 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 [52] need to change to allow for the introduction of renewable power generation, and allow for modern distributed generator technologies.

5.1 The Need for Revising of Performance Standards

It is investigated that the slow component of renewable power fluctuation negatively affects the performance standards such as policy P1 of UCTE (Union for the Coordination of Transmission of Electricity) performance standard [84], or the control performance standards CPS1 and CPS2 introduced by NERC (North American Electric Reliability Council) [27].

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 [85, 86]. 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 centralized 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 centers to decentralized frequency control through the creation of corresponding ancillary service markets [87, 88].

It is shown that the rate of frequency change (df/dt) following a disturbance is proportional to the power imbalance, and it also depends on the equivalent system inertia [89, 90]. 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.

For high wind penetration, frequency relay settings not only need revision, but current and voltage relays also need to be coordinated [91, 92]. 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, 36, 86, 87]. In Australia, the Australian Electricity Market Commission (AEMC) 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 [36]. National Electricity

Market Management Company (NEMMCO) sets out functional requirement for an Australian Wind Energy Forecasting System (AWEFS) for wind farms in market regions. In the USA, NERC is working to revise the conventional control performance standards [86]. 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 [56].

5.2 Using $\Delta f/\Delta t$ Rather Than df/dt

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. A further refinement to the emergency control protection schemes can be achieved by using $\Delta f/\Delta t$ settings rather than df/dt settings. Recent investigations have shown that power systems are prone to inter-modal oscillations during large disturbances [52, 85, 90]. 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.

Here, it is assumed that the advanced computing techniques and fast hardware facilities are available to measure the rate of area frequency changes in the appropriate time (e.g., less than *0.5 s*) to prevent spurious operation. The initial assessment, based upon studies on the Australia power system, suggest that load would have to be shed within less than *0.5 s* to be effective in the preventive loss of interconnections on the first swing.

Although the initial load shedding operation is slower with $\Delta f/\Delta t$ setting compared to the use of df/dt, the risk of spurious operation of the $\Delta f/\Delta t$ elements is significantly reduced. It is shown that with the current measurement technologies, the delay in obtaining $\Delta f/\Delta t$ can be reduced to 300 ms and less, which would be useful in speeding up the operation of the first blocks of an automatic UFLS scheme.

5.3 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 modeling 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 distribution systems should be designed to simplify the integration of RESs (towards a plug-and-play system). Some of the obstacles the grid of the future will need to consider include how islanded parts of the distribution systems can be operated and re-synchronized. Also the infrastructure requirements to allow RESs to be dispatched centrally (if desired) should be considered.

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

A more complete dynamic 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 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.

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, following issues show some important research needs in future:

- Response characteristic analysis in emergency conditions, and update the existing emergency control schemes for N-1 contingency,
- Economic assessment and 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,
- Quantification of reserve margin due to increasing RES penetration.

6. Simulation Study

The power outputs of some RESs such as solar and wind power generation systems are dependant 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 nine-bus power system including 567.5 MW conventional generation, a 2000 kW photovoltaic (PV) unit, and two wind farms with 35 MW is considered as a study system to simulate the impact of existing RESs (PV and wind turbine units) on the system frequency performance. It is assumed that the generator G_2 is responsible for regulating system frequency using a simple PI controller. The nine-bus system parameters are assumed the same as used in [93].

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 velocities V_W (m/s), the output power of wind farms P_{WT} (MW), and the output power of PV unit P_{PV} (MW) are shown in Fig. 3. The system response is shown in Fig. 4. This figure shows the produced power by conventional generators P_G (MW), and the frequency variation Δf (Hz) at generator terminals.

The system response following connection of the low capacity PV unit (only) is shown in Fig. 4b (dashed-line), and the frequency variation in the presence of both PV and wind turbine units are shown in the same figure (solid-line). When wind power is a part of the power system, additional imbalance is created when the actual wind output deviates from its forecast.

Fast movements in wind power output are combined with fast movements in load and other resources. Scheduling conventional generator units to follow load (based on the forecasts) may also be affected by wind power output. Errors in load forecasts are generally uncorrelated with errors in wind forecasts. The initial frequency rate change for the given simulation example, following 0.05 pu step load disturbance is shown in Fig. 5. A similar test is repeated on the nine-bus system without RES units, and a larger frequency rate change is achieved. Recalling (2) and (13) this behavior is easily understandable.

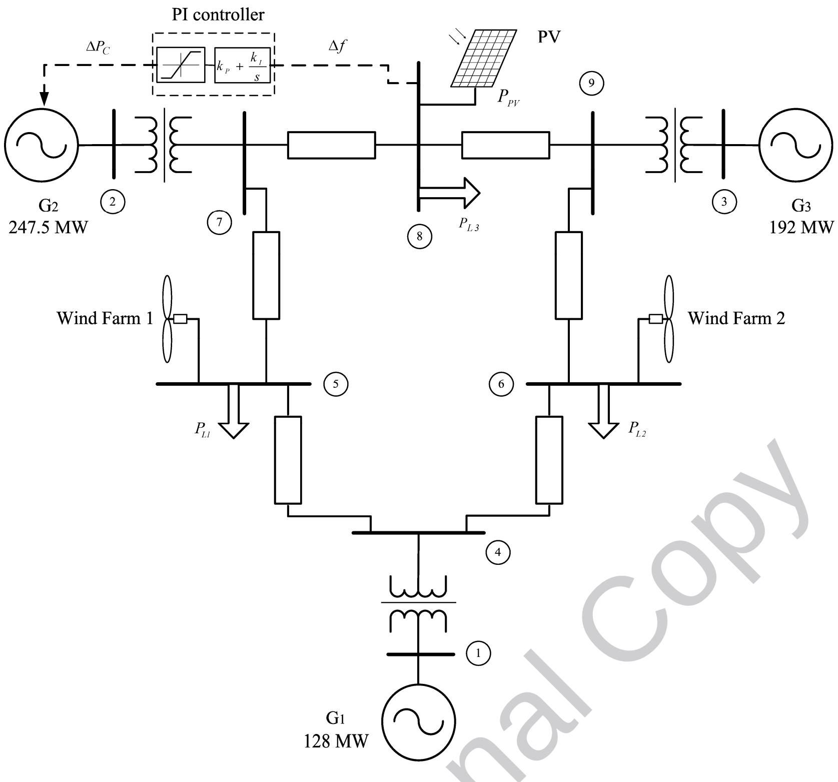

Fig. 2. Nine-bus system: three generators, two wind farms and one PV unit.

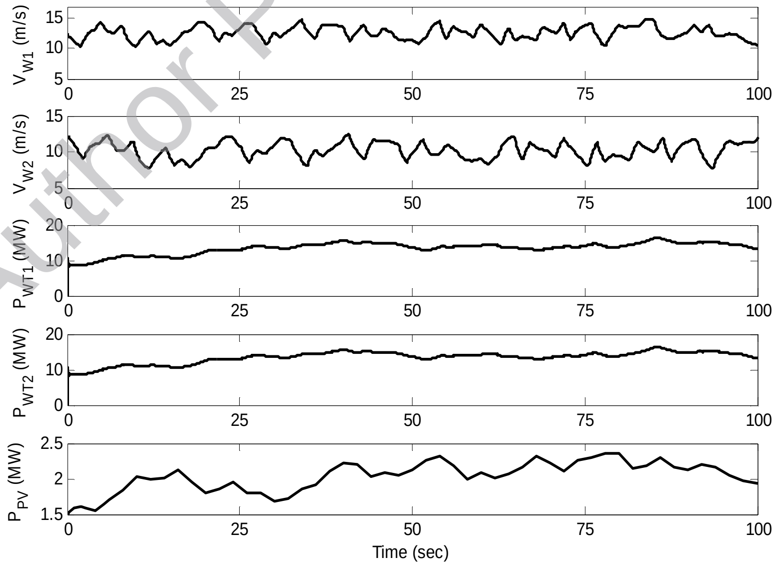

Fig. 3. Wind velocity in the wind farms, and output power of RES units.

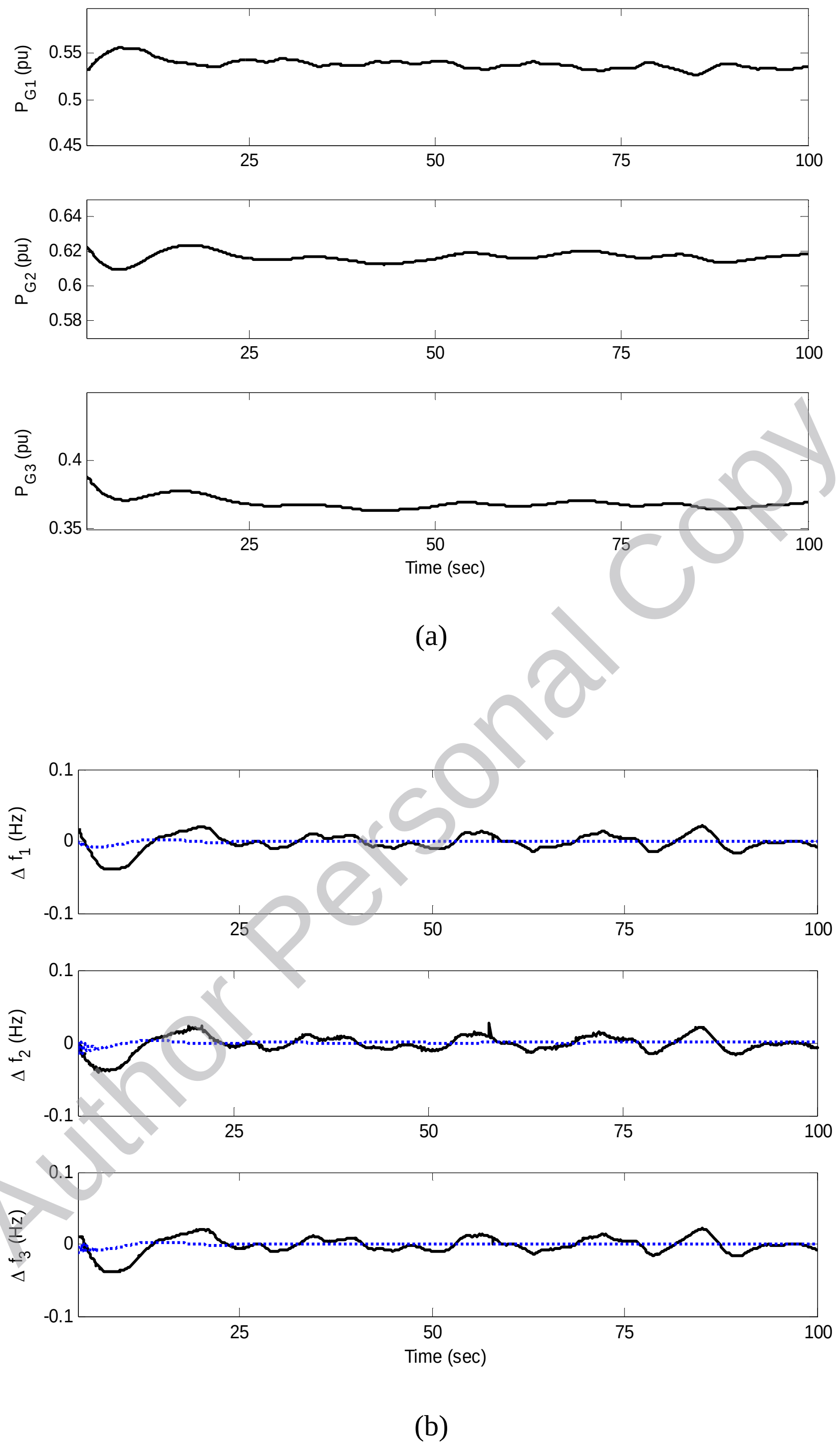

Fig. 4. Conventional generators response; a) output power, b) frequency change (dashed-line shows response with PV unit only).

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 isolated power system must be considered, and the LFC designs need to consider altering their frequency control strategies to avoid long rates of change of the system frequency.

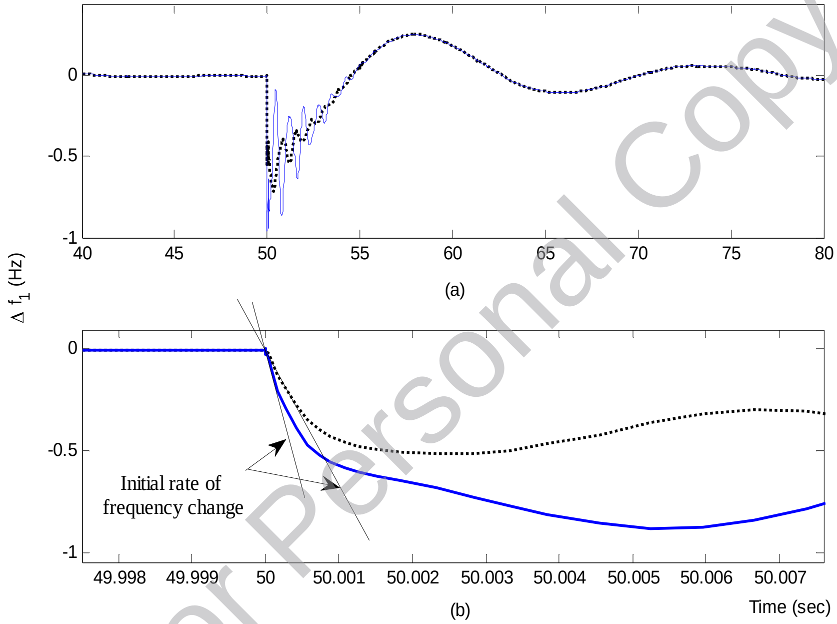

Fig. 5. Frequency deviation following 0.05 pu step load disturbance at 50 sec, with (dotted) and without (solid) RES units. Figure (b) shows a zoomed view around 50 sec.

In these cases, using compensation devices such as energy capacitor systems (ECS) and batteries [13, 94], and optimal/robust tuning techniques such as those described in [79-80], 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 [94]. In [94], 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.

7. Conclusion

This report presents an overview of the key issues concerning the integration of renewable energy sources (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 analyzed, and the need for the revising of frequency performance standards is emphasized. Finally, a nonlinear time-domain simulation study and a remark on the use of df/dt protective relays and future work is presented.

Appendix

Substituting $M_i(s)$ from [82] or [83] in (9) and (10), and using the final value theorem, the frequency deviation in steady state can be obtained from (9) as follows

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

where

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

$$\Delta P_{RES} = \underset{s\to 0}{Lim}\, s.\Delta P_{RES}(s) \tag{17}$$

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

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 [76], $g(0)$ is equivalent to the system's frequency response characteristic (β).

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

Using (18), the equation (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 ($0.05 \leq R_k \leq 0.1$) [83], for a given control system according to (19) we can write $R_{Sys} \leq R_{min}$. 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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