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Automatic Generation Control in Wind Integrated Power System: New Perspectives and Challenges

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Abstract

Green energy targets for coming decades advocate high penetration of wind energy in main energy matrix, which pose incendiary threat to stability and reliability of modern electric grid if their integration aspects are not assessed beforehand. Real-time balancing of demand and supply or Automatic generation control is a challenging task in modern electric grid when penetrated with unpredictable and variable wind power. Regulation power along with corresponding cost is expected to increase highly with increased penetration of wind energy in main grid. With conventional plants getting abridged under renewable energy targets; wind plants as largest energy contributor are expected to actively participate in providing frequency regulation. Even though ample literature exists describing traditional role of conventional fuel based generating system for frequency regulations in electric grid, yet very few of them deal with frequency regulation of wind energy integrated power grid till date. This paper reviews the existing research literature for automatic generation control involving secondary frequency regulation for wind integrated power system. An attempt has been made to give an insight to new perspectives & challenges for secondary frequency control which need more advanced investigation for future implementation in electric grid. A modelling approach for studying secondary frequency regulation with technologically advanced wind integrated power system is also presented.

Keywords: *Automatic Generation Control, Secondary Frequency Control, Area Control Error, Inertia, Intelligent AGC, Frequency Control Ancillary Service*

1. Background

The power grid is an enormous, intricate system and pervasive with interactions between all the different components and across time. When any new technology gets connected to this complex grid, its compatibility to rest of grid will be determined by a number of basic characteristics. Renewable as a future fuel security and price off-set option have become an attractive proposition in current global scenario. There is an eternal growing obligation for electricity from renewable energy sources (RES). The impact of the renewable energy technology on the grid and its contribution to the grid is still relatively unknown with a number of challenges needing to be overcome before mass deployment.

Wind power credentials as a rapidly deployable clean technology have put it at the forefront in the fight against climate change. Wind is the most cost competitive renewable source of electricity generation behind hydro power. This proven and mature technology has highly penetrated energy matrix at global level, hence among all available RES, maximum impact potential lies with wind power at largest scale. There has been a tremendous increase in generated megawatts by the RES all over the world. Wind energy has optimistic prospects as partner in energy resolution which can

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pave the way for shaping a new sustainable world for future generations. According to a 2013 published key report by Renewable Energy Division (RED) of the International Energy Agency (IEA) [IEA, 2013], wind power deployment has more than doubled, approaching 300 GW cumulative installed capacities led by China (75 GW), the United States (60 GW) and Germany (31 GW). Wind power now provides 2.5% of global electricity demand – and up to 30% in Denmark, 20% in Portugal, 18% in Spain. Wind energy is anticipated as a major contributor for the foreseeable future with 20% per annum growth forecast for global installed wind energy capacity. Although most wind-power developments still attract financial support - either in the form of capital subsidies or premium payments for the energy — the gap between the generation costs of wind energy and electricity from conventional plants continues to narrow and are close to cost-competitive with new natural gas generation due to continuing technological innovation. The onshore wind costs fell in 2014 and, a realistic best generation cost for onshore wind is now $71/MWh on a global basis [Milborrow, 2015] [BREE, 2014]. A Bloomberg report has listed wind as cheaper electricity producing fuel than fossil fuels for Australia which is world's biggest coal exporter. A new wind farm in Australia supplies electricity at a cost of 80AUD / MWh, while it comes out to be 143AUD / MWh for a new coal-fired power plant or 116AUD / MWh when supplied from a new natural gas powered station in 2013 [Bloomberg, 2013]. Prospective plunge in LCOE of wind is expected in the near future due to emergence of low cost but high technology wind turbine manufacturer. Allowing wind generation to provide economic offers in the electricity market will promote increased market efficiency as well as enhanced reliability and large savings to all market participants. Ancillary service markets could bring additional revenue streams. The analysis needs to be done to show that there is a potential for wind plants to aid power system reliability and to increase their own profits by providing regulation services. Integration of wind energy at large scale has widespread impacts on power system stability & reliability making it imperative to further improve the efficiency of an electricity system which is very different from what we had few years back. In the past, the balance between supply and demand in the electricity system rested primarily on generation technologies that were highly manageable; capable of regulating their production to adapt it to the evolution of the demand. Now the trend is changing. Increased penetration of wind generation in interconnected power system thus intrinsically calls for Load Frequency Control analysis with present and future wind technologies.

This paper introduces automatic generation control (AGC) involving secondary frequency control and reviews the existing research work related with wind energy penetrated power system. Section II presents the state-of-the-art load frequency control in presence of wind energy. Section III highlights the secondary frequency issues and approaches used in past by researchers and highlights the study line used till date. Finally, section IV emphasizes on new research challenges and issues for AGC in wind integrated power system.

2. Premises for Automatic Generation Control and Wind Energy

Wind power generation is a stochastic process that is a function of both space and time. Integration of this continuously variable wind power generation introduces uncertainty & instability in power system operation. Talking about wind integration in electricity grid has broad interpretation ranging from the very technical all the way to social issues. Quantification of wind impact on grid integration is a very active research topic with many challenging questions and issues. One of these issues is the need of frequency response capability of wind energy generating system. Fluctuations in the summated output of all wind farms connected to a power system will cause frequency to fluctuate and may change the anticipated power output of dispatchable generation affecting dispatch in the next few hours and unit commitment in the next few days. With wind being non-manageable primary energy, wind upward and downward ramp may reach ±1500MWh [REE, 2010]. Unexpected sudden changes in the summated output of wind farms, due to either a widespread change in wind conditions or in response to a power system disturbance are contingencies that must be assessed for their implications for reserve requirements. Recent studies have found that the renewable integration impacts on system frequency and power fluctuation are nonzero and become more significant at higher sizes of penetrations.

Preponderance on renewable sources like wind energy that demand different management as compared to conventional system, has moved the electricity grid in a transition phase to a new model. These sources having new production and nonlinear control technology imply new energy management system (EMS) with Automatic Generation Control (AGC) being one of the major units of EMS in modern power system [Stanton et al., 2007]. AGC in deregulated manifold environment plays a dynamic part in automation and ultimately reliable and stable operation of electric grid at a satisfactory level. AGC represents a remarkable economical function of EMS system for energy market dispatch of generating units and regulating frequency control ancillary service (FCAS) dispatch. It is an important tool for regulating the balance and distributing the imbalance between designated units. AGC makes up as part of real time energy market dependent upon load forecast. AGC system cost in modern power system consists of load frequency control time frame, economic dispatch; interchange scheduling of individual generators in many generating units. Cost of load following imposed on system due to variable wind power is also calculated on the basis of AGC set points and system dispatch requirements. The sensitivity of any power plant depends upon the response time taken by the automatic generation controller to control the frequency change due to load variation of governor control.

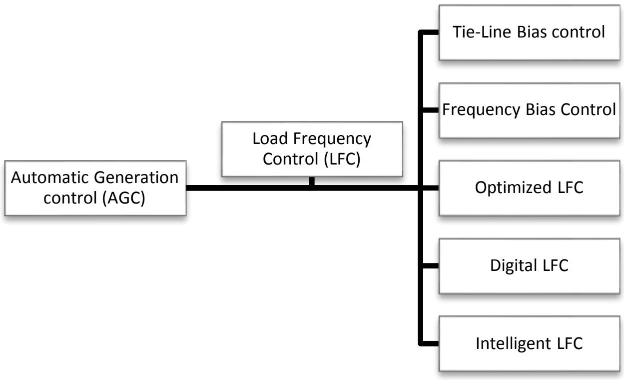

Figure 1: Conventional Power System Study Line for AGC

3. AGC & Wind Energy Research: Past & Present – A Literature Review

The AGC problem has been extensively studied during the last four decades and it has been one of the most highlighted issues in the design and operation of independent and interconnected power systems. This section highlights some of the issues and principles taken into account in studying frequency regulation in wind penetrated power system. It is the IEEE working group which provided the standard definition for power system AGC [IEEE, 1970]. AGC as defined by IEEE is the regulation of the power output of electric generators within a prescribed area in response to changes in system frequency, tie-line loading, or the regulation of these to each other, so as to maintain the scheduled system frequency and / or the established interchange with other areas within predetermined limits [IEEE, 1970] [IEEE, 1979] [Hassan et al., 2011]. Load-Frequency Control (LFC) is used as part of AGC to maintain a constant frequency and to regulate tie line flows. LFC represents the first implementation of a higher-level control system. It has made the operation of interconnected systems possible and today it is still the basis of any advanced concept for guidance of large systems. Figure 1 gives the general study line of conventional power system which has been followed for AGC research. Cohn extensively studied the static aspect of net interchange tie line bias control strategy [Cohn, 1957]. On the static analysis basis, Cohn has inferred that, for the minimum interaction between control areas, the frequency bias setting of a control area should be matched to the combined generation and load frequency response of the areas. However, no analysis was made regarding deciding the magnitude of gain settings for the supplementary controllers. Concordia & Kirchmeyer studied AGC problem of two equal thermal hydro systems by simulating system differential equations [Concordia et al., 1953]. Although they have extensively studied the effect of variation of several parameters on the dynamic responses, no explicit method was proposed by them for optimization of controller's gain. The first optimal control concept for megawatt-frequency control design of interconnected power systems was addressed by Elgerd and Fosha (Elgerd et al.,, 1970) [Fosha et al, 1970] which was concerned with classical approach to determine the optimum integrator gain for area control errors. AGC advanced fast from the period when the task was accomplished manually, through the days of analog systems to the present application of sophisticated and refined digital control systems. With changing power system scenario and constraints; variations to AGC definitions along with dynamic modeling of system have been presented over past time periods [Jaleeli et al., 1992] [IEEE, 1979]. System nonlinearities and dynamic behaviors such as governor dead-band and generation rate constraint, load characteristics, and the interaction between the frequency-real power and voltage-reactive power control loops for the AGC design procedure have been considered [Concordia et al., 1957] [Wu et al., 1978]. Digital load frequency control model was also designed and investigated to match the generation to the varying system demand and economic dispatch program giving minimum system cost [Mello et al., 1973]. Power system load frequency control had also been tested by applying the variable structure control to make the controller insensitive to the plant parameter variation [Benjamin et al., 1982]. An algorithm for the SCADA system involved in AGC system of the ellenic interconnected system had been developed [Vournas et. al., 1982]. Chemical battery energy storage [Kunnish et al., 1986] and small sized magnetic energy storage (SMEs) [Banerjee et al., 1990] as another option for providing load frequency control and instantaneous reserve has also been presented and implemented at small scale.

A control area regulated by hydro generation interconnected to another area regulated by thermal generation or gas generation, solar generation, wind generation is a usual combination in a mixed power system,. With increasing RESs integration into grid, it's a necessity to explore their impacts on AGC at the planning stage and in real time operation. It has been indicated by recent investigations that large penetration of wind energy will have an impact on modern power system frequency regulation along with AGC systems and other control operation issues. AGC is expected to be a major player in management of short term uncertainty of renewable power system output as well as in mitigation of short term impacts due to variable generation forecast error. Wind energy integration calls for modeling the optimal generation. Thus lot of research is underway to review and analyze wind energy association with AGC performance criteria, capabilities and technologies for ensuring proper system performance. Figure 2 illustrates the line of thoughts being followed for studying AGC impact of wind energy penetration. Michael et al. developed a methodology to enable wind farm participation in automatic generation control using energy storage devices [Michael, 2012]. Energy storage devices are used to neutralize the uncertainty of wind power plant output and maximize the dispatch ability. Fast charging and discharging of stored electricity in cost effective electricity storage devices smoothen fluctuations in frequency thus reducing the obligation for back-up capacity to balance load and supply. These technologies are further needed to be evaluated on the basis of various technical benchmarks like working principle, startup response time, power capacity, shelf life and cyclability along with economical benchmarks like investment price & expected lifetime. With reduced uncertainty, wind farms are shown to have better AGC performance. Conventional AGC model assumes a direct physical connection generators set point change and secondary control signal provided by the transmission system operators. The conventional LFC designs based on classical control have less adaptability, are not very efficient and are therefore not suitable for modern power systems with large interconnections, varied structure and more penetration of renewable energy sources, specifically wind energy with varied uncertain source and exigent demand for power quality. It is expected that application of modern robust, automatic and intelligent control techniques to the LFC schemes will be more adaptive and appealing approach for wind based power system to overcome impositions set up by technical standards of energy market regulators.

Application of several computational techniques have been researched for the frequency regulation in conventional power system; however, the large integration of wind energy system have created a gap in theory and application with just few reports available on the frequency control design in the presence of wind power units. A critical analysis of few studies dealing with AGC implementation under the presence of wind is given in Table 1.

Table 1: Wind – AGC: A Review

Ref.	Methodology	Special Findings
[48]	Wind farms incorporating energy storage systems for AGC participation	Software simulations along with in-lab grid were used to evaluate energy storage controller. A control structure for wind participation in AGC was presented but didn't shed any light on technical aspects of wind farms and AGC impact on their performance.
[22]	Modelling framework for studying wind energy impact on power system frequency performance metrics	Presents analytically traceable AGC model based on nonlinear differential algebraic equation (DAE) formalism but utilizes wind energy system based on first model differential equations and third order DE for synchronous generators. Modelling framework can be tested for higher order DE based wind energy systems.
[37]	Hierarchical AGC system for wind farms	Designed and tested AGC real wind farms data. Good AGC performance was observed with better grid integration during simulations with introduction of variable wind, large electrical disturbance.
[25]	DFIG based variable wind power was disintegrated into slow, fast, and ramp components to evaluate their impact on power system operation	Variations in wind power can be absorbed easily within most power systems. Wind penetration approaches and control area performance measures were also discussed. HyperSim software was utilized for simulation studies of isolated power system. Wind impact on system response was analyzed but would be interesting to learn system frequency deviation impact on wind farms.
[42]	DFIG based wind farm integrated with thermal energy system was used in study	Implementation of AGC in wind farms calls for close interaction with other generation plants. It is estimated in this study 5% of rated plant power can be accepted as perturbation power by thermal plants, without exceeding the 1%frequency deviation margin.
[41]	Fixed speed and DFIG based wind energy system was used in Matlab based simulation to show wind penetration effect	Single bus bar model of Ireland electricity system was implemented to access demand-response imbalances. Rates of change of system frequency increases due to contrary inertial response characteristics posed by high wind penetration.
[10]	Two area Dutch power system is formulated to model the imbalance control by PRPs via minimization of their energy program deviations	Wind AGC performance is accessed. Wind variability has direct and indirect impact on area control error and commissioning-Decommissioning of conventional plants.
[5]	Designed APC controller and field tested for NREL's 550kW 3-bladed Controls Advanced Research Turbine (CART3)for AGC participation	Wind power AGC is fast and accurate especially at high wind speed and AGC error is low with multiple turbines in wind farms.
[62]	Two-tier structure of flatness-based control for automatic generation control (AGC) of a multi-machine system with high penetration of wind energy	Distributed AGC is easier to design and implement and shows promising performance with wind penetration.
[6]	Two control levels for AGC & hierarchical system	Improved AGC performance and better integration of wind with grid when supervisory system controls active and reactive power while machine system controls turbine power set points.
[29]	Wind plant level AGC	Blade pitch and generator torque control for reference power signal tracking at plant level
[23] [18] [26] [12]	Fuzzy logic PI control, Isolated wind-micro hydro-diesel hybrid power system using neuro-fuzzy controller, Particle swarm optimization technique, Genetic algorithm GA for PID controller	Frequency deviations correction improved low settling time with application of these computation techniques but needs to be accessed further for different wind energy technologies. These techniques need to be assessed for implementation feasibility and corresponding impact on various parts of wind energy system.

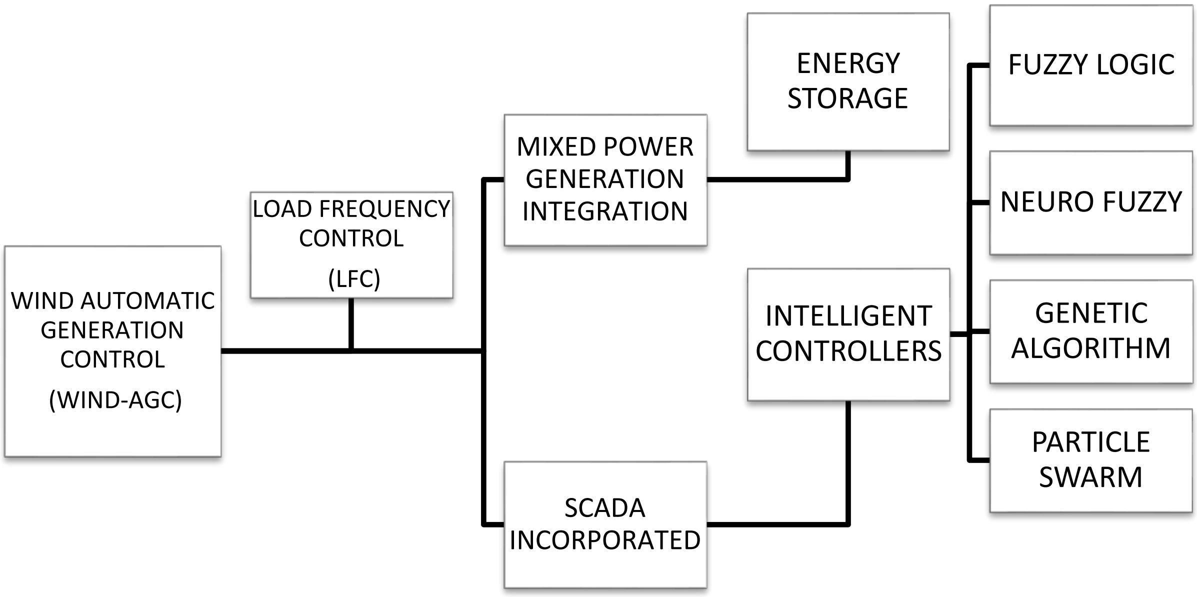

Fig 2: Present Wind Energy Study Line for AGC

4. AGC & Wind Energy Research: New Perspectives & Challenges

Wind energy has the potential to maintain and even exceed the dynamic growth rate of the past several years. It remains important for researchers to develop more reliable designs and technology to help wind integration with electric grid and provide knowledge base to concerned authorities so as to maintain long term growth and innovation in generation, transmission and demand technologies and commercial arrangements. This section provides some insights into frequency related issues which needs more research for implementation in the wind farm future grid code development. Implicit implementation of these issues can lead to development of wind farm grid codes and implementation policy which will pave way for wind farm operation that is optimally balanced between energy cost and technical performance.

4.1 Spatially Distributed Wind Farm AGC

A comprehensive literature exists which deals with lots of variability and uncertainty in wind power output [Undrill, 2010] [Martinez et al., 2010] [Illian, 2010] [Mackin, 2010]. Wind variability ramp down event is not as abrupt as sudden loss of conventional generator and not as smooth as load ramp-down daily cycles [Garcia, 2012]. Inspite of technological development and implementation, there is a limitation on ability of modern wind energy based power system in contributing to regulating frequency under few seconds after a contingency. Most of the solution proposed in literature mimics the traditional AGC response of synchronous generators. In a highly wind penetrated power system, with varying wind power and load uncertainties, there is a spatial variation of frequency standards and required regulation over control area. So for wind energy system (WES), traditional lumped ACE input changes to distributed ACE and conventional AGC changes to spatially differentiated frequency regulation. One of the studies indicates that wind farms spread over large geographical area have relatively low regulation limits [Holttinen, 2006]. As shown in Figure 3, power fluctuation smoothens out for greater wind diversity over a spatial region.

At normal operation, the power output of a wind farm can vary up to the 15% of installed capacity within 15 minutes [Ackermann, 2005]. The spatial distribution and intermittency of wind resources affect power system on time scale being followed by AGC and raise the cost of wind based electricity. A research from NREL done under German weather conditions shows that ancillary service requirements decrease substantially for large number of turbines and due to spatial diversity of wind resources. Regulation analysis from same report also advocates that the physical separation of wind plants has lesser effect on regulation burden than number of turbines [NREL, 1999]. Advance investigation is needed for such spatially distributed & large aggregation of wind turbines on AGC under various grid codes. AGC system along with economic dispatch of respective electric network needs improved modeling to account for unique features of wind generation and mitigating its variability effect.

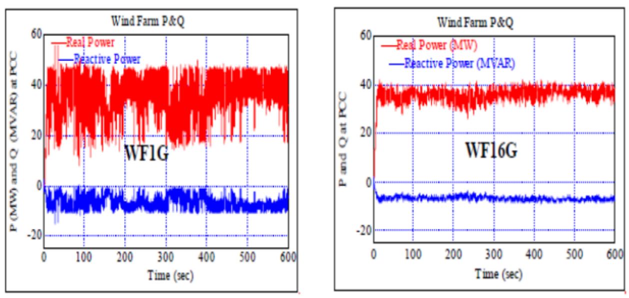

Figure 3: Real and Reactive Power Output of Wind Power Plant a) For Single Turbine b) For Sixteen Turbines [Martinez et al., 2012]

4.2 Inertia Supported Wind Farm AGC

It is well known that AGC action is preceded by primary regulation activity in a power system. Load frequency control (LFC) action assumes same area control error (ACE) throughout the concerned power system but this assumption does not completely satisfy with wind power based system. High wind penetration in power system induces large imbalances and brings instability and power quality issues. With secondary regulation getting exhausted due to wind load variability, it is very likely that primary control actions of power electronics based generation technologies also reducing frequency regulation capabilities in case of a fault [Miller et al., 2011]. Primary regulation is provided by power system inertia which controls the system frequency rate of change in case of an imbalance of load and demand in the system. Power system rotational inertia is normally time-variant and gets reduced non-uniformly with respective grid topology. Primary inertial control can improve frequency nadir but do little for improving settling time as inertia of a system is directly related to mass of generating machine and respective prime movers. A high stable power system has high inertia and low RoCoF. Due to energy economics, quantity of synchronous generators operating will be less in case of low load demand and high penetration of wind energy, leading to reduced total grid system inertia. Frequency regulation and hence sensitivity and stability of total system is largely dependent upon total system inertia. Managing total system frequency thus stability without inherent inertial response will be difficult for wind penetrated power system. Studies indicate that power system having equal value of spinning reserves but having different inertia levels express varied frequency responses in case of any contingency. Research indicates that low inertia will have worst effect for power system having slow frequency response [Andreas et al, 2014]. So modern wind based systems are supplementing their inertial response by adopting additional controllers and using energy storage systems and synchronous condensers. Modern wind plants have the ability to control active power output in response to grid frequency by providing inertial and governor response. The wind turbine can fast store or release a large amount of kinetic energy in the rotating mass because of the power electronic converter control, large moment of inertia and wide rotational speed range. Wind turbine inertial response is essentially energy neutral, meaning that the period of increased power is followed by a period of decreased power. The inherent inertial response by wind turbines is also not same under all operating conditions but depend upon active controls. Wind farm operation based on the maximum power capture curve to extract maximum wind energy needs replacement to de-loading curve to save the available power as reserves for the long-term frequency control. Various supplementary inertial controls attribute and designs have been proposed in literature to achieve active frequency regulation; inertial control and droop control being prominent one. Inertial control acting as extra loop utilize rate of change of frequency while droop control use frequency difference between measured frequency and actual frequency to adjust power to reduce frequency deviations. There is no standard to quantify the effect of supplementary frequency regulation loop on the maximum rate of change of frequency (RoCoF). The wind inertial control increases the system inertia but the inertial power may mask the load changes for a few seconds because of the considerably released kinetic energy from the rotating mass. Therefore, the synchronous generators may delay their responses to the frequency events. Varied decentralized and/or distributed control methodologies to implement inertial and AGC response at turbine level and real scale power plant level with high RoCoF ride-through capability is still very nascent and needs more attention as research in this field appears to be sparse.

4.3 Intelligent AGC

Conventional optimization techniques based on various mathematical programming methods have been previously utilized in power system operation and control but they are constrained to perform search operation for local optimum. Modern smart grid with multigenerational integrated power system calls for computational intelligence (CI) and evolutionary computation (EC) techniques for robust and optimum results in AGC regulation. Bevrani and Hiyama advocates the usage of an intelligent configuration as best solution for improving the contribution of a renewable power plant in AGC function [Hassan et al., 2011]. It has been established that overall deviations in grid frequency and regulation time can be reduced by incorporating intelligent controllers and distributed AGC in a general power systems operating under restrictions and certain operating ranges. With the availability of highly capable variable generators, automatic response to frequency is getting improved for wind plants. Pitch angle control and rotor seed control have been deduced as popular frequency control techniques at turbine level [Juankorena et al., 2009] [Ma et al, 2010] but absence of intelligent controllers in a wind penetrated system can cause stability problems and penalties causing consequent losses in revenues. Application of intelligent algorithms incorporating high degree of optimization and control strategies can better respond to existing complex variables of power system models and supports AGC in mitigating the demand and load imbalance in interconnected system. Intelligent load frequency controllers will be front runners to enhanced performance, improved tuning and adaptive competencies. More advanced simulation involving high fidelity system models and control capability is needed to analyze the full potential and impact of AGC for wind penetrated system. These needs to be real time verified and investigated for wind integrated system with application of intelligent techniques like neural networks, genetic algorithms, multi agent systems.

4.4 Fault Ride Through (FRT) Capable Wind Farm Effect On AGC

With increasing renewable energy penetrations in modern power system, all national TSOs have put stringent ride through capability limits on these power systems. Ride through capability refers to the ability of generators to remain stable and connected during normally cleared balanced and unbalanced electrical faults on a transmission grid. This constraint has been enforced as mandatory to evade substantial loss of wind energy generation in the occasion of grid faults. Earlier trend of disconnection of wind farms pose significant damage to frequency and voltage regulation leading to black out in case of major fault. So as per various national grid codes, their current wind plants are required to limit their active power as a function of system frequency in case of over frequency event. Australian grid code [Western Power, 2011] requires their wind plant to provide ride through multiple faults even though it is not cleared during reclosing sequence of transmission lines. Even though technical solutions exist now for overcoming fault ride through behavior, there are other rising issues which need to be further addressed. More involvement of type 3 & 4 wind turbine by displacing synchronous generators will result in higher RoCoF and instability in total system. For longer duration faults, turbine blade pitching strategies along with turbine converter control becomes necessary. FRT compliance is generally assessed at point of connection (PCC) while manufacturers specify operating range of wind turbine generators at its low voltage (LV) terminals. Depending upon short circuit ration (SCR) at point of coupling (PCC) and wind turbine type, there can be varying stress on different parts of turbine when it is subjected to near-to-generator disturbances. Integration of wind energy with network having low short circuit ration (SCR) has increased risk of system instability even though with FRT capable wind turbines. Wind farms with such fault ride through (FRT) capabilities are very likely to deteriorate frequency regulation as frequency deviations generally result in voltage instability. As a result, energy withdrawn by FRT action may increase the size of any contingency and thus the magnitude of frequency deviations leading to total system instability. In order to analyze FRT implementation impact on frequency regulation performance of wind farms; it is important to conduct more research & assessment of these FRT capable wind system by modeling their electromagnetic characteristics and wind turbine generator speed over the timescales.

4.5 Frequency Control Ancillary Service (FCAS) As AGC Output

Frequency control, one of the ancillary service requirements are calculated on the basis of contingency size, total inertia of power system and load demand. Frequency control ancillary service (FCAS) providers bid their services into the FCAS markets in similar fashion like generating units bidding into the energy market and receive financial incentives. Payments for ancillary services include payments for availability and delivery of the services. Service providers must be able to show their conformance to the ancillary services specification. FCAS represents a guarantee that power will be continued to be delivered in case of contingency. Primary control and secondary control makes up an important factor in this regulating market for balance responsibility. FCAS availability holds a very important value for high wind penetrated power system with low inertia. Wind energy which produce electricity at low prices can gain financial revenues if participate in provision of regulation services. In a deregulated environment, energy market participants are required to make supplementary control contributions to transmission system operator (TSO) for stable and reliable power system. In order to meet control area performance criteria, AGC participants must track and keep record of instantaneous fluctuations in demand load for continuous duration so as to keep ACE within limits. For a transmission system operator, assignment of control duties gets constricted with presence of wind system. System operator aims to minimize the payments to participants for providing AGC ancillary service while wind participant strives to maximize their revenues. AGC manages continuous correction of frequency deviations as regulation raise or regulation low service as part of market based ancillary service in Australian market. Australian energy market operator (AEMO) has the requirement for FCAS to ensure the frequency to be contained within 49 to 51 Hz in the event of step changes in supply that result from credible contingencies known as "separation event". According to Australia's national electricity market (NEM), it is compulsory for generators >=30 MW to participate in FCAS [Thorncraft et al., 2007] though none of the wind farms participate in it. An impact assessment of large scale renewable energy target done for Australian Energy Market Commission (AEMC) reported an increase in regulation requirement from ±120MW to ±800MW and increase in frequency regulation cost from 10 million pa to 200 million pa in 2020 due to projected increase in intermittent wind energy. Causer-pays methodology is being implemented in Australia for settling regulation costs, with generators or loads paying for any deviation from their expected dispatch. With increased wind penetration, majority of cost is anticipated to be borne solely by wind farms leading to an escalation in regulation costs for wind generators from around \$0.40 /MWh at present to \$6 - 8 /MWh in 2019-20 [AMEC, 2011]. This increase in wind farm costs could have significant repercussions. Wind farms can boost their revenue and decrease total costs by implementing frequency regulation technology. North American Electric Reliability Corporation (NERC) has enacted control performance standard (CPS) for evaluating frequency control performance in a control area. Control areas must not be less than 95 % compliant with CPS1 and no less than 85% compliant with CPS2 [NERC, 2014]. A Study by Wang & McCalley indicates that CPS1 & CPS2 deteriorate with increasing wind penetration and this effect is observed more for large interconnected systems (Wang 2013). Improved load forecasting along with better AGC is required to improve these control performance standards. According to European Network for Transmission System Operators for Electricity (ENTSO-E), all TSOs must ensure regulation service which should be at least 50% operational within 15 seconds and fully operational within 30 seconds of any contingency exceeding ±20mHz [ENTSO-E, 2004]. A very fast response is needed to seize frequency decline and control frequency nadir within first 5-10 seconds. Energy storage technologies have fast response making them suitable for providing frequency regulation ancillary services. According to a report by California Energy Commission (CEC), application of energy storage for regulation purpose can be around two to three times as effective as adding a combustion turbine to the system [KEMA, 2010]. Besides technology, market policies as well as system infrastructure also play vital role satisfactory AGC performance in a wind energy integrated power system. More research in terms of technology, policies and infrastructure is needed for incorporating AGC in wind system to enable their active participation in FCAS, better energy economics and compliance to control performance standards. Proper management of FCAS can be a key factor for better penetration of wind in a deregulated complex power system.

5. Basic Modelling Approach

For smaller power systems with low inertia or system with low primary frequency response, frequency stability may be a problem when large amount of wind is integrated to the system. There is direct coupling between power system frequency and active power output and corresponding torque of synchronous generators in conventional generating plants as in Eq. (1).

$$\Delta F(s) = [\Delta P_{Gen}(s) + \Delta P_{Wind}(s) - \Delta P_{load}(s) - \Delta P_{Tie}]\frac{K_P}{(1+sT_P)} \quad (1)$$

$$T_P = \left(\frac{2 * Heq}{D * f^0}\right), \text{power system time constant}$$

$$K_P = \frac{1}{D}, \text{power system gain}$$

For pool operation, tie-line bias control is desired as represented in Eq. (2):

$$\Delta P_{tiei} = T_{ij}[\Delta F_i(t) - \Delta F_j(t)]; i, j = 1,2,3; i \neq j \quad (2)$$

ΔP_{tie} is Tie-line power deviation and ΔF is the frequency deviations. Each area involved in pool operation supply its own load and such portions of others load as had been agreed upon in normal steady-state. Transmission system operators (TSOs) control the amount of wind power to be captured by sending balance control or delta control signals to AGC capable wind plants. It is required that the steady state tie-line power deviation following load changes must be brought to zero which is accomplished by finding area control error as a linear combination of incremental frequency and incremental tie-line power. With large wind penetration in area 2, corresponding ACE signal representing generated wind power changes can be given as Eq. (3)

$$ACE = b\Delta f + (\sum(P_{tie-con,act} - P_{tie-con,sched}) + \sum(P_{tie-WTG,act} - P_{tie-WTG,estim}) - IM3 \quad (3)$$

Where, Ptie-con, act is actual conventional power and Ptie-con, sched is scheduled conventional power & Ptie-WTG, act is actual wind power and Ptie-WTG, estim is estimated wind power. bΔf is frequency bias setting (MW/0.1Hz) multiplied with frequency changes between scheduled and actual values. This is also known as flat frequency control. IME is interchange (tie line) metering error which is accounted from meters installed at end of tie-lines. More advance formula for ACE can be found from WECC [WECC, 2006].

Researcher aims to study some of above mentioned challenges using the basic AGC model for three area ring topology interconnected power system model as given in Figure 4. Each control area block models the equivalent machine dynamics of the different combinations of thermal, hydro and gas based generating plants. Wind farm integrated second control area equivalent inertia is considered lower than other two areas. IEEE defined generator-load, thermal & hydro turbine governor models (Kundur, 1984) along with GAST model (based on split shaft) [Hajagos et al, 1999] [Nagpal el al, 2001] are used in this model. Technological developments in modern wind-turbine generators (WTGs) have produced nearly comparable inertia constants with those of conventional turbine-alternators. The generator speed of these VSWTs can drop to as low as 0.7 p.u. speed giving wide range of speed change operation, while conventional unit speed can only drop to as low as 0.95 p.u. speed. Other important feature of VSWT is the possibility for their active power outputs to be controlled as required by system operators. This is an important feature, although the steady-state active power delivered to the grid by a VSWT depends on the mechanical energy transferred from the wind, the electric power can be transiently controlled, to a certain extent, by resorting to the mechanical system kinetic energy. It is now expected to utilize kinetic energy of wind to provide temporary primary frequency control support to the grid in the event of a load/generation mismatch. Doubly fed induction generator (DFIG) based variable speed wind turbine model [Clark et al, 2009] reflecting dynamics of pitch controller loop, active power-torque control loop has been utilized in wind farm model as shown in Figure 5. In presented wind farm model, a reference wind speed Wref is generated for maximum power tracking based on electric power Pe function -0.67Pe2 + 1.42 Pe + 0.51. A supplementary control loop reacting to system frequency emulating inertial response of a synchronous generator is added with torque controller. The principle of inertial response is to modify the reaction torque in response to a change in system frequency by adding an extra torque term to active power-torque control loop.

Load frequency study conducted by researcher provided varying response for inertia emulated wind farm integration with different generating system in terms of dynamic frequency response & frequency deviation settling time with best combination obtained for wind integrated with base load plant - thermal based plants followed by hydro and then gas based plant. RoCoF was assesses as varying from -2.7446 hz/sec for thermal wind to -2.33hz/sec for hydro-wind and -3.075hz/sec for gas-wind. A supplementary control loop reacting to system frequency emulating inertial response of a synchronous generator was added with torque controller loop of wind farm. Introduction of the supplementary inertial response from wind turbine indicated a smoothing effect on overshoot and undershoot of total system frequency response from AGC. Dynamic response as achieved by the developed three area model is given in table 2. The supportive role of wind turbines during frequency drops is still not clear enough, although there are many proposed algorithms. It was also observed that wind integrated area tries to closely match AGC response of other two areas though frequency nadir, rate of change of frequency (ROCOF) & settling time is more for wind integrated area.

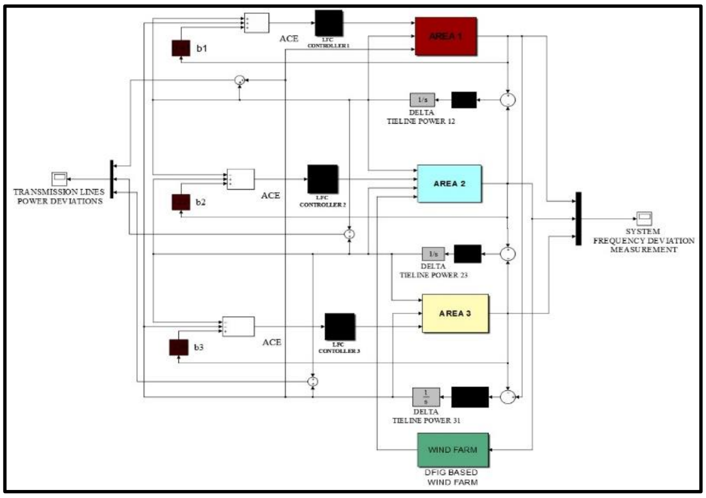

Figure 4: Ring Interconnected Three Area Wind Integrated AGC Model

Table 2: Dynamic Response for 3 Area AGC Model

System	Response	Settling Time (s)	Comments
Thermal-Thermal-ThermalWind	Frequency	15	Peak overshoot: 2.795, FNadir :-1.99, $\Delta f/\Delta t$ = -2.7446hz/sec
	Tie-line Power	25	
Thermal-HydroWind-Thermal	Frequency	40	Peak overshoot: 3.81, FNadir :-1.612, $\Delta f/\Delta t$ = -2.33hz/sec
	Tie-line Power	50	
Thermal-Gas-HydroWind	Frequency	60	Peak overshoot: 3.279, FNadir :-2.08, $\Delta f/\Delta t$ = -3.075hz/sec
	Tie-line Power	60	

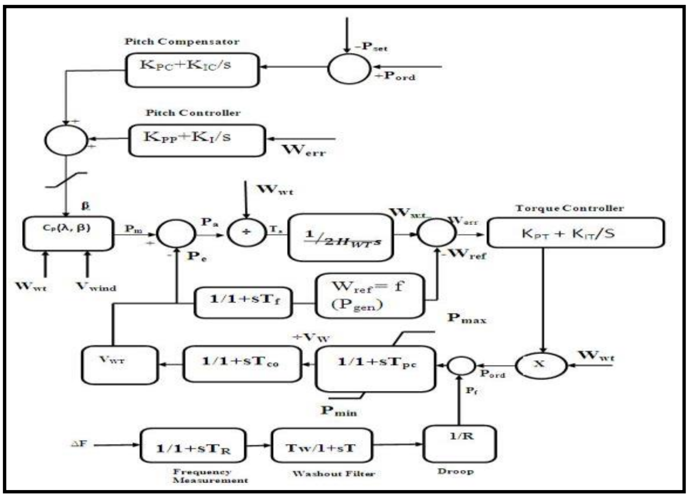

Figure 5: Single Mass Generic Type Three DFIG Wind System Model for Frequency Response

6. Concluding Remarks

Imbalance between energy production and its consumption is best indicated by frequency in a power system. Primary and secondary regulation comes into act to return the balance in the system. Research has established that higher wind penetration induces large variations in system frequency and reduces regulation capability to large contingencies. A number of solutions have been proposed to mitigate wind penetration effect on frequency regulation but research on impacts of wind energy on secondary regulation performance and its integration with electricity market is still very sparse. AGC is expected to be a major player in management of short term uncertainty of renewable power system output as well as mitigation of short term impacts due to variable generation forecast error. It is expected that application of modern robust, automatic and intelligent control techniques to the LFC schemes will be more adaptive and appealing approach for wind based power system to overcome impositions set up by technical standards of energy market regulators. Still a lot of research is required to review and analyze wind energy association with AGC performance criteria, capabilities and technologies for ensuring cost effective, industry prone frequency regulation system leading to a stable wind integrated large power system. With improved turbine and intelligent controller technologies, AGC researchers have to look deeply into several new aspects for achieving long term economic sustainability of wind energy.

As reflected in Figure 6, modern wind AGC system differentiates itself from conventional AGC system by being spatially distributed AGC which also considers synthetic inertia and fault ride through capable wind system. The intelligent AGC strives to emerge as an important FACS output for a highly wind penetrated power system. Effective research and implementation of these terminologies in AGC will help wind energy market participants to make better contributions to frequency control ancillary services to transmission system operator (TSOs) and an overall more reliable power system.

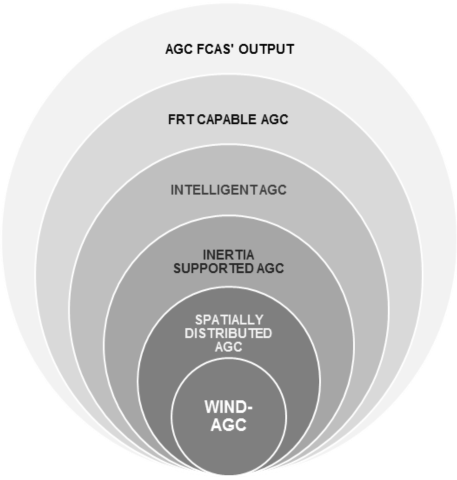

Figure 6: Evolving Challenges for Wind-AGC

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