An Integrated Wind Turbine and Power Grid Mode

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***Abstract*— Growing penetration of renewable sources of power generation around the world causes a decline in the inertia of power grids. This poses a direct risk to safe operation of power systems, as frequency stability becomes difficult to be maintained and managed. Being able to predict and react to grid frequency variations is crucial to ensure reliable supply of electricity. This paper developed an integrated model of wind turbine system with power grid model for frequency stability investigation with the objective to evaluate how renewable wind generation impacts the frequency stability. A model of the conventional 10 GW power generation system based on load frequency control and automatic generation control incorporated with 2 MW full power converter wind turbine, was demonstrated in this paper. The proposed model will demonstrate a loss of 1 GW of generation for a 10 GW grid, the model will then be examined and simulated to ensure the validity of the results. It has been concluded that load frequency control was not able to restore system frequency to nominal on its own and automatic generation control is needed to fully restore the 50 Hz of the grid.**

Keywords*— *Load frequency Control, Automatic Generation Control, Wind Turbine, Power System, Frequency Stability

I. INTRODUCTION (*HEADING 1*)

Power system is a complex network of interconnected generating stations, transmission lines, transformers, and other equipment, all integrated to deliver electrical power from generation sites to consumers, or more recently between prosumers and the grid [1]. The power generation based on fossil fuel economy has begun to be more problematic and its negative impact on environment became more evident, therefore, the move towards more environmentally friendly means of power generation becomes vital [2]. Such move, will beneficial the environment and allow our economy to reach carbon-neutral status in the future, but will create new challenges for the energy market and the power grid stability [3]. The dynamic response of the nonlinear power system is influenced by a wide range of machines with different characteristics and response levels [4], such as rapid load and generation output changes, loss of synchronisation of generators, short-circuiting transmission lines, and other parameters that are affected by the environment and operation disturbances. Moreover, the penetration of renewables and the development of power system introduce new types of stability problems [5-7]. In the AC power system, the system inertia is one of the vital factors ensuring and maintaining stability of the system. However, in line with the current modernisation an decarbonisation of the power grid, heavy conventional generators are being decommissioned and replaced with wind turbines and other generating resources that provide considerably less inertia and reliability than their massive conventional predecessors [8]. The lower system inertia, the less robust it is against disturbances caused by sudden losses of demand or generation, which, can lead to a blackout. A significant effort would be then needed to gradually bring the grid back on-line, while the downtime may lead to severe repercussions in the economy and public safety of the affected areas [9].

As the penetration of renewable sources of the power grid increases, an overall decrease in equivalent grid inertia which poses a risk to power grid stability [10]. Due to the complexity of wind turbine system, most models available in literature are either too complex for large scale frequency analysis, or oversimplified and hence missing key considerations, where different types of wind turbines respond to disturbances differently. In case of fixed-speed turbines, the dynamic response depends mainly on the generator itself, while for variable-speed turbines, the response is governed by the characteristics of their electronic power converter system [11].

Muljadi et al. [12] examined the impact of adding a wind turbine to the weak interconnected grid, where the remote load is connected to the bulk grid by a single transmission line and was considered very susceptible to faults as there was no additional generation present in its vicinity. Ekanayake et al. [13] investigated the frequency response provided by doubly fed induction generator (DFIG) and full power converter (FPC) based wind turbines. Morren et al. [10] investigated how wind turbines can provide inertial response to changes in grid frequency. This has been implemented by connecting the turbine inertia directly to the grid and implementing additional control loop in the power converter on the wind turbine.

Horta et al. [14] developed a control mechanism for controlling frequency and voltage of the power grid, by using a load frequency control (LFC) consisting of a negative feedback loop with proportional gain to regulate the power output by controlling the amount of mechanical power provided to the prime mover. Muhssin et al. [15] developed a simplified model of power system consisting of two blocks of generation: generators providing primary response only (LFC using speed governor), and generators providing primary and secondary response (LFC and Automatic Generation Control AGC) using integral controller).

Postnikov and Albayati et al. [16] present validated approach of controlling bulk set of distributed retail refrigerators to provide firm frequency response. Albayati et al. [17] investigated the impact of responding to the secondary static demand side response events on the supply power profile and energy efficiency of the widely distributed aggregated commercial refrigeration systems. Atkinson et al. [18] investigated the impact of the generation loss on the transient behaviour of the grid frequency. The impact of the main generation system parameters such as system inertia, governor droop setting, load damping constant, and the high-pressure steam turbine power fraction, on the primary frequency response, were examined. Cheng et al. [19] developed a control algorithms for a virtual energy storage system (VESS) using existing Flywheel Energy Storage Systems (FESS) and present power network assets to coordinate demand response from domestic refrigeration and conventional flywheel energy storage.

Fairley [20] addressed the feasibility and profitability of using flywheel energy storage systems to help stabilising the grid frequency. Amiryar and Pullen [21] conducted a review of flywheel energy storage systems and their applications. Whilst Sandia National Laboratories [22] claimed that flywheels are used in only few dedicated frequency regulation applications such as Spindle Grid Regulation LLC plant in Stephentown, NY, USA which employs a 20 MW flywheel system that provides frequency regulation for New York Independent System Operator (ISO). The empirical data shows that a 1 MWh of fast-response flywheels storage can provide between 20 and 30 MW of response, and that it was up to three times more response that could be achieved from an average ISO's generator [23].

From the literature review, detailed modelling studies on the effect of wind turbine generation on the frequency stability of the power grid have not been adequately studied. Specifically, not much examination has been given to the load frequency control (LFC) and automatic generation control (AGC) of large generating systems incorporated with smaller (e.g., 1–2 MW) full power converter wind turbines.

In this paper, a model of power grid integrated with renewable generation sources will be presented to examine the impact of wind turbine generation on the frequency stability of the power grid. A model of the conventional 10 GW power generation system based on load frequency control (LFC) and automatic generation control (AGC) incorporated with 2 MW full power converter wind turbine, was demonstrated in this paper. The proposed model will demonstrate a loss of 1 GW of generation for a 10 GW grid, the model will then be examined and simulated to ensure the validity of the results.

II. MODEL DESCRIPTION

Frequency stability of the power system depends on the ability of the power system to maintain steady frequency caused by a disturbance and subsequent imbalance between generation and load [24, 25]. The deviations in frequency needs to be regulated and maintained by certain control applications [26, 27]. A simplified model of steam turbine generator consisting of speed governor, prime mover, and generator presented in Fig.1 [28], which can be adopted to model the rotary speed of a synchronous generator [15].

The assumption is made that the grid can be simplified into a lumped single machine model. The generator time constant TM will be replaced with equivalent grid inertia constant Heq, which is calculated for the whole grid using inertia constants H of individual generators as given in [13]. The damping of the whole grid lumped into a single parameter D will be added into the denominator of the transfer function, which is reported to be equal to 1 as reported in [13-15]. Thus, the simplified model is shown in Fig. 2.

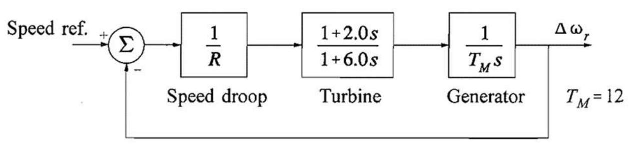

Fig. 1. A simplified model of steam turbine generator.

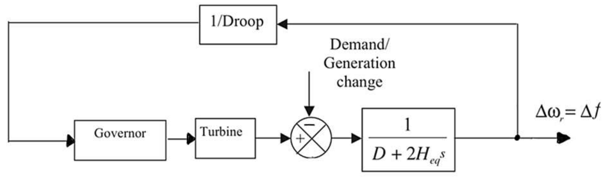

Fig. 2. A single-machine grid representation.

The single-machine representation allows us to sufficiently represent the power system behaviour on a longer timescale which is suitable for stability studies, while avoiding the need to compute more complex generator models [10], a simple first-order domain transfer functions for only these parts of the system that are important for stability on the bulk grid scale, will be adopted. This analytical approach stems from the definition of the swing equation as given in Eq. (1), which states that the change of power provided to the machine (i.e. difference between power generation and demand) is directly proportional to the change in rotational speed of the machine and hence frequency and the inertia constant H. Thus, the change of power on the grid is directly proportional to the change of grid frequency [9].

$$P_G - P_D = 2H \cdot \omega \cdot \frac{d\omega}{dt} \quad (1)$$

The simplified model of the power grid with conventional generation is shown in Fig. 3 [28]. The output of the model is per unit change of frequency (Δf) that depends on the difference of power provided by conventional generation and per unit change of power caused by loss of generation ($\frac{P_{trip}}{P_{gen}}$). The change of frequency is then fed back into the frequency control blocks – load frequency control (LFC) and automatic generation control (AGC) that act to change the power output of the generators. LFC is represented as the $\frac{1}{R}$ gain, where R is the speed governor droop, usually expressed in % [9]. This acts as the regulation mechanism present on every generator connected to the grid, that proportionally reacts to the change of grid frequency [15]. The AGC is modelled as the integrating element with a gain ($K_i \frac{1}{s}$), that represents the integral action taken over longer time to increase or decrease generator power output in order to restore the system frequency [14]. Essentially, LFC along with the turbine inertia [9] forms the primary response, while the AGC represents the secondary response [14]. The LFC and AGC contributions are then fed into the middle block representing the steam turbine. Both signals are negative, as in this model the goal is to bring the controlled value, which is the change in frequency to zero. A positive sign would result in an unstable system. The difference signal is fed into the final block of the system inertia of the whole grid, and the final output of the system is the change of frequency resulting from the injected change of power on the grid. The change of grid frequency according to the power model in Fig. 3 is as represented in Eq. (2).

$$\Delta f(t) = \left[-\Delta f(t-1)\left(\frac{1}{R} + \frac{K_i}{s}\right)\frac{2s+1}{(0.2s+1)(12s+1)(0.3s+1)} - \frac{P_{trip}}{P_{gen}}\right] \times \frac{1}{2H_{eq}s + D} \quad (2)$$

The terms in the s-domain transfer function of Eq. (2), $\frac{1}{R}$ is the load frequency control (LFC), $\frac{K_i}{s}$ is the automatic generation control (AGC), $(\frac{1}{0.2s+1})$ is the speed governor, $(\frac{2s+1}{12s+1})$ is the re-heater, $(\frac{1}{0.3s+1})$ is the steam turbine, and $(\frac{1}{2H_{eq}.s+D})$ is the grid inertia, where $\Delta f(t)$ represents the change in frequency (p.u.), $\Delta f(t-1)$ is the change in frequency from previous iteration, R is the steam turbine governor droop, K_i is the AGC integral gain, P_{trip} is the loss power of the grid, P_{gen} is the total power of the grid before loss of power incident, H_{eq} is the equivalent grid inertia constant, and D is the grid damping coefficient. The initial condition is $\Delta f(0) = 0$, as the frequency at the very instant of the trip is not changing yet.

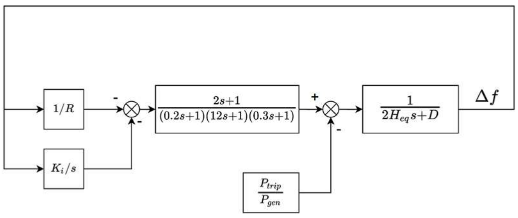

Fig. 3. Conventional power grid model.

A simplified model of 2 MW full power converter (FPC) wind turbine presented in [13] is adopted in this research for the frequency analysis, as shown in Fig. 4. The governing equation and the parameters used in this model are presented in Eq. (3). Where, $\Delta f(t)$ is the change in frequency (p.u.) provided by grid model, $\dot{\Delta f}(t)$ is the derivative change of frequency, k_1 and k_2 are the first and second supplementary controller gains, $(\frac{s}{s+1})$ is the supplementary frequency controller block, k_i and k_p are the internal wind turbine integral and proportional gains, R_s is the stator resistance (p.u.), T_1 is the time constant, $(\frac{1/R_s}{1+sT_1})$ is the wind turbine generator (WTG), N_{wt} is the number of wind turbines in the farm, and $P_{wt}(t)$ is the output active power provided by the wind farm [10, 15, 19].

The adopted model is a simplified version of various wind turbine models available in literature [29-31]. While these detailed models represent the wind turbine considering individual turbine parameters, such as rotor and stator inductances or magnetising reactance, they proven to be too complex for large scale frequency stability studies. Hence, the developed FPC wind turbine model omits parameters such as inductances, only taking into account the per unit rotor resistance R_s, and focuses on the actions taken by the wind turbine controller to stabilise grid frequency response where supplementary frequency controller was also implemented based on [31].

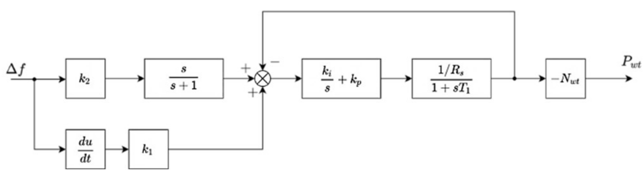

Fig. 4. A Model of 2MW variable speed wind turbine with full power conversion.

$$P_{wt}(t) = -N_{wt}\left(\frac{\left(\frac{k_i}{s}+k_p\right)/R_s}{1+sT_1+\left(\frac{k_i}{s}+k_p\right)/R_s}\right) \times \left(k_1\dot{\Delta f}(t) + k_2\Delta f(t)\frac{s}{s+1}\right) \tag{3}$$

The power generated form the wind turbines will be added to the power generated from conventional generation, thus Eq. (2) can be represented for the combined grid-wind farm model system as given in Eq. (4). Then by substituting Eq. (3) in Eq. (4), yields Eq. (5) as presented below.

$$\Delta f(t) = \left[-\Delta f(t-1)\left(\frac{1}{R}+\frac{K_i}{s}\right)\frac{2s+1}{(0.2s+1)(12s+1)(0.3s+1)} - \frac{P_{trip}}{P_{gen}} + P_{wt}\right] \times \frac{1}{2H_{eq}s+D} \tag{4}$$

$$\Delta f(t) = \left[-\Delta f(t-1)\left(\frac{1}{R}+\frac{K_i}{s}\right)\frac{2s+1}{(0.2s+1)(12s+1)(0.3s+1)} - \frac{P_{trip}}{P_{gen}} - N_{wt}\left(\frac{\left(\frac{k_i}{s}+k_p\right)/R_s}{1+sT_1+\left(\frac{k_i}{s}+k_p\right)/R_s}\right) \times \left(k_1\dot{\Delta f}(t) + k_2\Delta f(t)\frac{s}{s+1}\right)\right] \times \frac{1}{2H_{eq}s+D} \tag{5}$$

The model represents the combined thermal conventional power generations and FPC variable speed wind turbines integration is as shown in Fig. 5, while Fig. 6 shows the Simulink block diagram of the developed model. The change of frequency output from the grid model is fed into the wind turbine model. The observed grid frequency value is obtained by multiplying the change of frequency $\Delta f(t)$ (p.u.) by the nominal frequency (f_n), and then adding the initial frequency value (f_0) normally 50 Hz for both values. In Fig. 6, the purple blocks represent conventional generation model consisting of prime mover (speed governor, re-heater, and steam turbine) and the frequency control mechanisms (LFC for primary response; and AGC for secondary response), whilst the blue blocks represent wind turbine model. Outputs from these two blocks representing active power that are fed into the Grid inertia block, representing the whole grid as single machine. The yellow block is responsible for providing the per unit disturbance generation loss. The model parameters for the combined thermal conventional power generation integrated with wind turbine systems are presented in Table I [10, 15].

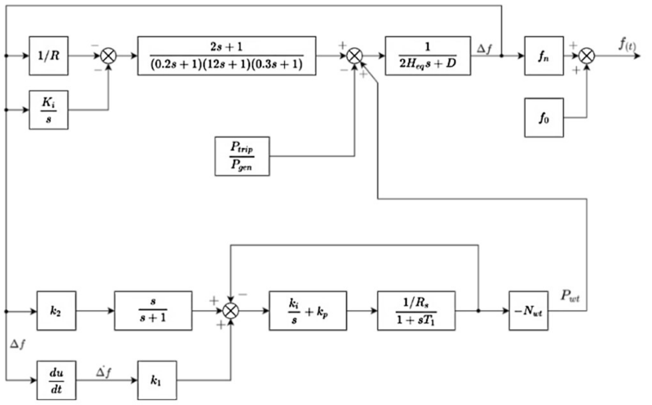

Fig. 5. A combined thermal conventional power generation integrated with wind turbine system.

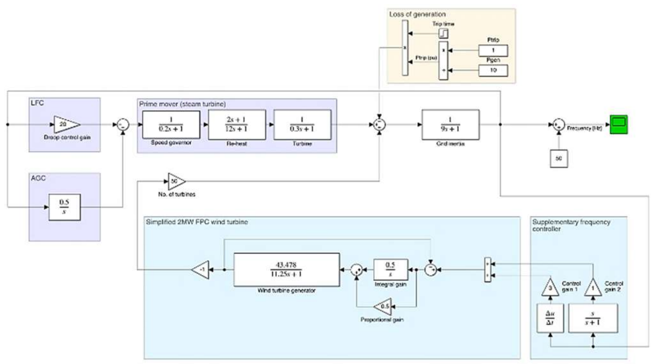

Fig. 6. A Simulink block diagram for the combined thermal conventional power generation integrated with wind turbine system.

TABLE I: MODEL PARAMETERS FOR THE COMBINED THERMAL CONVENTIONAL POWER GENERATION INTEGRATED WITH WIND TURBINE SYSTEMS [10, 15].

Parameter	Value
Speed governor droop, R	5% = 0.05
AGC gain, K_i	0.5
Equivalent grid inertia, H_{eq}	4.5
Grid damping, D	1
Wind turbine stator resistance, R_s (p.u.)	0.00491
Wind turbine time constant, T_1	11.25
Wind turbine control gain 1, k_1	3
Wind turbine control gain 2, k_2	1
Wind turbine proportional gain, k_p	0.5
Wind turbine integral gain, k_i	0.5

III. RESULTS AND DISCUSSION

A. System validation

The proposed model will demonstrate a loss of 1 GW of generation for a 10 GW grid. The disturbance occurred after 10 s from starting the simulation and both the primary and secondary response mechanisms are included, and the response to the change of grid frequency following the disturbance are as shown in Fig. 7. Whilst the response of the adopted proposed model in this paper for the same operational and disturbance scenario is demonstrated in Fig. 8. From Fig. 7 and Fig. 8, after the initial frequency drop caused by the disturbance, the frequency drop is greater in the adopted model of Fig. 8, which is caused by different values for the equivalent grid inertia used in the published model of Fig. 7. The initial frequency transient evolved over the first 50 seconds of simulation, where the primary response is evident and acted to stabilise the frequency to a new steady-state value of around 49.65 Hz after around 20 seconds following the loss. After the initial frequency stabilisation by primary response, the secondary response in the form of automatic generation control acts over a longer period to steadily bring the frequency back to the nominal value of 50 Hz. The results for both cases the frequency reaches the nominal value by the time of 30 minutes of simulation. We can therefore conclude that the model is valid, as it realistically simulates the grid behaviour for the same operational and disturbance scenario.

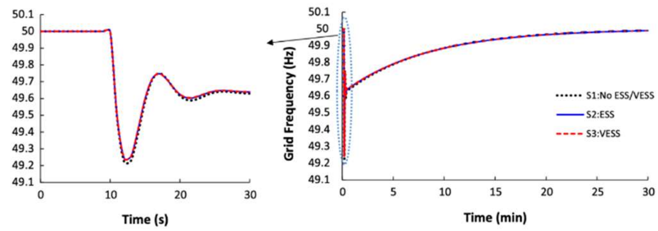

Fig. 7. Variation of grid frequency after the loss of generation presented in the model of [19].

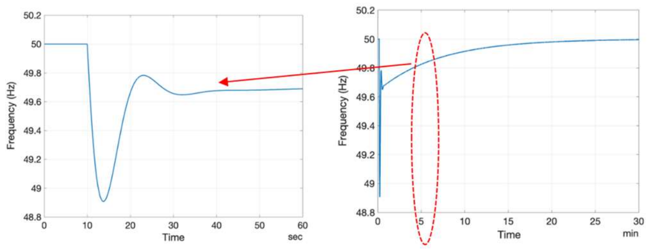

Fig. 8. Simulation of grid frequency after the loss of generation for the adopted model.

The power output of the 2 MW full power converter (FPC) wind turbine in responding to frequency drop from 50 to 49.75 Hz as developed in [13] is as shown in Fig. 9. Whilst the power output for proposed developed model for the same operational and disturbance scenario is presented in Fig. 10. The turbine reacted sharply to the change in grid frequency in Fig. 9. This sharp reaction is not present in the proposed model of Fig. 10, as the model was further simplified by not including the maximum power limiting feature. Explanations for power curve control have not been provided in the main source [13], and no alternate sources describing this control block in detail were available. However, the adopted model still shows similar reaction to the disturbance.

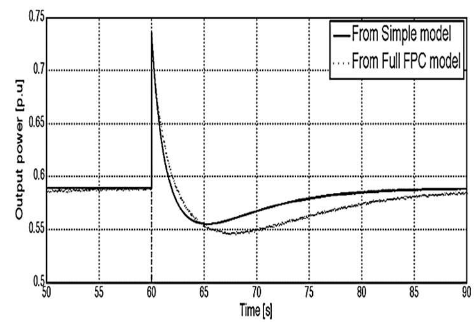

Fig. 9. Power output of the wind turbine presented in the published model of [13].

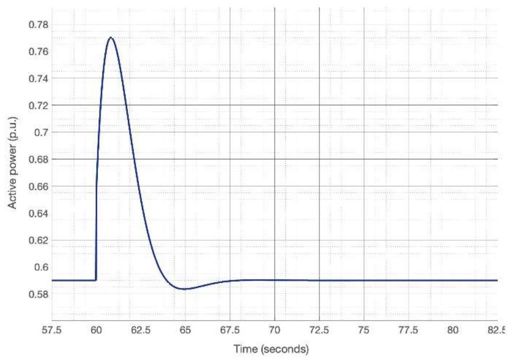

Fig. 10 Simulated power output of the proposed developed wind turbine model.

B. *Frequency responses of the power system with the incorporation of AGC*

The model is used to simulate a grid of 10 GW of responsive conventional thermal plants. The frequency stability is examined by dropping a 1 GW active power load after 10 s from starting the simulation in 2 scenarios: with (LFC and AGC) and without automatic generation control (LFC only), as shown in Fig. 11. It can be noticed that with no AGC incorporation, the primary response provided by load frequency control (LFC) stabilised the frequency at 49.7 Hz after 30 s from the power dropped incident. While when AGC is enabled (both LFC and AGC were active), after an initial overshoot, the frequency was gradually stabilised and restored to 50 Hz after 110 s from the power dropped incident. As the grid is represented as a single machine model, where transmission lines, transformers, and individual generation plants are not included, therefore, we will not be able to identify the interactions and differences between generation stations that might normally be responding to the disturbance differently, this explains the identical magnitude of frequency drop for both cases (with and without AGC). It has been concluded that primary response is provided by load frequency control (LFC), where grid frequency reaches steady state. Whilst secondary response is provided by an automatic generation control (AGC) to bring the frequency back to 50 Hz nominal. It is also noted that LFC was not able to restore system frequency to nominal on its own and AGC is needed to fully restore the 50 Hz of the grid.

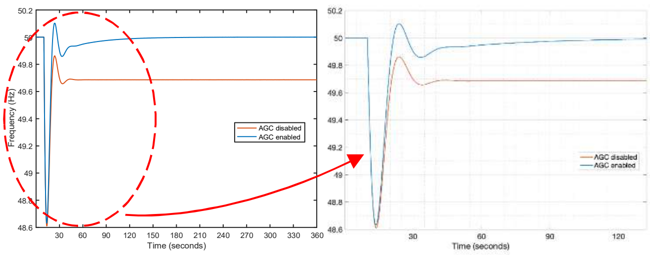

Fig. 11. Primary frequency response for a standalone conventional generation, with no incorporation form wind turbines, in responding to a 1 GW of generation loss.

IV. Conclusions

To examine the frequency stability of a power system, a model of convention 10 GW of power system incorporated with a full power converter wind turbines has been developed and proposed. The model was then examined and validated to ensure the reliability of results. It was then used to carry out simulations of 10 GW grid of responsive conventional thermal plants. A 1 GW active power load was used to examine its frequency stability by initiating the simulation in 2 scenarios namely with automatic control (LFC and AGC) and without automatic generation control (LFC only). It was shown that without incorporating AGC, the primary response provided by load frequency control (LFC) stabilised the frequency at 49.7 Hz after 30 s from the power dropped event. With AGC activated (i.e. LFC and AGC active), the frequency was gradually stabilised and restored to 50 Hz after 110 s, after an initial overshoot, from the power dropped incident. It was hence concluded that load frequency control (LFC) was not able to restore system frequency to nominal on its own and automatic generation control AGC is needed to fully restore the 50 Hz of the grid. The integrated conventional and wind turbine power generation model will be used in the future to simulate various grid events to examine the frequency response following disturbance. Further investigation is required to simulate losses of generation associated with wind turbines incorporate into the power grid to examine their impact on frequency stability. The comparison will be made between different sources of frequency response.

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