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Deviation of Frequency and Inertia with penetration of Renewable

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Abstract: Inertia response is a function of bulky synchronous generators with large rotating rotor masses that cover the instantaneous difference between supply and grid demand, typically in power grids. The rotor rotation frequency helps speed up or slow down the rotor rotation due to the lack of adequate gap between the power supply and the electrical power demand. When demand increases or a fault occurs, or load fluctuations exceed the balance of supply and demand, grid inertia is always induced at this stage. This helps the automatic grid operator rebalance the system to avoid speed drifts, resulting in a relatively small change in AC frequency over the system's frequency range. But the system consists of a system with low or zero inertia, like the wind, it lacks the effect of inertia and could not gain equilibrium. So, to balance and to reach the target frequency; the frequency deviation of the system due to the lack of inertia of the wind turbine is improved by the droop control technique in this research because the wind system reduced the total inertia of the system. Droop rate control mode for AC generator techniques was used to control the frequency fluctuations due to the lack of inertia of the renewable energy system. A synchronous generator connected to the mains was used as the governor control mode. It works by controlling power generation using the mains frequency of the prime mover. This mode allows synchronous generators to run in parallel and share the loads with the same drooping technique in proportion to their rated output. Injected grid inertia increased generator inertia on large power grids.

Keywords: Renewable Energy sources (RES), Frequency Restortion Reserves (FRR), Rate of change of frequency (ROCOF), Energy Storage System (ESS)

1. Introduction

An important source for the advancement of any country in the world is there electric power consideration. The growth can be categorized as financial, industries and urbanization. Considering both classical and un-classical inceptions of power are utilized for formation of energy. Due to naturally friendly nature and molecular structure, wind and solar are the most famous renewable

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energy source [1]. Prior to considering the efficiency of power system is involving, the expectation from this crucial source could not meet the stochastic need. By considering the main obstacle of renewable system has overcome through their interaction either the grid connection infrastructure. Additionally, the standard source of energy is merged with the hybrid renewable energy system to construct a new arrangement of power system instead of the traditional system [2].

They execute and make the energy in simultaneous or sequential system. Power is harnessed in the converging way in one method and in another method the power is generated alternatively. Acquiring the suitable result in the development clear environment, low carbon emission, abundant electricity and higher efficiency either enhanced energy that was the reason the UN has declared 2014-2024 as the 10 years of sustainable energy. As mentioned, 19.1 % of the total energy where of renewable resources. Discussing about the global facts and the beneficial affords of internal energy agency (IEA), the production of renewable energy would exceed up to 39% by 2050. In advancement of that, the emergence of this Green renewable source the increase in the temperature would also be limit to only 2 to 2.4 degree centigrade.

1.1 Problem Statement

The dominant problem in Generation system form Green energy sources in the low or almost zero existing inertia and the frequency Miss-match. Inertia does exist a little in wind Turbine but that is still not suitable to arrest the frequency deviation. On the other hand, in Solar panels they have zero inertia response. When these renewable are added to the generation mix they can cause some serious frequency deviations and can lead to load shedding conditions.

1.2 Objectives

- To compare the effect of replacing conventional power plants with renewable energy sources on frequency control.
- To design a system that can efficiently generate power from these renewable sources and transfer it to the load side without any interruptions. And to trigger automatic load shedding if the frequency drops below a threshold.
- Improve low inertia and frequency issues due to the integration of renewable resources into the system with the help of various control techniques and energy storage system.

2. Stability of Power System

To define the power system stability, the ability of system at which it remains stable after disturbance occurs. The inadequate storage system makes power system uneconomical and insufficient, despite of advancement in technological improvement. Therefore, generation power and consumption power should be equalizing, which is unavoidable. For that purpose, 50Hz or 60Hz frequency should be maintained as shown in Fig. 1.

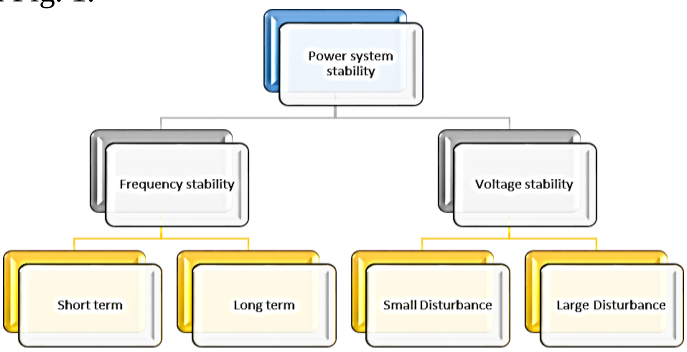

Fig. 1 - Different types of power system stability

In case of imbalance condition the frequency would have deviated from pre-defined value [3]. To save the system from any damage, power plants have to be shut down, which leads towards black out. Frequency stability is classified as short term where disturbance varied for tens of seconds and frequency deviation occurs fast. In long term the disturbance continues for few minutes and required huge amount of storage system that could endure the change in frequency in order to maintain it in nominal value.

2.1 Inertia

The inertia of the system actually the behavior of frequency from the time of disturbance. Two types of frequency would be produced under frequency and over frequency. Over frequency can be handle easily as compare to under frequency. This inertia, which is not more them few seconds, allows the mechanical system that control most power plants time to detect and respond to the failure.

2.2 Storage or Reserves

To meet the frequency deficit, extra quantity of active power is available to power system for its components through high voltage DC link. The primary control or governor response is called frequency containment reserves. FRR (frequency restoration reserves) techniques also help to restore the frequency, by providing synthetic inertia to power system that could be feed through wind turbines. They may be automatic FRR or manual FRR.

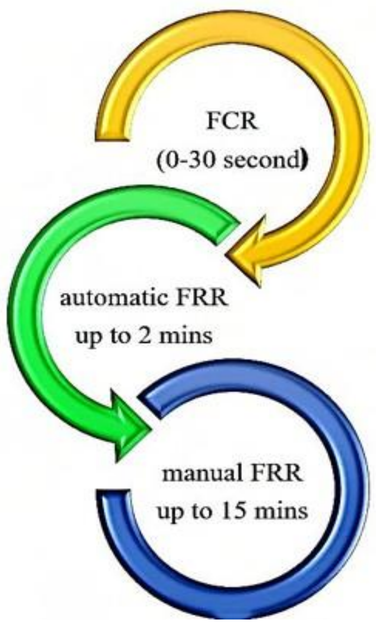

Fig. 2 - Different techniques for frequency deficit minimization

2.3 Active Power

The difference between the load and the generation during the faults is called the active power. A larger frequency deviation is caused by a larger active power asymmetry. The largest perturbation is called a reference or dimensional event, which varies on the order of several megawatts. Whenever disturbances occur due to an increase or decrease in the demand for electricity, the following responses are received and can be categorized as follows:

a) Inertial response: In an effort to reduce the rate of change of the frequency deviation, the wind generator employs and extracts the inertial energy stored in the mass of the generator in the form of kinetic energy.
b) Primary frequency response: The second response of the generator after disturbances, when the wind farm or power plant arranges to provide the necessary energy to increase the frequency to meet the system requirements and stabilize the system frequency.

Secondary frequency response: This is also called automatic generation control when stopping frequency deviations and trying to control the error as best as possible towards the limit.

2.4 Grid Inertia in Power System

Renewable energy sources reduce reliance on non-renewable resources, improve power system reliability, and voltage profile. Challenges remain with inertia and frequency control. Wind turbine systems use electronic converters to disconnect on high wind speed variation. Solar systems lack inertia improvement techniques. UK firm estimates 70% reduction in overall inertia from 2013 to 2034 through renewable energy integration. Penetration of renewables increases ROCOF or frequency deviation. In addition, this is mandatory on the part of power system operator to assess the value of declining frequency during the moments of disturbance. So, that appropriate and timely action may be taken to keep the system intact.

2.5 Frequency Control in Power System

Frequency assessment and control in power systems involves predicting and responding to changes in frequency immediately after a disturbance occurs. Accurate prediction or real-time estimation of frequency response is essential for implementing effective control mechanisms to support the system's frequency and ensure smooth operation. Under normal conditions, the frequency remains stable at 50 Hz or 60 Hz, depending on generator speed. However, during generation-demand mismatches, the frequency can deviate, and accurate assessment and control are crucial for maintaining grid stability and reliable power supply as in equation 1:

$$\frac{\Delta f}{\Delta t} = \frac{fnl\ \ (Pmech - Pelec)}{2H\ Pgen} \tag{1}$$

Where Δf/Δt is the rate of change of frequency, H is the inertial constant for power system, Pgen is the power rating of generator, Pmech is the mechanical power, Pelec is the electrical power and fnl is the system frequency.

Generator uses potential energy storage for up to 10 seconds to address frequency deviation. Primary frequency controller is activated after 30 seconds if deviation persists. Secondary regulator restores frequency to normal, followed by tertiary frequency controller for system stabilization. However, in the contracted primary and secondary controller, the power system needs manual adjustment of the generator by changing the scheduled periods [4]. In terms of inertia and frequency control methodology, renewable energy systems can be divided into two main types.

3. Background and Literature Reviews

Generation Company provides power products with frequency control and extra power capability. General Electric's Wind INERTIA offers mechanical inertia for incremental energy, and Wind CONTROL adjusts active power rate. Siemens' Net Converter System allows for variable speed operation with power and frequency control, while ABB conducts research on impact under varying speed conditions.

3.1 Related studies at Asia

Out of the total installed wind power plant of 44.79 GW, it produced 49.99 TWh of energy [9]. A significant part of this system is that 28% of this power needs to be stepped down to be usable to ensure that grid power remains stable due to limited transmission line capacity and insufficient system regulation margin [10]. In this particular situation, China has to resort to auxiliary frequency regulation with active power reserve.

3.2 Related studies at Europe

European countries such as Denmark, Spain, Ireland and the United Kingdom have established new network codes and special projects. To meet grid codes, a UK wind turbine company must provide a frequency response of up to 10% to match the actual load condition in the event of any frequency disturbances. [11]. In a further effort and according to the regulations approved by the Spanish network codes, to overcome the primary frequency and the inertial response, the WT operator must supply energy through a wind farm equal to 1.5% of the required amount. Studies carried out in Denmark to ensure inertial response and combat frequency droop for the grid. Eltra and Elkraft, the main Danish transmission system operators, have therefore ensured that the reserve power compensates for the impact of frequency disturbances of 47 to 50 Hz at the primary level and 49.9 to 50.1 Hz at the high level as required by system operation. [12]. According to the German network code E.on reduce the active power more linearly by 40% for every increase in Hertz frequency up to 50.2 Hz.

3.3 Related work at Australia

Australia's national electricity system and an additional 30 MW of wind generation capacity will be commissioned in a semi-scheduled program mode. This reserve power would not be considered a check-in priority and can be used at any time whenever the output exceeds the limits of the stable network. [13].

3.4 Related work at North America

Some notable conclusions have been drawn by the Federal Energy Regulatory Commission based on falling frequency

i. Frequency deviation control phenomena do not require a large amount of wind energy as a reserve, but an effective control system for dynamic characteristics and some generation energy in addition to control the secondary action.

In Canada, major hydro-Quebec TSO Trans engineering introduced new types of codes for a large wind farm to improve system performance and focus on inertial response. The main advantage of the system is that it does not need to run in relief mode, because the kinetic energy is stored in the massive rotors of the generator, so that all even large disturbances and the supporting frequency can be observed. This 10MW assembly has the ability to withstand a large frequency deviation of around 0.5Hz for a shorter period of time, which is less than 10 seconds. This therefore contributes almost 5% of the given rated power for 10 seconds [14]. In addition, the technical requirements for the transmission provider are mandatory for the wind farm with inertia capability in response to a large frequency deviation with an inertia constant of 3.5 seconds.

4. Research Methodology

The research methodology stats form the discussion of implantation of our system model on MATLAB, it is a numerical simulator. First step is to construct a generation system, so from MATLAB library the generators, three phase transformers and transmission lines have been taken. They have to played an essential role in completing the simulation process. While adding the renewable energy into the classical system the inertia and frequency get unstable. To make it stable different control techniques are being in consideration. They are the Fast Power Reserve technique, De-leading techniques, Droop control technique etc. In the company of these techniques we have chosen Droop control technique. In order to reduce the influence of the high RESs penetration, different frequency and inertia control techniques for RES while considering Energy storage system (ESS) wit and with it. For the impetus of reduction of frequency and deterioration given techniques such as droop control and fast reserve control technique has been used. Figure 3 and Figure 4 shows the general tree diagram for the inertia and frequency changing technique without energy storage and figure 3 shows the inertia and frequency changing technique with and without energy storage technique. Figure 4 shows the work flow diagram using MATLAB simulation.

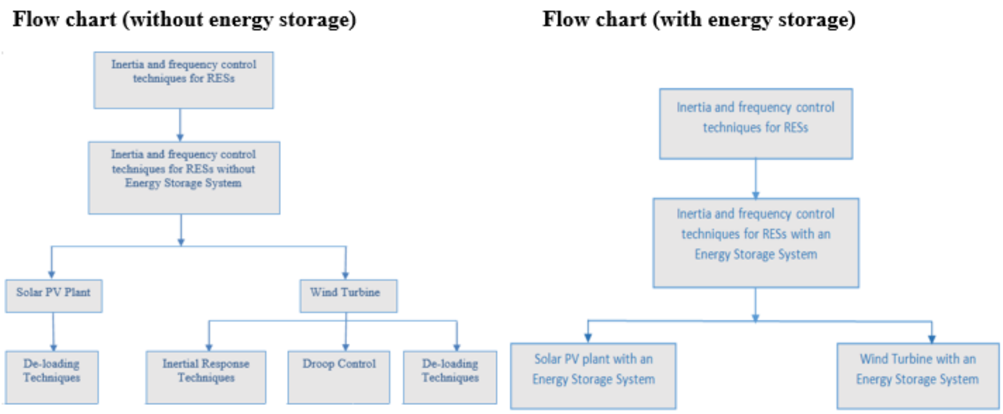

Fig. 3 - Block Diagram of inertia and frequency regulation techniques without energy storage and with energy storage

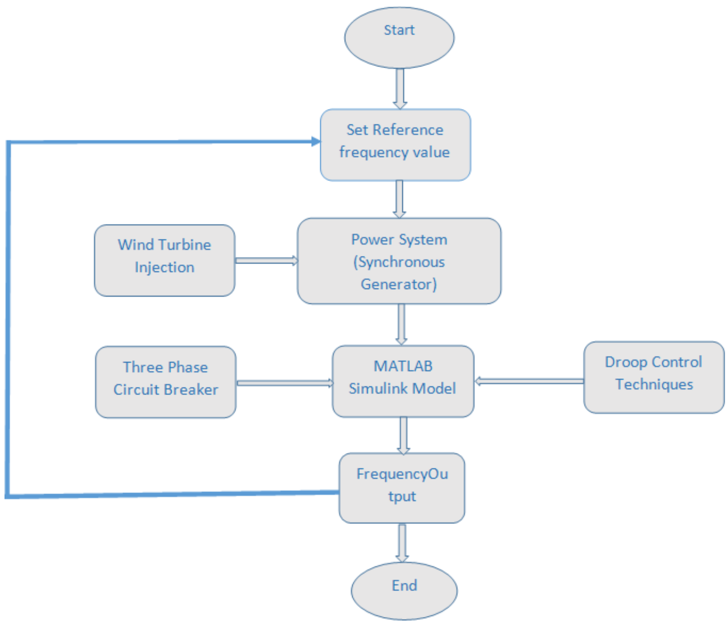

Fig. 4 - Work flow diagram of MATLAB simulation

4.1 Frequency Control (w/o Energy Storage)

1) Wind Turbine

There are two control techniques in wind turbines for addressing inertia response: inertia emulation and fast power reserve. In inertia emulation, new control loops are used to reduce the impact of kinetic energy stored in the revolving blades, generating additional power to terminate frequency deviation during unbalanced events. Fast power reserve is used to quickly stop frequency deviation and also for frequency regulation by providing a constant flow of power for a specified duration.

2) Inertia emulation

Utilizing a power electronics converter combined with the controller which will enables the variable speed of the wind turbine and hence it will release the kinetic energy stored in their rotating blades. The kinetic energy produced in this method is used as an inertia response in the range of 2-6s [11]. Going through the knowledge of response generally there are two types of responses one is one loop inertia response and other is two loop inertia response. In one loop response there is a release of kinetic energy that rotates in the blades and on other hand two loop inertia response is for only frequency deviation. In [15-18] the one loop inertia response is added to the speed control system to enable the wind turbine to respond to the ROCOF. This control loop is called inertia emulation, which exactly emulates the inertia response of conventional power plants.

3) Fast power reserve

Commonly, the response of inertia can be challenging, as the control signal depends heavily on the ROCOF. Fast power reserve can be defined as a constant 10% of the nominal active power for 10s, in spite of various wind speeds [19]. FPR is the kinetic energy that is stored in the rotating mass of the turbine. This can be acquired by controlling the rotor speed set point.

4) Droop control

Frequency drop is increased when every there is increase in load. Speed droop is for this defection as it limits the reference speed as load increase. The droop control scheme shown in Fig. 3.3. The active power is adjusted according to linear characteristics, and is given by equation 2 [34–36].

$$\Delta P = P_1 - P_0 = f_{meas} - f_{nom} \tag{2}$$

F_{meas} and P_1 are the new frequency and wind turbine output power, respectively, while f_{nom} and P_0 are the initial operating points. The linear relation between frequency and the active power of the wind turbine. When the frequency drops from f_{nom} to f_{meas}, the wind turbine increases the output of power from P_0 to P_1 to counteract for frequency variation.

In Droop characteristic/control Simulink model though MATLAB show some parameter which are

- Frequency measurement
- Three phase voltage wave form
- Load (to show the effect of addition or drooping of load to the power system).
- Three Phase circuit breaker

The 3-phase circuit breaker is energized when the load value exceeds the predefined limit, with an external signal determining its connection to the grid (0 for open, 1 for connected). Droop control method is used to simulate the drooping feature of conventional generator sets, making it suitable for events with multiple communication lines. Free inverters are linked in parallel, with each inverter capable of disclosing its own output power while adjusting voltage amplitude and frequency through droop control. Droop control methods facilitate proper allocation of active and reactive power in the system. In micro grid connection droop control method is also pertinent as in equation 4 and equation 5.

$$P_n = \frac{UU_n}{X_n} \delta_n \qquad (4)$$

$$Q_n = \frac{UU_n - U^2}{X_n} \qquad (5)$$

Where U is integration voltage, U_n is output voltage of the inverter power supply, X_n is output impedance of the inverter power supply, δ_n is angle in b/w U_n U.

As per equation 2.4 the active power usually depends on δ_n, However the Reactive power depends upon the output voltage amplitude of inverter power supply U_n. By regulating the angular frequently or frequency of inverter U_n and the phase could be directly control. Which has expressed as follow in equation 6.

$$f_n = \frac{\omega_n}{2\pi} = \frac{d\,\delta_n}{dt} \qquad (6)$$

As per equation 6 the active power usually depends on δ_n, However the Reactive power depends upon the output voltage amplitude of inverter power supply U_n. By regulating the angular frequently or frequency of inverter U_n and the phase could be directly control. Which has expressed as follow in equation 7.

$$f_n = \frac{\omega_n}{2\pi} = \frac{d\,\delta_n}{dt} \qquad (7)$$

It has been found from equation 6 and 7 by regulating the reactive output the output voltage of the inverter could beregulate. Similarly, due to regulate the active output the output frequency could be regulate.

5. Results and Discussion

5.1 Grid Inertia and Frequency Improvement Simulation

5.1.1 Renewable energy

A grid dominated by renewable energy, with low capacity due to high demand, could face challenges in maintaining grid inertia. Grid inertia is essential for power quality and reliability, and is provided by heavy rotating machinery like steam turbines and gas turbine driven generators. Decommissioning such infrastructure to replace with renewables could inadvertently undermine grid resilience. Upgrading existing infrastructure could reduce pollution and improve the overall reliability of renewable energy grids, avoiding the need to operate at low generation capacity to maintain stability.

5.2 Simulation of Power Generation Grid without integration

5.2.1 Power System Frequency Calculation Simulink Design

A Simulink design for frequency calculation and real-time monitoring is shown in Fig. 4.3. The system frequency is set to 60 Hz and is well observable through the Simulink model. A Simulink model for the frequency waveform is shown in Figure 4.2, which takes the complex signal from the Power system and decomposes it into magnitude and phase components. The phase component is converted to radians for the frequency block. The frequency simulation of generating unit 02 is shown in Fig. 4.4, which is on the right side of the Simulink model. The average frequency response simulated for all generators of genset 01 and 02 is shown in Fig. 5

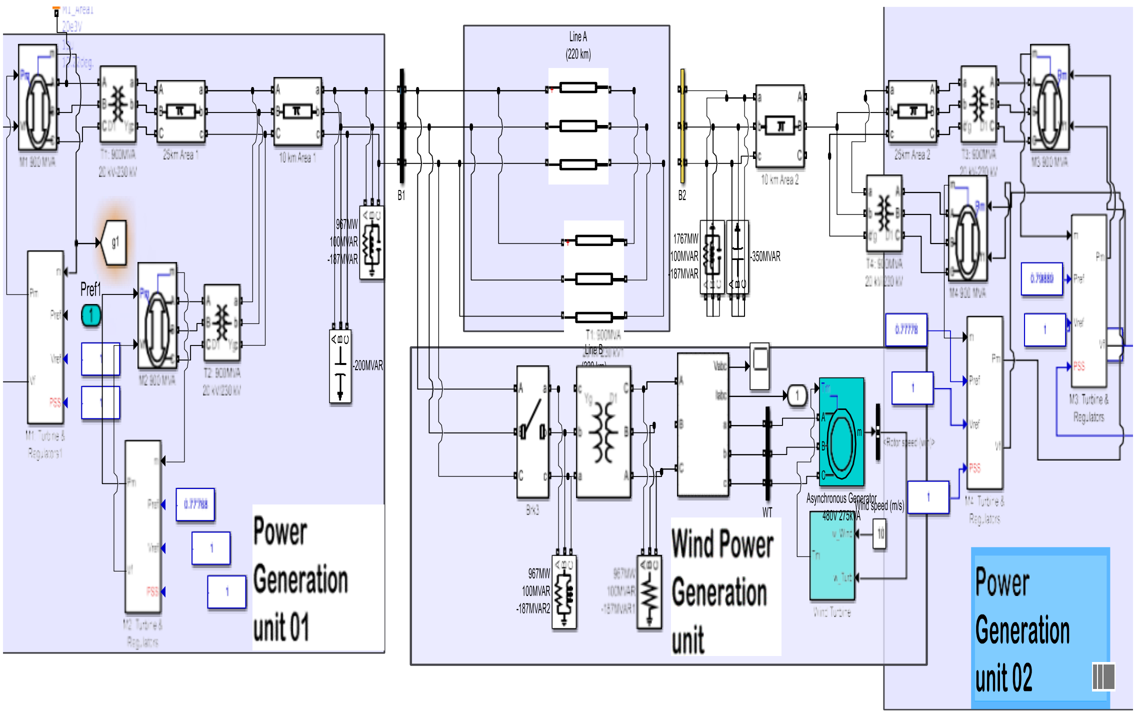

Fig. 5 - Simulink Design of the Power System with wind

5.2.2 Grid inertia Response

Grid inertia is a characteristic of large synchronous generators that helps to balance the instantaneous disparity between power supply and demand in electrical networks. When there is an imbalance between mechanical and electrical power, the rotational frequency of the generators either accelerates or decelerates, allowing the grid operator to rebalance the system and avoid changes in AC frequency. The Simulink grid inertia constant block is shown in Fig. 6.

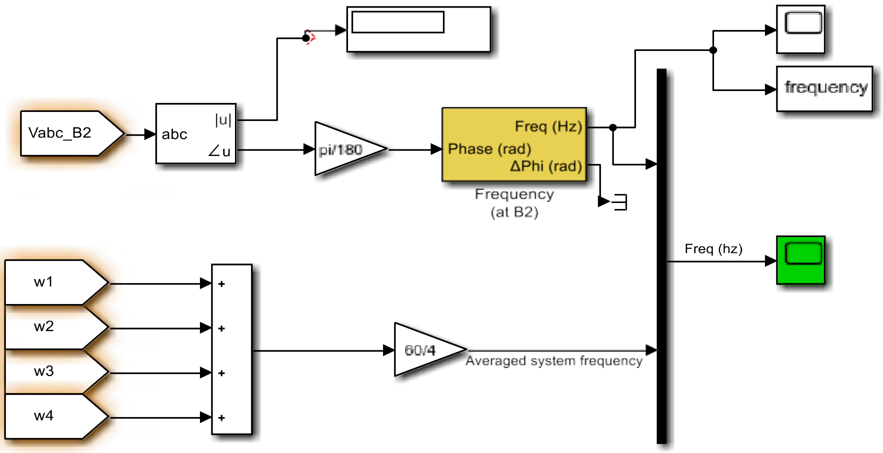

Fig. 6 - Simulink model for the Frequency calculation

and the mathematical model of network inertia is represented by equation 1. Network inertia simulation is calculated based on the generator's rotor speed and can be integrated into the system for further analysis.

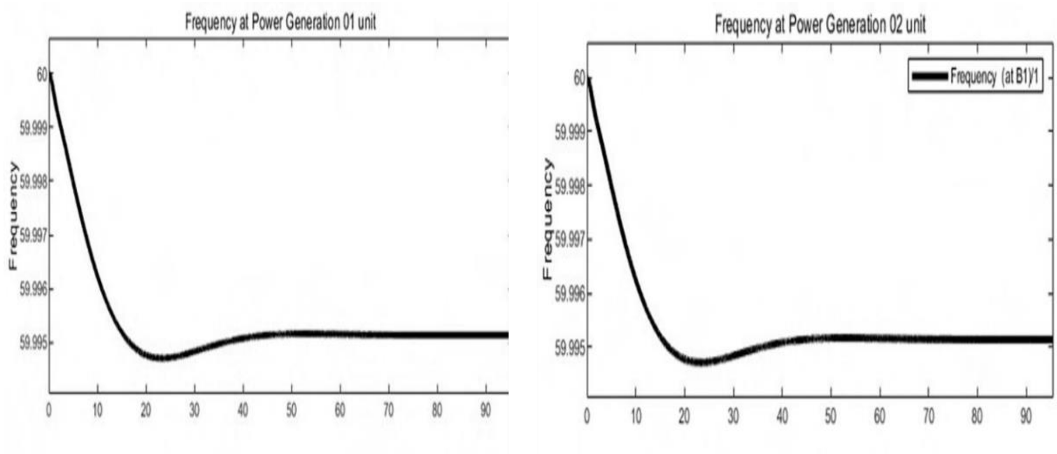

Fig. 7 - (Generation unit 01 Frequency waveform and Generation unit 02 Frequency waveform)

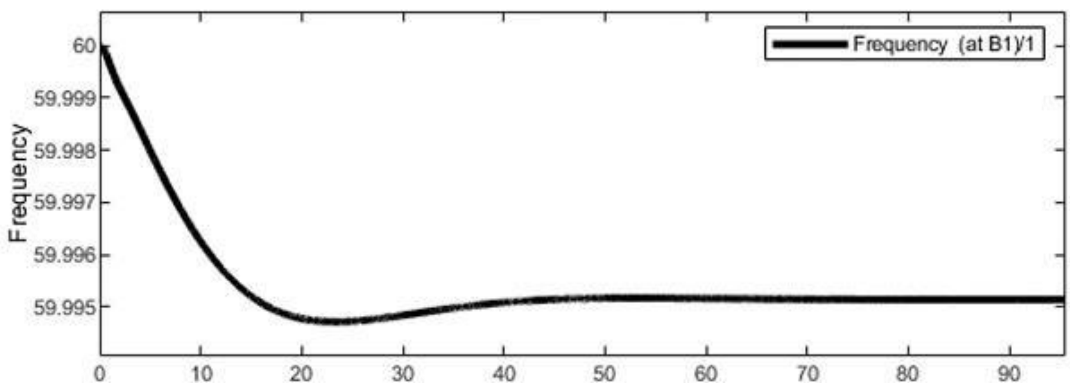

Fig. 8 - Average System Frequency

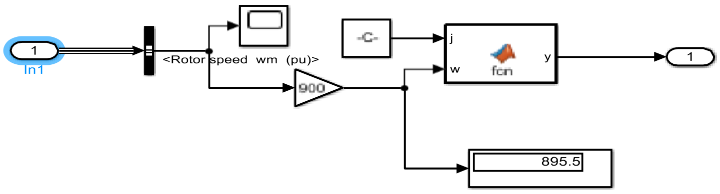

Fig. 9 - Simulink Block of Inertia Constant Calculation for Grid

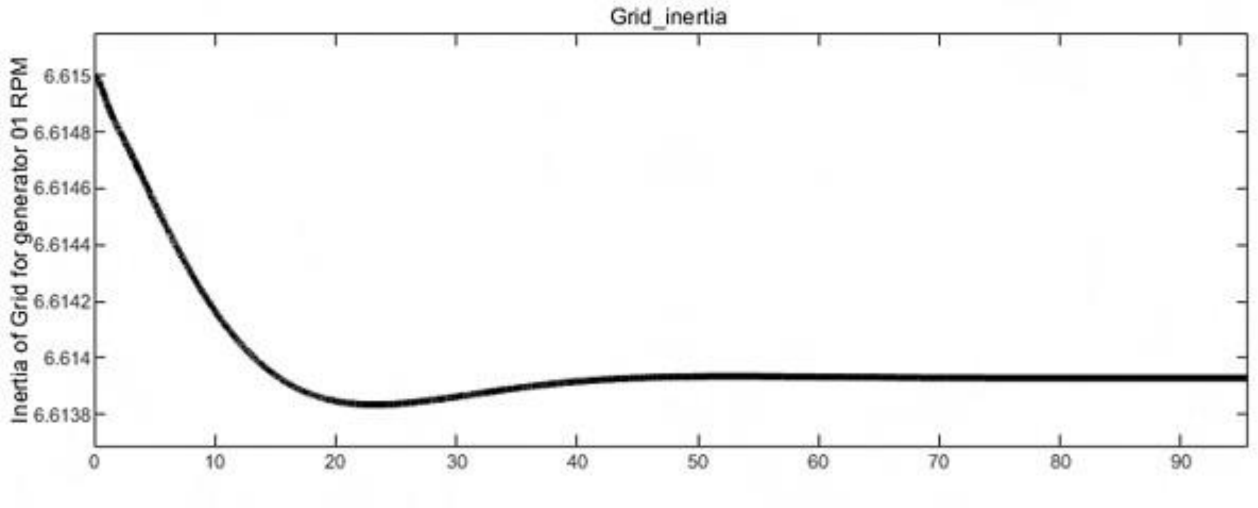

Fig. 10 - Grid inertia of Power system from Generator 01

5.2.3 Wind Renewable energy

The renewable wind energy system is shown in Fig. 11 Wind renewable energy system. The voltage and current waveforms are shown in Figures 12 and 13, recorded at 476 V (RMS) and 60 Hz with the load connected. The machine specifications are power, emf (RMS) and frequency 275 KVA, 480 V, 60 Hz.

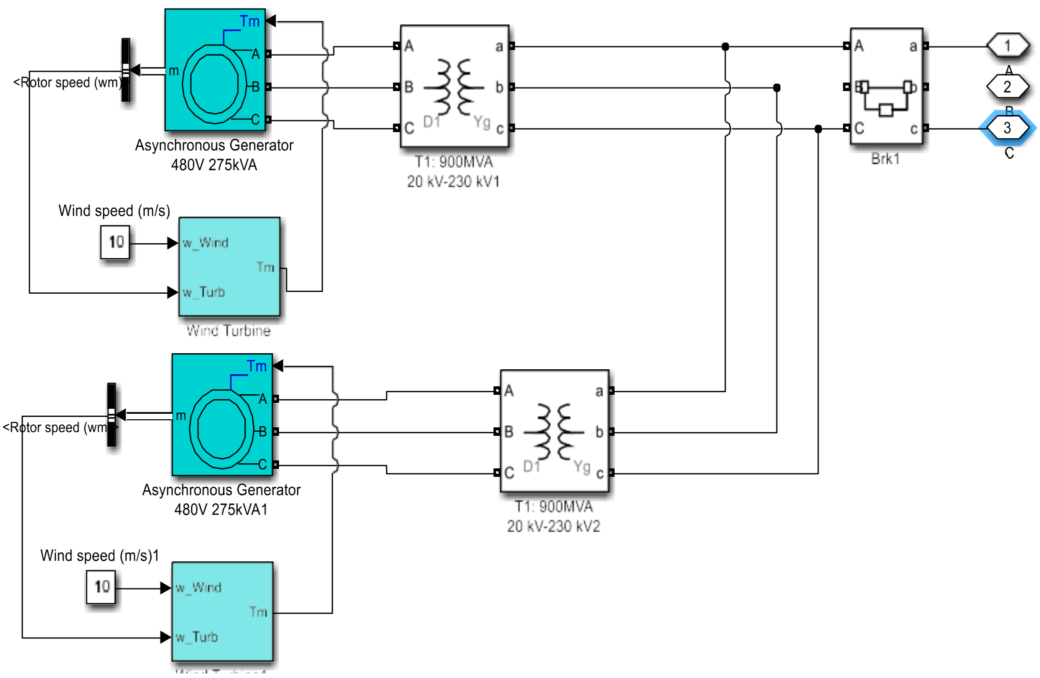

Fig. 11 - Simulink Design of Wind Energy System

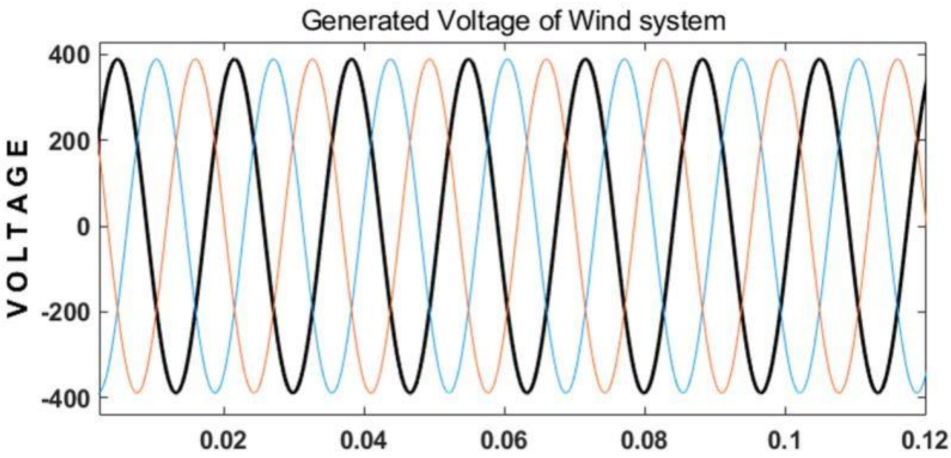

Fig. 12 - Wind Generated Voltage Waveform

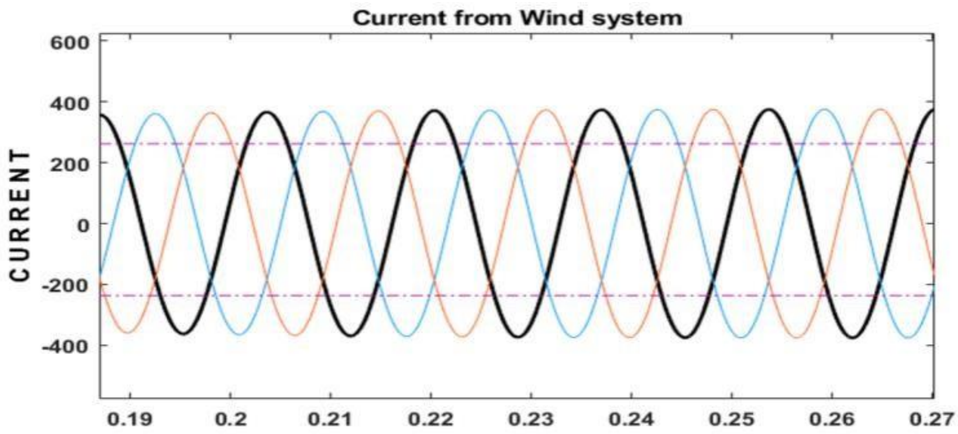

Fig. 13 - Current waveform from the wind turbine

5.2.4 Integration of wind system

The integration of a wind system connected to a power system can affect the frequency and inertia of the grid, as shown in Fig. 14 and Fig. 15. In the absence of a grid. The design of the wind system without inertia by direct disconnection from the system is integrated with the Power system and disconnected for 60 seconds. The figure shows that the frequency is suddenly affected and decreases. The inertial response taken from generator 01 is shown in Fig. 15.

5.2.5 Improvement Technique of Grid inertia and Frequency

Droop control mode for AC generators. It is usually used to drive a synchronous generator connected to the mains as a governor speed control mode. It works by controlling the power generated by the prime mover's mains frequency. This mode allows synchronous generators to follow in parallel and share the load in proportion to their rated output between generators with the same deceleration curve. In reality, the droop curves used on large power grid generators are not necessarily linear or equal and can be changed by operators. This allows the proportion of power used to vary with load

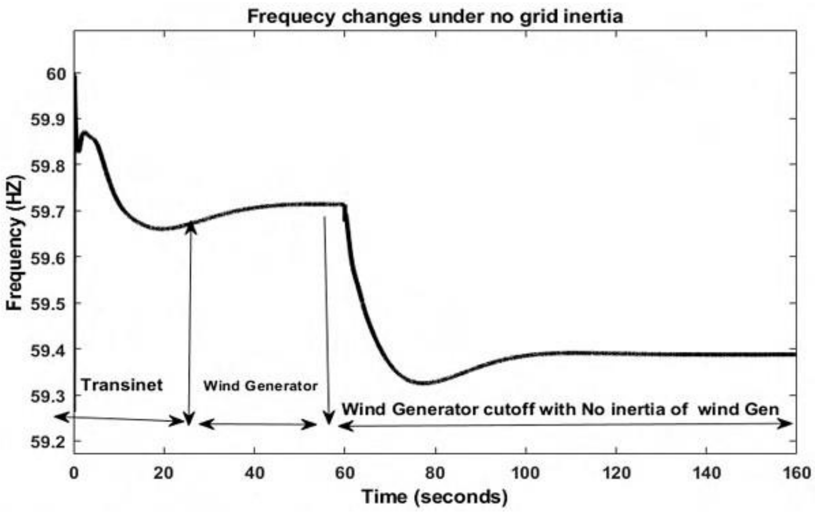

Fig. 14 - Failure effect of wind system treated as no inertia

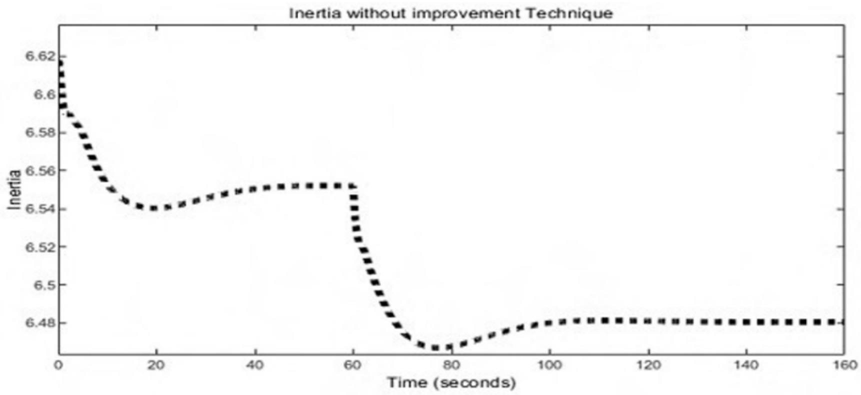

Fig. 15 - Inertia without improvement Technique

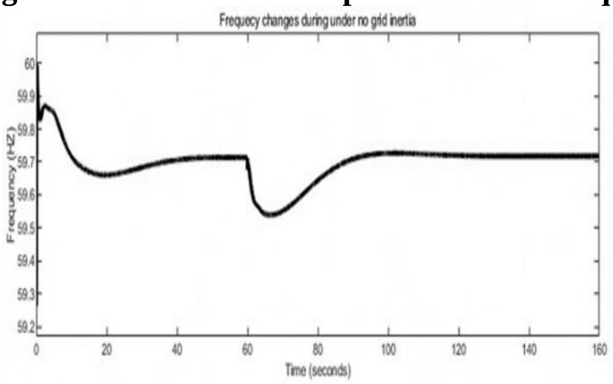

Fig. 16 - Frequency improvement using droop technique

so that when demand is low, base load generators can generate a higher proportion. A monotonically decreasing frequency function within the operating frequency spectrum is needed for stability. Fig 15 Frequency improvement using the droop technique; a comparative analysis is shown in Fig. 16, which identifies the course.

6. Conclusion

Grid inertial response is a feature of synchronous generators with large rotating masses that helps address the instantaneous mismatch between power supply and demand on power grids. When there is a power imbalance between the mechanical supply and the electrical supply (such as excessive power demand), the rotational frequency of the synchronous generators in the network can be accelerated or decelerated to rebalance the system and avoid speed changes, resulting in a relatively small shift in AC frequency within the system's frequency range.

The lack of inertia in wind turbine systems can cause frequency deviation in the power grid, typically ranging from 59.7 to 59.4 Hz. This can be visualized from the inertial waveform, which shows a reduction in the total inertia of the system from 6.56 to 6.54. To control these frequency fluctuations, the droop rate control mode for AC generator techniques is commonly used in renewable energy systems. This mode regulates the power generated by the synchronous generator based on the mains frequency of the driving machine, allowing synchronous generators to run in parallel and share the load between generators with the same deceleration curve relative to their rated power.

The droop technique used by generators on large power grids is not inherently linear or uniform, and it can be adjusted by the operator. This allows the power ratio to be adjusted based on the load, enabling base load generators to provide a larger share of power at low consumption, improving the overall efficiency of the system. The injected grid inertia from synchronous generators can also help improve the inertia constant, which is a measure of the system's ability to maintain frequency stability, from 6.54 to 6.56.

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