# Analysis of the Effects of Frequency Variations on Power Systems

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**Abstract**

*In power system networks, evolving operational conditions present various stability challenges, one of which is the influence of frequency deviations on system dynamics. These deviations occur due to imbalances between power generation and consumption, leading to frequency fluctuations as a result of changes in demand and generation. A key problem addressed in this study is the occurrence of over-frequency and under-frequency events within the power system. The research focuses on the effect of these frequency deviations, which are important for maintaining network stability. The aim of this research is to thoroughly examine the impact of frequency variations on power system dynamics. The method employed was analytical method, which involves identifying system components and their interactions with frequency fluctuations. MATLAB Simulink simulations are used to assess the real-time effects of frequency deviations on the power system. Data collected from these simulations are presented in tables and graphically to analyze the extent of frequency deviation within the system.*
**Keywords: Consumption, Frequency deviation, Imbalance generation, Power system stability, System dynamics.**

## I INTRODUCTION

The operation and expansion of power system networks have introduced new stability challenges. Frequency plays a vital role in power systems, with imbalances between supply and demand leading to frequency deviations. An excess in power supply results in a frequency rise, whereas an excess in demand causes a frequency drop.

In the modern power grid, frequency serves as a silent sentinel constantly reflecting the balance between electricity generation and demand. Under ideal conditions, systems in Nigeria operate at a nominal frequency of 50 Hz, sustained by the inherent rotational inertia of conventional synchronous generators. These slowly turning rotors act as a natural buffer, absorbing sudden imbalances and cushioning frequency fluctuations without requiring intervention (Ulbig *et al.,* 2013; Fernández-Guillamón *et al.,* 2020).

However, the energy landscape is shifting. Inverter-based renewable sources like solar photovoltaics and many wind installations lack physical inertia and decouple power generation from rotor dynamics. As a result, grids incorporating high shares of such resources become more vulnerable to rapid frequency deviations (Fernández-Guillamón *et al.,* 2020; He *et al.,* 2024). The diminishing inertia in power systems raises risks such as abrupt rate-of-change-of-frequency (RoCoF) events and deeper frequency dips, potentially triggering protective load-shedding or widespread outages (Energy Reports, 2022).

Fortunately, emerging solutions are stepping in. Techniques such as synthetic (or virtual) inertia, enabled through battery energy storage systems or grid-forming inverters, can mimic the stabilizing effects of traditional spinning masses (Roy, 2024; Energy Systems, 2023). These approaches, alongside fast frequency response strategies, are essential to safeguard frequency stability in low-inertia environments. Still, ensuring seamless integration requires robust control methods and coordination mechanisms adapted to dynamic grid conditions.

This study examines how frequency variations affect power systems especially those with reduced inertia and evaluates both traditional and modern control strategies. By analyzing causes, impacts, and mitigation techniques, the research aims to contribute toward designing resilient and adaptive power systems capable of thriving in the era of renewable energy.

Historically, power systems have evolved from basic configurations to complex modern networks due to rising electricity demand. Early power systems, with fewer generators, made frequency regulation relatively simple (Vittal *et al.,* 2019).

The advantages of AC systems led to the widespread use of both single-phase and three-phase configurations. Initially, various electric utilities and independent producers operated at different frequencies. However, the necessity for interconnected and parallel operations prompted the standardisation of frequencies to either 50Hz or 60Hz. This shift also contributed to the rise of extra high voltages (EHVs), primarily for commercial use (Saleh *et al.,* 2018).

The frequency of an alternating current (AC) power system serves as a key indicator of its stability and plays a crucial role in maintaining the synchronization of generators, transformers, and other critical components. Variations from the standard operating frequency, known as frequency deviations, significantly impact power system performance, making their study a vital area of focus in electrical engineering. The complete integration of a network system is referred to as the power grid. When the system is segmented into multiple geographical zones, these divisions are known as power pools. Within an interconnected grid network, fewer generators are needed as reserves for peak demand and spinning reserve capacity. The power grid enhances energy transmission and distribution efficiency, offering greater reliability and cost-effectiveness by enabling the seamless transfer of power between regions. (Pathak, *etal*, 2016).

**Objectives**

The specific objectives are to:

i. Examine the current power system under review for potential enhancements.
ii. Investigate the impact of frequency variations on power system performance.
iii. Develop a simplified power system model using MATLAB.
iv. Analyze frequency deviations in the power system using the frequency response technique in MATLAB.
v. Obtain and interpret results to evaluate the effects of frequency deviations on power system stability and operation.

The influence of power generation and consumption on a power system's frequency can be characterized by an imbalance between demand and generation. This imbalance, often caused by a loss of generation or load, results in fluctuations in the system frequency.

Generators are vital components of a power system, responsible for producing the electrical energy distributed across the network. Most generators achieve this by converting mechanical energy into electrical energy through the interaction of a magnetic field. The mechanical energy required for this conversion originates from a prime mover, a device that drives the generator's rotation. Common prime movers include steam and water turbines, while diesel engines are often utilized in remote areas. Prime movers can be powered by various energy sources, such as water, coal, natural gas, oil, and nuclear energy. Among these, water-based prime movers are particularly advantageous as they are non-polluting and incur no fuel costs (Dumkhana & Biragbara, (2025); Chinweikpe, 2025; Qazi *et al*., 2016).

To carry out this function, certain generators are designated to handle secondary control using a dedicated reserve capacity. This reserve is determined by the requirements of each Transmission System Operator (TSO) and is typically a percentage of the generator's maximum available power, with a predefined minimum threshold to ensure reliability regardless of the generator's maximum capacity.

When the system frequency falls below its nominal value, additional generation capacity must be activated. Conversely, if the frequency exceeds the nominal level, some generation capacity needs to be reduced, or the load demand must be increased. Secondary control is generally automated, with all participating generators adjusting their output based on specific set-points issued by a central controller (Abdulraheem *et al.,* 2016).

## II MATERIALS AND METHOD

The following materials are essential for a proper analysis of the effects of frequency variations on power systems. By assembling these materials, the process of analyzing the effects of frequency variations on power systems

can be systematically achieved through a combination of system design, control techniques, and careful selection of components. Each material must meet the specified criteria to ensure optimal performance. The key materials required include:

i. Frequency meter
ii. Transformer
iii. Temperature sensor
**iv.** System connectors
**v.** Breakers

### Method Used

The approach employed in this research is the "Analytical method." This method involves examining the system in relation to its design components. The analytical method is used to assess the various steps and techniques involved in studying the impact of frequency variations on power systems. It was derived from the research conducted throughout the course of this study.

**Frequency Deviation Conditions**

Frequency deviation occurs when the system frequency moves outside its normal operating range, typically due to an imbalance between generation and demand. In a power system, the allowable maximum frequency limit is set to prevent equipment damage and ensure system stability. Under normal operating conditions, the frequency should remain within a specific range, with deviations beyond this range indicating potential issues with generation or load. Maintaining frequency within the acceptable limits is important for the reliable operation of the power system and to avoid triggering protective mechanisms.

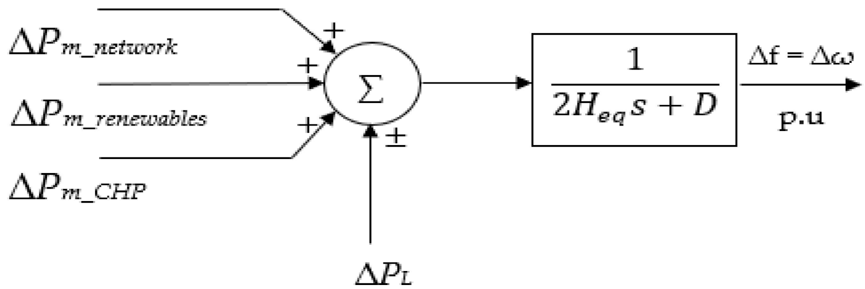


**Figure 1: Basic model for frequency regulation**

Equation 3.1 presents in detail the change which occur when mechanical power $\Delta P_m$ of the system is in operation for the reliability of the system under consideration. (Vittal *etal*, 2019).

$$\Delta P_m + \Delta P_e = 2H_{eq} \frac{d}{dt} (\Delta w_m) \quad (3.1)$$

While equation 3.2 also presents the change in Electrical power $\Delta P_e$ due to the changes in frequency as expressed when the system is in operation for the overall reliability and performance of the system.

$$\Delta P_e = \Delta P_L + D.\ \Delta w_m \quad (3.2)$$

By re-arranging equations 3.1 and 3.2 and its laplace transform which represents a simplified model with an equivalent inertia constant $H_{eq}$ and lumped load-damping D constant, as shown in previous equations. Thus, when there is an increase on the power demand, $\Delta P_L$ will have a negative sign, and a positive for the decrease on the power demand.

$$\Delta P_m + \Delta P_L = \Delta w_m \;\; 2H_{eq}s + D \quad (3.3)$$

The frequency control model used to determine the operating stability of the system involves assessing how the system responds to frequency variations, considering the inertia constants of the generators. The inertia constant is a important factor in understanding how quickly the generators can react to changes in grid frequency. A higher inertia constant implies that the system can better withstand frequency fluctuations, as it has greater resistance to changes in rotational speed. The model takes into account these inertia values to simulate the response of different generation systems, such as nuclear, coal, gas, and combined cycle gas turbine (CCGT) plants. Table 1 presents the inertia constants for various generation systems, providing a basis for comparing their stability during frequency disturbances (Biragbara, 2025; Bopp *et al.,* 2016).

## III RESULTS AND DISCUSSION

### Effect of frequency deviation on power system

Under normal conditions with a frequency impact deviation at 60 Hertz in a power system, the behavior remains stable and within the designed operational parameters. The power system, accustomed to a nominal frequency of 60 Hertz, operates efficiently and reliably. Electrical devices and equipment connected to the system experience consistent voltage and frequency levels, ensuring optimal performance. The waveform of the voltage in the power system follows a sinusoidal pattern at the nominal frequency of 60 Hertz.

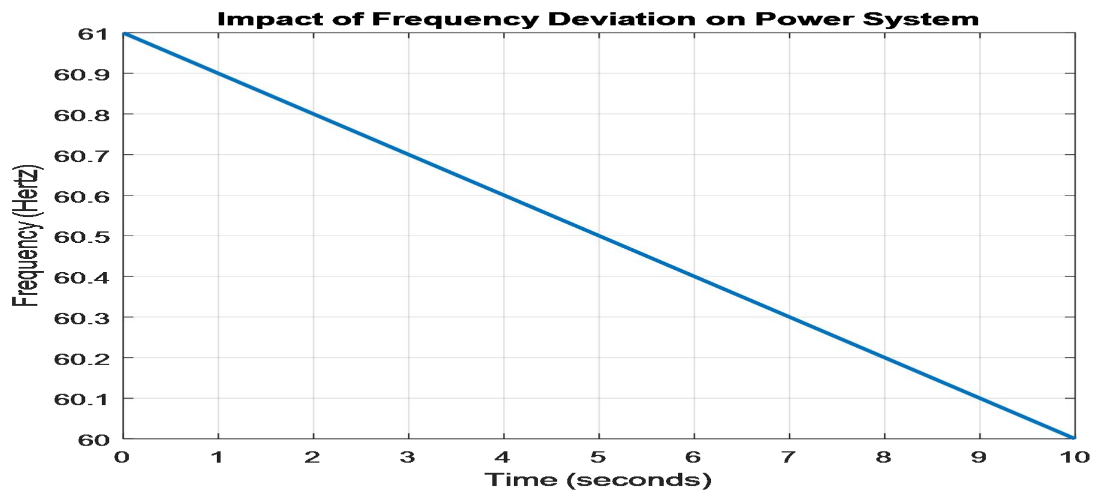


**Figure 2: Impact of frequency deviation at 60 hertz**

This presents in detail the effect of the deviation of the system frequency when introduced at a frequency of 60hz and the corresponding behavior when the system was operated at 60hz to determine if the frequency influence was more on the system. However, the relationship which exist between the frequency and the deviation is actually shown in the linear graph of figure 2 from the MATLAB plot.

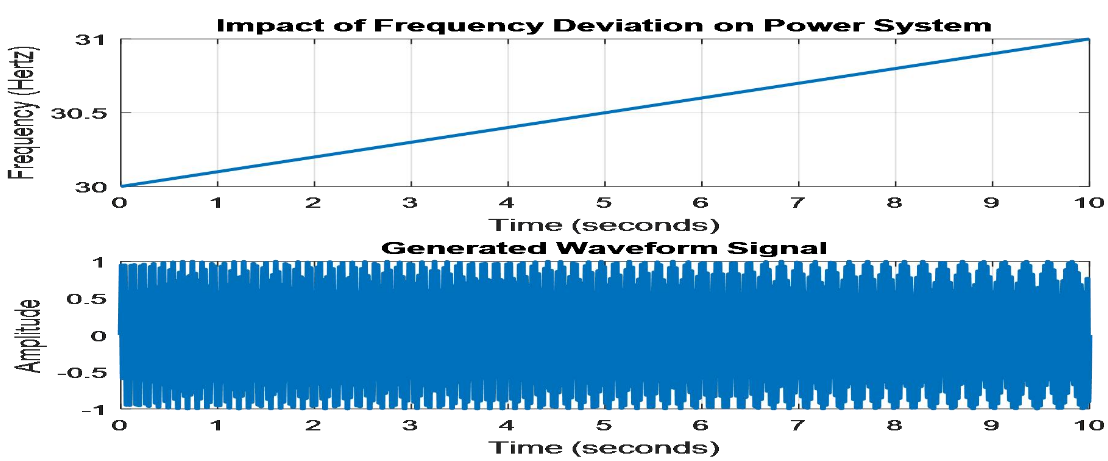


**Figure 3: Abnormal frequency deviation at 30 Hz**

This is a waveform generated from the tool used in (MATLAB) environment. It considered the amplitude of the wave signal which is the maximum vibration of the wave about its axis and the time in seconds which it takes the wave to be generated. However, from the graph presented in figure it shows when the frequency is abnormal, that is when the frequency is low at 30Hz with corresponding deviation in frequency.

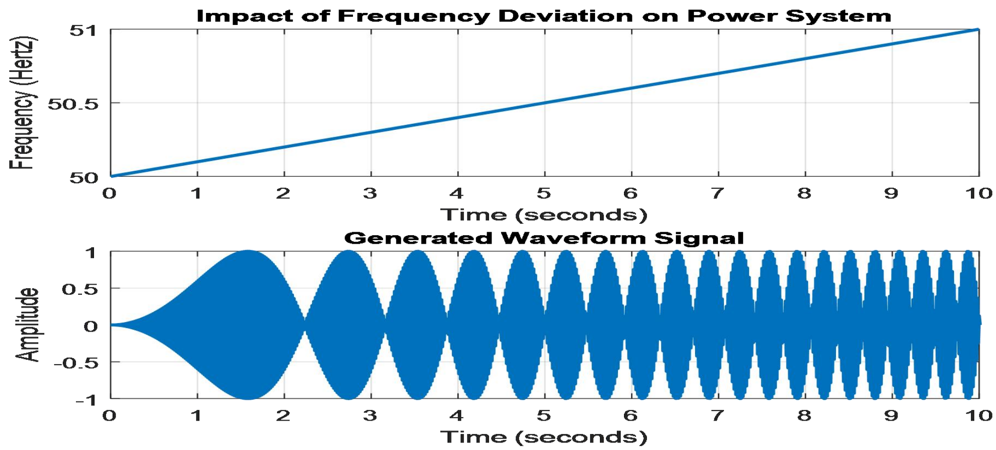


**Figure 4: Normal frequency deviation at 50 Hz**

This shows the waveform generated from the tool used in (MATLAB) environment and also describing when the frequency is normal. It considered the amplitude of the wave signal and the time in seconds which it takes the wave to be generated. Again, from the graph presented in this figure shows when the frequency is normal with a deviation in frequency of 50Hz which is a normal frequency that is expected to stabilize the system components

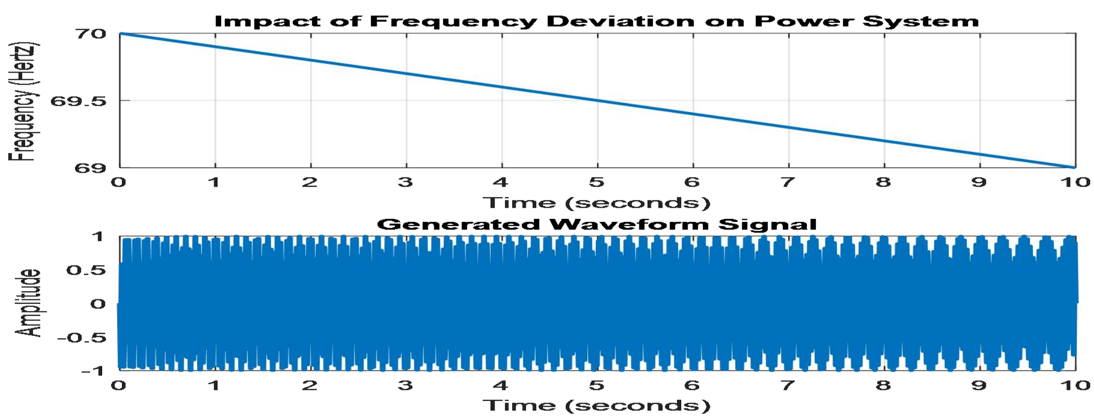


**Figure 5: Abnormal frequency deviation at 70 Hz**

The plot presented here shows a waveform generated in MATLAB environment. It explained the amplitude of the wave signal and time in seconds which takes the wave to be generated. However, the graph shows when the frequency is high with a system deficiency in deviation in frequency of 70Hz.

**Table 1:** Initial values of the parameters for the primary frequency response simulation of the power system model.

| Parameters | T1/T2 | *D* (p.u.) | *TG* (s) | *TT* (s) | *Heq* (s) | *Req* (Hz/MW) |
|---|---|---|---|---|---|---|
| Values | 0.27 | 1.0 | 0.2 | 0.3 | 9 | 0.04 |

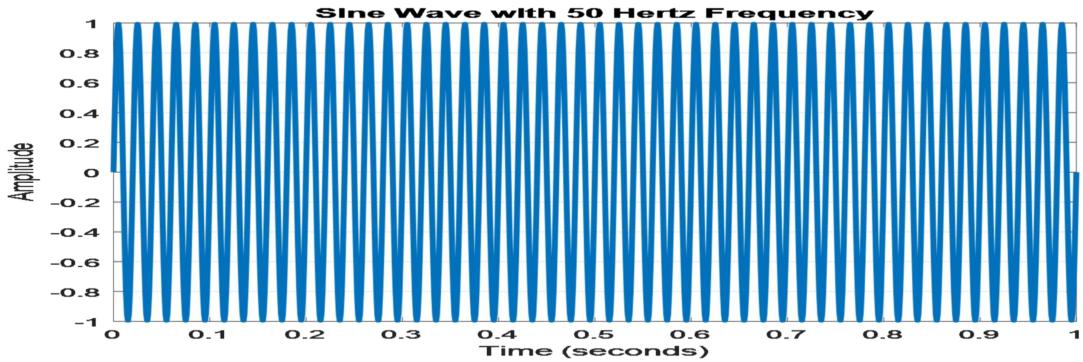


**Figure 6: Normal Frequency**

The waveform in figure 4.9 is a normal sine wave with a normal deviation in frequency of 50Hz which has good impact on the system under consideration, the amplitude of the wave signal does not have much impact on the system.

## IV CONCLUSION

In this study, a simplified power system model was created to investigate the effects of variations in key generation system parameters—such as the equivalent system inertia (Heq), governor droop setting (Req), load damping constant (D), and the power fraction of the high-pressure steam turbine (T1/T2) on the primary frequency response. The analysis focused on the system's behavior in addressing frequency disturbances caused by a generation loss, which was simulated to occur five seconds after the simulation began.

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