



## The Role of Frequency Regulation in Enhancing Power Systems Utilizing Renewable Energy Resources

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### Abstract

Modern power systems rely heavily on frequency regulation to keep them stable and reliable, which is particularly important given the growing use of RES such as small hydro, wind, and solar. Variability and intermittent nature of RES, in contrast to traditional power facilities, might cause changes in system frequency and destabilize the grid. Successful frequency regulation keeps power generation and consumption in balance, avoiding disruptions that might harm equipment, cause power outages, or lower power quality. The capacity to control frequency in systems with a high penetration of RES is greatly improved with the combination of demand-side management approaches, energy storage systems, and sophisticated control strategies. In response to frequency variations, technologies like flywheels, supercapacitors, and battery energy storage can react quickly, while smart grid frameworks allow for adaptive control and real-time monitoring. Additionally, state-of-the-art optimization methods, which use AI and ML, enable adaptive and predictive frequency management, better tolerating the fluctuation of RES. Frequency control is becoming more important in the energy mix due to the increasing number of renewables. It is crucial for operational stability and for building power systems that are sustainable, robust, and ready for the future, since they must be able to cope with changing energy needs.

**Keywords:** Frequency Regulation, Enhancing Power Systems, Utilizing, Renewable Energy

### Introduction

One of the most important things we can do to combat climate change, deplete fossil fuels, and achieve sustainable energy objectives is to incorporate renewable energy sources (RES) into current power systems. This will help reduce emissions of greenhouse gases and enhance energy security. Solar, wind, hydro, and biomass power are some of the most popular renewables because they are good for the environment and because their prices have dropped thanks to technology (Aldeen, M. 2016). Because they are so sensitive to changes in the weather and the seasons, renewable energy sources (RES) are notoriously unpredictable and intermittent, in contrast to traditional thermal power plants. With regard to system frequency stability in particular, this volatility creates substantial obstacles to sustaining a steady and dependable power supply. Equipment failure, load shedding, or widespread blackouts can result from power system frequencies that deviate too far from the permitted range, which represent the real-time balance between power generation and consumption (Salah, K. 2022). The increasing prevalence of RES, frequency control is becoming an increasingly important function in maintaining grid stability in the face of these oscillations. Keep the system frequency within acceptable limits, usually about 50 Hz or 60 Hz regionally, by monitoring, managing, and altering the balance between generation and demand (Pimpinella, L. 2012).

To accomplish this, a number of tools are utilized, including sophisticated grid management technologies, demand response programs, conventional generating units with quick ramping capabilities, battery energy storage systems, and automated generation control (AGC). In renewable-dominated grids, the function of frequency regulation is

even more complicated since inverter-based resources are gradually replacing classic synchronous generators, which have no intrinsic inertia and make the system less resistant to abrupt frequency shifts. This is being addressed by creating and implementing creative solutions including synthetic inertia, virtual synchronous machines, and quick frequency response mechanisms (Liberati, F. 2012). In addition, the integration of AI and ML into grid operations enables optimization of frequency control activities in real-time and predictive modeling, which improves responsiveness and efficiency. In order to encourage prosumers, microgrids, and distributed energy resources to provide ancillary services like frequency support, regulatory frameworks and market mechanisms are also changing (Banerjee, S. 2016). When considering the integration of renewable energy sources into current systems on a wide scale, frequency regulation becomes more than just a technical need; it becomes a strategic facilitator. It guarantees that the switch to renewable energy sources will not negatively impact the dependability and quality of power. More adaptable, flexible, and robust power networks are possible because to frequency regulation, which encourages developments in storage technology, grid automation, and hybrid energy systems (Li, S. 2020).

### Methodology

#### 1. Power System Modelling

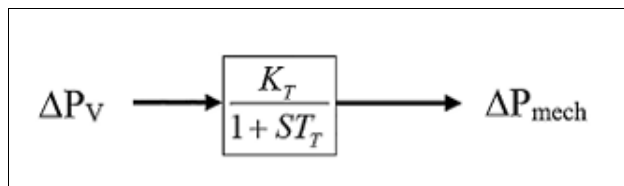
Electrical power system simulation makes use of power system modeling to assess electrical power systems with the use of design/offline or real-time data. Software designed to mimic the operation of electrical power systems is known as power system simulation software. One way to conceptualize s-domain control systems mathematically is

using the transfer function model. Due to its simplicity, it is frequently used for power system modeling. The 62-bus traditional Indian power system is used as the utility system network in this investigation.

**2. Modeling of Test System**

**▪ Turbine Model**

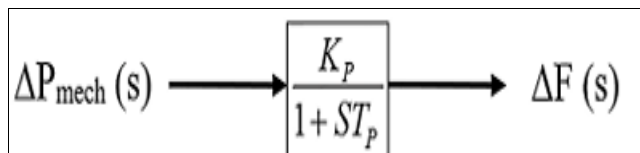
Power in the form of mechanical watts (W) may be produced by mechanical devices known as turbines by converting the energy of fluids like steam or water into it. Mechanical energy powers the generator. The difference between the two powers ( $\Delta P_T - \Delta P_G$ ) determines how the generator's speed changes. The generator's load fluctuations determine the increase in turbine power. In Figure 2.1, we can see the mathematical model of the transfer function of a turbine.



**Fig 1:** Turbine transfer function

**▪ Generator-Load Model**

Electricity is created from mechanical work done by the turbine by use of a generator. Given the limitations of current energy storage technologies, it is of the utmost importance to keep the electrical energy market well-balanced. Figure 3.2 shows the effect that results from increasing generator power  $\dot{P}_G$  on load demand  $\dot{P}_D$ . Constant regulation of the generator's output power ensures that it meets the grid's demands.



**Fig 2:** Generator-Load Transfer function

**3. Improving Steady State Accuracy**

Improving the steady state accuracy by decreasing the steady state errors is the first contribution of this work. Just adjust the PID controller as needed to achieve this. Integral Time Absolute Error (ITAE) is the desired function for configuring the controller parameter. To maximize the advantages of PID controllers, performance indicators such as the ITAE criterion are utilized. For example, they help reduce volatility in other performance indicators like Integral Absolute Error (IAE), Integral Time Squared Error (ITSE), and Integral-Squared Error (ISE).

**4. FA-based Model**

The second important takeaway from this research is the optimization method FA that was used to enhance the performance of the PI controller in the power system model that was suggested. Firefly, an algorithm for load frequency control (LFC), is used to optimize the PI controller in a

four-area linked power system. We use the Ant Search Optimization (ASO) and the Improved Chimpanzee Algorithm (IChimp) to choose the PID controller for LFC tuning. As inputs to the self-tuning process, the Fuzzy controller design took the error and the rate of change of the error, and as outputs, it produced the gains (Kp, Ki, Kd). The FLC uses the conventional PI/PID controller to adjust the controller's settings in response to changes in the signal error and the rate at which it is changing.

**5. Optimization Algorithms for Power System**

**▪ Genetic Algorithm (GA)**

An AI search heuristic that mimics the behavior of natural selection is known as a Genetic Algorithm (GA). Helpful solutions to optimization and search problems are frequently generated using this heuristic, which is also occasionally referred to as a Meta heuristic. Genetic algorithms are a subset of the broader class of evolutionary algorithms (EA), which find solutions to optimization problems by applying methods stimulated by natural selection, such as legacy, change, choice, and hybrid.

**▪ Artificial Neural Network**

A complex network of interconnected neural pathways makes up the human brain, which acts as a decision-making framework underneath the surface level of the person. When it comes to solving complex problems that arise during human execution, the brain outperforms any computer processor. Multiple neuronal layers in the human brain work in tandem under normal conditions.

**Results**

**1. Simulation Results for Model**

The primary objective of the first model is to enhance the reliability of the power grid's steady-state performance when it is linked to renewable energy sources. The proposed model, together with its component designs and results, is detailed in this section. The steady-state accuracy and gains of the PI controller were enhanced using the ITAE fitness function. The adjustments were made in the PI controller. "Fine tuning" a PID controller is making short, exact changes to the proportional (Kp), integral (Ki), and derivative (Kd) gains following an initial tuning stage. The aim is to optimize the system's response by balancing factors like steady-state error, overshoot, and settling time, all while keeping stability. This is usually accomplished by gradually increasing or decreasing each gain value while closely watching the system's behavior under different conditions. Before making exact adjustments, start with a PID controller that has been stabilized using a Ziegler-Nichols or Cohen-Coon method.

Components such as the power grid linked to the suggested frequency regularization process are shown in Figure 3.1. Three residential connections for electricity use, a battery, and renewable energy sources make up the power system. The suggested model of the power system with frequency regularization is illustrated in Figures 3.2 to 3.8, which depict the design of the different components together with their parameter values. To prove how effective the suggested model is, Figure 3.9 displays the results of the simulations for each scoop.

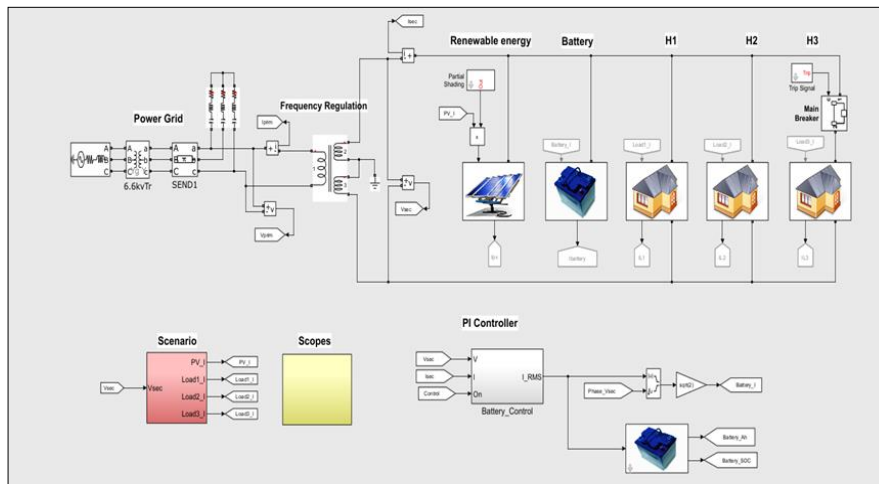


Fig 1: Power system model connected with renewable energy

Three-Phase Source (mask) (link)  
 Three-phase voltage source in series with RL branch.

Parameters Load Flow

Configuration: Yg

Source

Specify internal voltages for each phase

Phase-to-phase voltage (Vrms): 66e3 66000

Phase angle of phase A (degrees): 0

Frequency (Hz): 60

Impedance

Internal  Specify short-circuit level parameters

3-phase short-circuit level at base voltage(VA): 100e6 100000000

Base voltage (Vrms ph-ph): 25e3 25000

X/R ratio: 7

Base voltage (Vrms ph-ph) (Name: BaseVoltage)

Fig 2: Design of three phase source model

Three-Phase PI Section Line (mask) (link)

This block models a three-phase transmission line with a single PI section. The model consists of one set of RL series elements connected between input and output terminals and two sets of shunt capacitances lumped at both ends of the line.

RLC elements are computed using hyperbolic corrections yielding an exact representation in positive- and zero-sequence at specified frequency only. To obtain an extended frequency response, connect several PI section blocks in cascade or use a Distributed Parameter line.

Parameters

Line length (km): 1

Frequency used for rlc specification (Hz): 60

Positive- and zero-sequence resistances (Ohms/km) [ r1 r0 ]:  
 [ 0.01273 0.3864 ] [0.01273,0.3864]

Positive- and zero-sequence inductances (H/km) [ l1 l0 ]:  
 [ 0.9337e-3 4.1264e-3 ] [0.0009337,0.0041264]

Positive- and zero-sequence capacitances (F/km) [ c1 c0 ]:  
 [ 12.74e-9 7.751e-9 ] [1.274e-08,7.751e-09]

Fig 3: Design of three phase PI model

Linear Transformer (mask) (link)  
 Implements a three windings linear transformer.

Click the Apply or the OK button after a change to the Units popup to confirm the conversion of parameters.

Parameters

Units pu

Nominal power and frequency [Pn(VA) fn(Hz)]:  
 [75e3 60] [75000,60]

Winding 1 parameters [V1(Vrms) R1(pu) L1(pu)]:  
 [ 6600 0.00005 0.0002 ] [6600,5e-05,0.0002]

Winding 2 parameters [V2(Vrms) R2(pu) L2(pu)]:  
 [ 100 0.00005 0.0002 ] [100,5e-05,0.0002]

Three windings transformer

Winding 3 parameters [V3(Vrms) R3(pu) L3(pu)]:  
 [ 100 0.00005 0.0002 ] [100,5e-05,0.0002]

Magnetization resistance and inductance [Rm(pu) Lm(pu)]:  
 [ 50 50 ] [50,50]

Fig 4: Design of linear transformer for frequency regularization

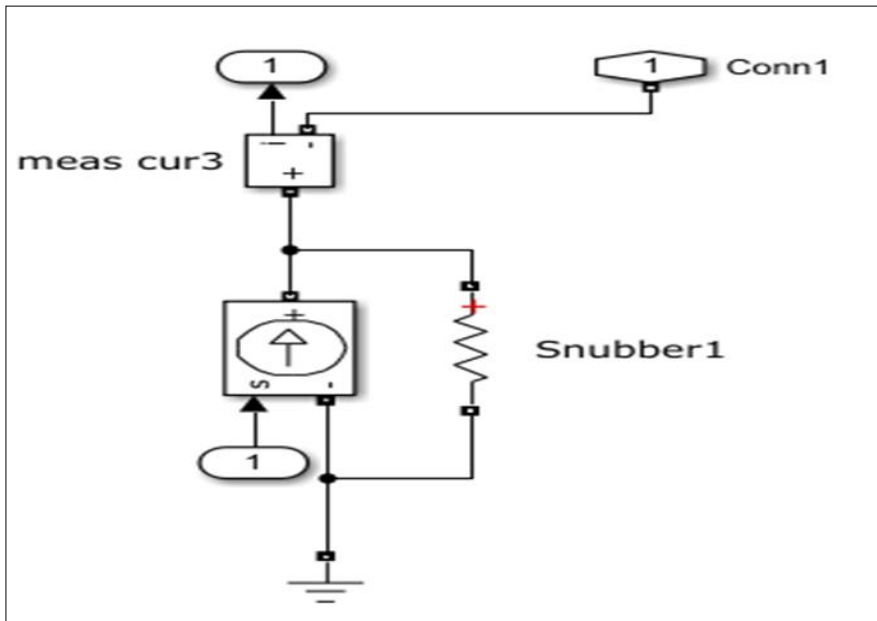


Fig 5: Design of renewable energy sources

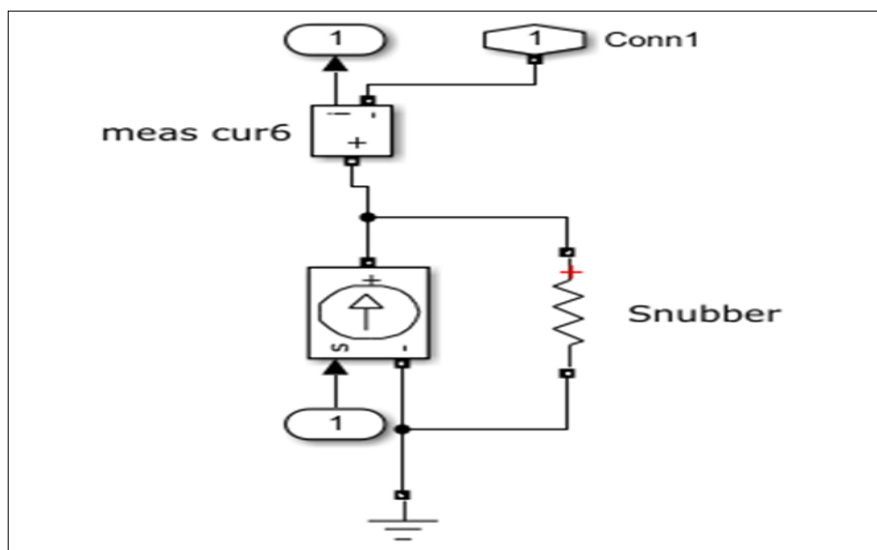


Fig 6: Design of battery system

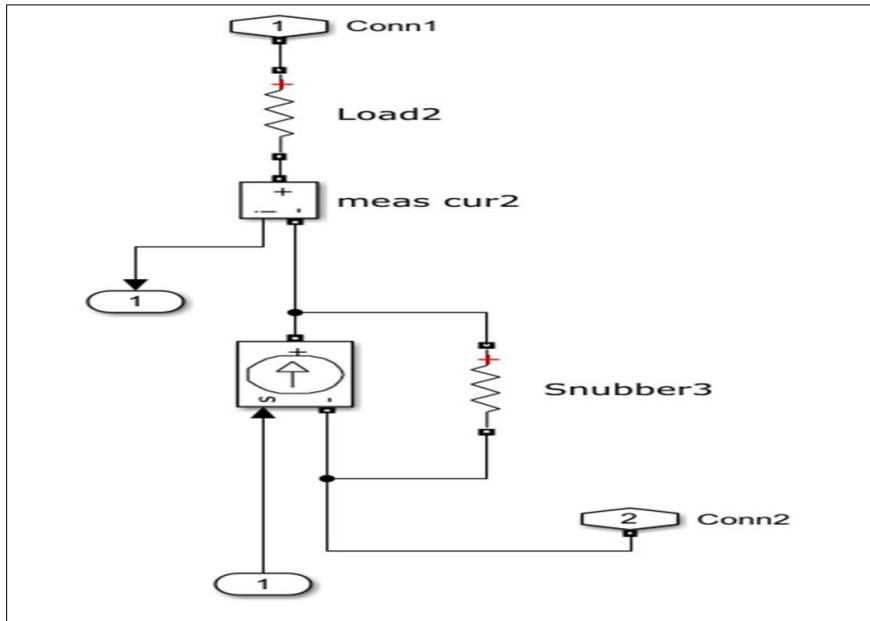


Fig 7: Household power system demand

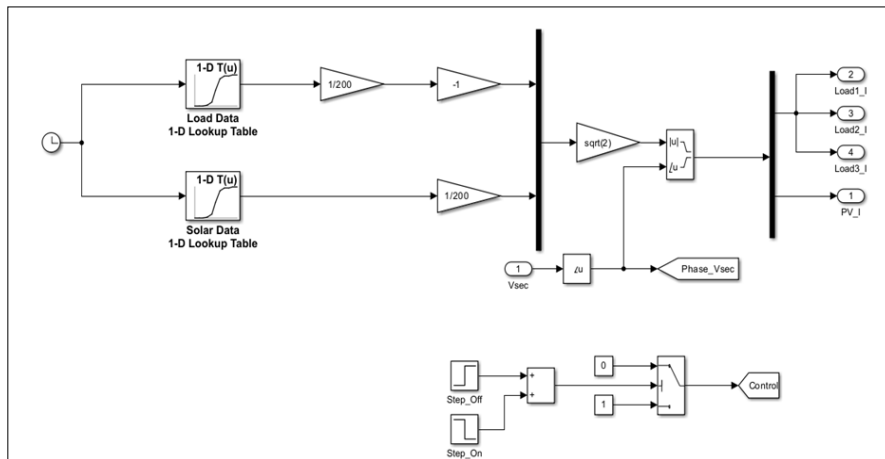


Fig 8: Power system load model

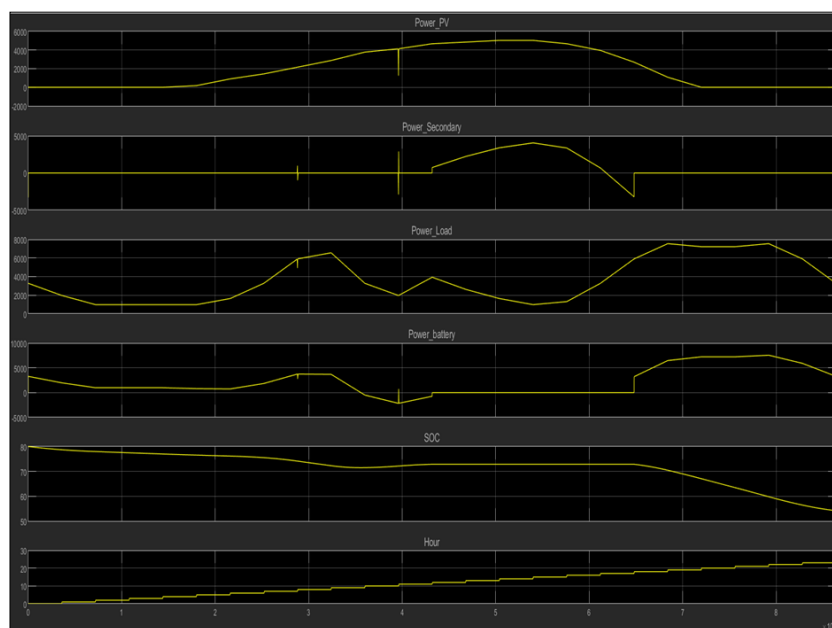


Fig 9: Simulation results for the power system model

The power PV usage study of solar panels as a renewable power source is shown in the first plot of Figure 3.9. Short circuit current ( $I_{sc}$ ), open circuit voltage ( $V_{oc}$ ), maximum power point voltage ( $V_{mp}$ ), current at maximum power point ( $I_{mp}$ ), fill factor (FF), module efficiency, and temperature coefficient are the main photovoltaic (PV) parameters in a power system. These parameters essentially define the electrical properties of a solar panel and its ability to transform sunlight into electricity as it is subjected to different conditions. The results demonstrate that the suggested method made good use of the solar power that was recovered in relation to the electricity demand. Figure 3.9's additional findings show the power load, secondary power, and battery power, which together show the available power system load and the powers used by the secondary and batteries for that load. By optimizing the PID controller using the provided fitness function, the battery charge is maintained at a high level until the end of the day, and the majority of the energy load is met by renewable sources, as shown by the state of charge of the battery.

### Conclusion

Ultimately, power systems that heavily rely on renewable energy resources (RES) rely on frequency control to maintain stability, dependability, and efficiency. When renewable energy sources (RES) like solar and wind are not properly controlled, the resulting power output variations can cause frequency deviations and jeopardize grid stability. These effects can be reduced by efficient frequency management, which maintains a system frequency within acceptable bounds by balancing generation and demand in real time. Energy storage system integration, demand-side management tactics, and advanced control strategies all contribute to more responsive and accurate frequency regulation in renewable-based networks. Improved system resilience, faster reaction times, and optimized control actions are all possible outcomes of using intelligent algorithms like machine learning and artificial intelligence. Market mechanisms and regulatory frameworks that encourage dispersed and flexible resources to provide frequency assistance enhance grid performance even further. Effective frequency regulation is crucial for modern, renewable-rich electricity networks because it allows for greater integration of renewable energy into the grid, guarantees a sustainable transition to low-carbon power systems, maximizes operational efficiency, and minimizes risks of instability.

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