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Virtual Inertia Control of Power Systems with High Sharing of Renewable Energy Resources

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Dedications:

I dedicate this modest work to my family that has always supported and encouraged me to work harder.

To all my friends that have been there for me in times of need, especially my colleagues at school.

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Virtual Inertia Control of Power Systems with High Sharing of Renewable Energy Resources

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Abbreviations

RES	Renewable energy system
VRE	Variable renewable energy
RL	Reinforcement Learning
VIC	Virtual inertia Controller
VSG	Virtual Synchronous Generator
MG	Micro grid
ML	Machine Learning
BSS	Battery storage system
ESS	Energy storage system
SAC	Soft Actor Critic
PCL	Primary control loop
SCL	Secondary control loop
LFC	Load frequency control
WTG	Wind turbine generator
V2G	Vehicle to Grid

Symbols

K_{VI}	Virtual Inertia Constant
Δf	Frequency deviation
RoCoF	Rate of Change of Frequency
K_I	Integral coefficient of secondary control loop
1/R	Droop Control
H	System inertia

D	System damping
R_{VI}	Virtual droop
D_{VI}	Virtual damping
ΔP_L	Load power changes
ΔP_M	Mechanical power deviation
ΔP_E	Electrical power deviation
ΔP_{VI}	Virtual inertia power injection
ΔP_{PCL}	Control changes of PCL
ΔP_{SCL}	ACE action changes of SCL
ΔP_{TPP}	Thermal power plant power
ΔP_{PV}	Photovoltaic power
ΔP_{WTG}	Wind turbine generator
ΔP_{Wind}	Wind power deviation
ΔP_{Solar}	Solar power deviation
ΔP_{RES}	Renewable energy sources power deviation
ΔPg	Governor dead band limits
Tg	Governor Time constant
Tt	Turbine time constant

Abstract:

The intermittent and non-synchronous nature of Renewable Energy Resources (RES) poses critical challenges for system stability and frequency regulation due to the lack of inherent inertia provided by power electronics interfaces RES into system. Therefore, the synthesis and control of virtual inertia control is crucial for maintaining power system stability. This work investigates virtual inertia control in microgrid with high penetration of renewable energy sources (RES), various virtual inertia control strategies are explored, including traditional derivative control, Proportional-Integral (PI) controller, and Fuzzy logic controller. The microgrid is modelled and simulated through Matlab/Simulink, incorporating RES, energy storage and virtual inertia controllers. The performance is evaluated under different disturbance scenarios using metrics such as frequency nadir, rate of change of frequency (RoCoF) and integral absolute error (IAE). The study demonstrates the potential of integrating advanced control techniques for enhanced frequency support in low inertia systems.

Résumé

Ce mémoire étudie le contrôle de l'inertie virtuelle dans les micro-réseaux à forte pénétration des énergies renouvelables (EnR).

La nature intermittente et asynchrone des EnR pose des défis en termes de stabilité de fréquence du système en raison de l'absence d'inertie inhérente.

Pour y remédier, différentes stratégies de contrôle sont explorées, notamment le contrôle dérivé traditionnel, la méthode proportionnelle-intégrale (PI) et la logique floue.

Le micro-réseau est modélisé et simulé avec Matlab/Simulink, intégrant des modules EnR, de stockage d'énergie et d'inertie virtuelle.

Les performances sont évaluées dans différents scénarios de perturbation à l'aide de mesures telles que le nadir de fréquence, le RoCoF et l'IAE.

L'étude démontre le potentiel de l'intégration de techniques de contrôle avancées pour une meilleure gestion de la fréquence dans les systèmes à faible inertie.

الترددات، تحدياتٍ حرجة لاستقرار النظام وتنظيم (RES) ملخص: تُشكّل الطبيعة المتقطعة وغير المتزامنة لموارد الطاقة المتجددة
حـ كم في النظام. لذلك، يُعدّ تركيب الت (RES) نظرًا لغياب القصور الذاتي المتأصل الذي تُوفّره واجهات إلكترونيات الطاقة
كم ضي والتحكم به أمرًا بالغ الأهمية للحفاظ على استقرار نظام الطاقة. يبحث هذا العمل في التحبـ الـ قـ صور الـ ذاتـ ي الافـ ترا
ويستكشف ،(RES) بالقصور الذاتي الافتراضي في الشبكات الكهربائية الصغيرة ذات الانتشار العالي لمصادر الطاقة المتجددة
،(PI) حكم التناسبية التكامليةبما في ذلك التحكم التقليدي بالمشتقات، ووحدة التـ ،استراتيجياتٍ مُختلفة للتحكم بالقصور الذاتي الافتراضي
جةً مصادر مُدمـ ،Matlab/Simulink ووحدة التحكم المنطقية الضبابية. تمّت نمذجة الشبكة الكهربائية الصغيرة ومُحاكاتها باستخدام
تي الافتراضية. يُقيّم الأداء في ظلّ سيناريوهات الـ طاقـ ة الـ مـ تجددة، وتـ خزيـ ن الـ طاقـ ة، ووحدات الـ تحـ كم بـ الـ قـ صور الـ ذا
تُبيّن .(IAE) والخطأ المطلق التكاملي ،(RoCoF) اضطراب مُختلفة باستخدام مقاييس مثل أدنى قيمة للتردد، ومعدل تغير التردد
ذاتـ يالدراسة إمكانية دمج تقنيات التحكم المُتقدّمة لتعزيز دعم الترددات في الأنظمة منخفضة القصور الـ

Objectives

- To model and simulate a micro grid with high renewable energy sharing
- To design and evaluate various control strategies for virtual inertia support including PI and RL based controllers

- To compare the effectiveness of each control approach based on performance metrics such as RoCoF, frequency nadir and IAE

Motivation:

The rise of renewable energy sources (RES) in modern microgrids has significantly reduced system inertia, making frequency regulation increasingly difficult. This work explores and compares virtual inertia control strategies: a traditional virtual inertia control method, proportional-integral (PI) controller, fuzzy logic based controller. The controllers are implemented to counteract disturbances such as load changes and renewable generation variability.

Research questions:

In the research work we tried to find answers for the following research questions:

- How does virtual inertia affect system frequency stability under high-RES penetration?
- Advantages of different virtual control methods?

CHAPTER 1

INTRODUCTION

Introduction: Access to electricity contributes greatly to the industrial growth, economic growth and sustainable development of countries. Electricity is essential for improving quality of life. It powers lighting, transportation, communication and nearly all modern technologies. Without reliable electricity, daily life becomes difficult to imagine.

Consequently, the traditional integrated power system consisting of thermal, hydro and gas units; fossil fuel-based energy has become one of the reasons for global warming caused by a lot of pollution especially from the thermal power plants.

Also, with rapid growth in plug in electric vehicles or vehicle to grid (V2G) technology there has been a rapid increase in demand for electric power.

For the future of power engineering, an important step is to move towards the concept of renewable energy.

Moreover, the International Energy Agency (IEA) predicts that by 2030, global electricity consumption will increase to 30,000 TWh, i.e. twice the energy consumed in 2010.[4]

These changes significantly increased demand for renewable energy sources, which should replace traditional power plants due to their eco-friendly nature and zero CO2 emission with energy storage devices offering support for grid operation.

1.1 **Impact of high renewable energy penetration**

The generation of stable and sustainable power from natural sources is a big challenge for today's infrastructure because AC power networks that are most widely used, were designed to be provided by power with stable generation and high inertia.

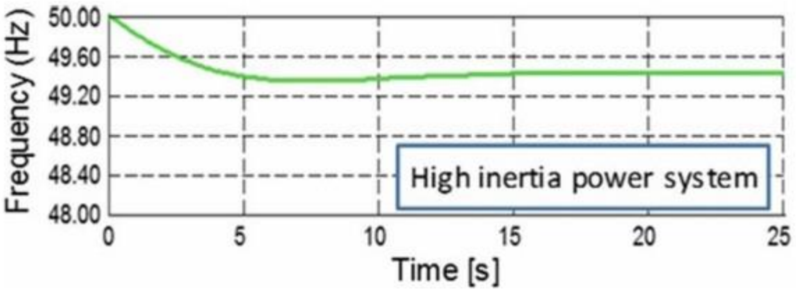
In contrast, renewable power sources, including wind turbines and electronics-based solar panels, are unstable, variable and have low inertia.

Therefore, REs are applicable for grids designed to adapt generators with decreased inertia.

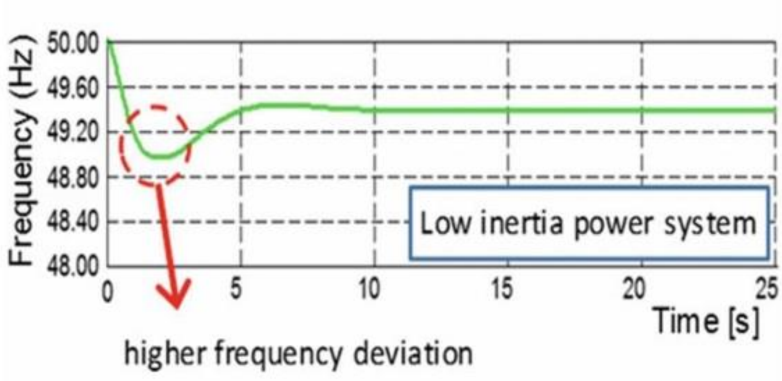
An isolated micro grid is a great example of this power system, where a high-inertial thermal power plant works alongside low inertial wind generators and PV panels.

If inertia becomes too low, there is a high risk of a short-term grid shutdown and damage to many electrical devices. This can happen due to a drop in frequency and a high rate of change of frequency/RoCoF [5].

The illustration of the correlation between inertia and frequency is shown in figure 1.1. It is clearly shown that with lower system inertia, frequency nadir subject to a frequency event would be lower.



a)



b)

Figure1.1; Illustration of the correlation between inertia and frequency: frequency response to a particular frequency event in the high inertia power system (a) and low inertia power system (b)[7]

Therefore, low-inertia phenomena appeared due to the transition from a generator-dominated to an inverter-dominated power system.

Moreover, micro grids introduce a complex network of interconnected generators with varying inertia which calls in the critical need for frequency support.

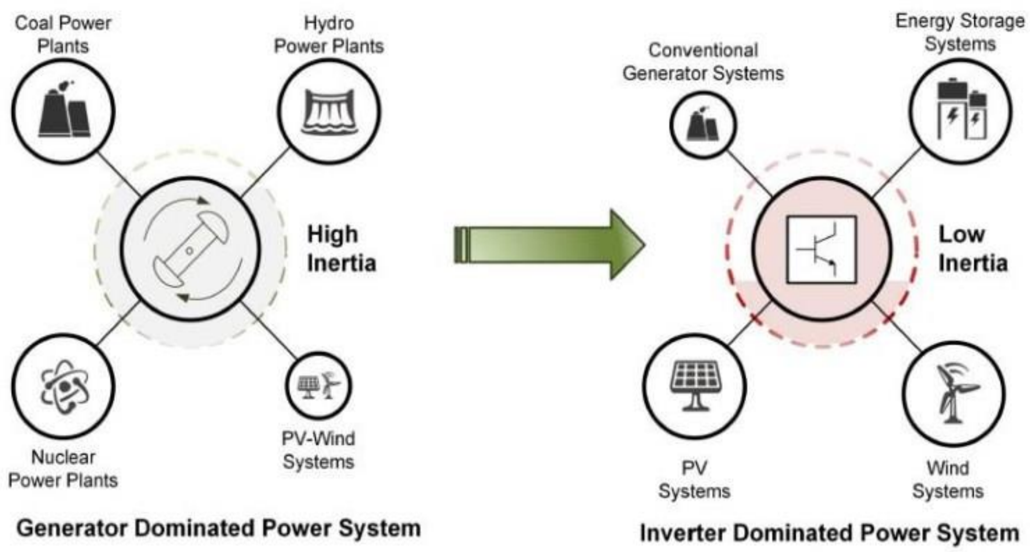


Figure 1.2; Representation of the evolution of power system from generator based to inverter dominated adopted from [2]

With the increasing RESs penetration, micro grids lack inertia creating a difficulty in stabilizing system frequency causing the weakening of micro grid stability and resiliency.

Therefore, a virtual synchronous generator concept is presented to imitate the nature of traditional generating units virtually into power systems enhancing system inertia and micro grid stability. Virtual inertia control is a specific part of VSG operation where the action of traditional power generators is emulated to support system frequency stability.

The virtual inertia control employed in the energy storage systems (ESS) will enable the ESS to operate as a traditional generator, exhibiting inertia and damping properties of traditional generations to the system. Virtual inertia control can offer a basis for maintaining the share of distributed generations (DGs) in the micro grid without compromising stability. Without virtual inertia control, RESs might cause micro grid instability and cascading outages in the case of disturbances.[1]

1.2. Micro grids

A micro grid is a small electric grid system comprised of a generation unit(s) and distribution lines often not connected to main electricity networks, that link to households and /or other consumers.

Micro grids comprise a variety of technologies: renewable sources such as photovoltaic and wind generators are operated alongside traditional high-inertia synchronous generators, batteries and fuel-cells. Thus, energy is generated near the loads, enabling the utilization of small-scale generators that increase reliability and reduce losses over long power lines. The location of the micro grid network enables improved energy management.

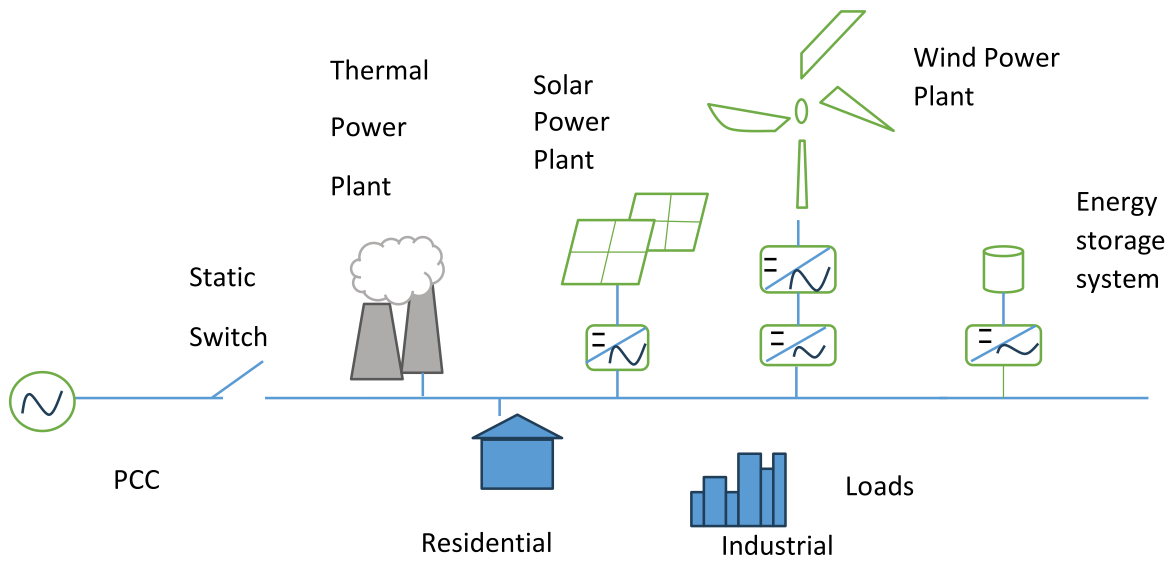


Figure 1.3: Schematic representation of a typical micro grid, including power conversion devices, power generators with different inertia

Therefore, micro grids with high-RES penetration are a challenge for integration into massive distribution networks, creating various challenges such as:

- active/reactive power imbalance and voltage droop in transmission lines
- production/consumption imbalance in distribution loads
- frequency mismatch with other micro grids and the rest of the power grid

A challenge is the regulation of the grid’s frequency, considering the high penetration levels of renewable sources.

To overcome this problem, we have installation of fast-reacting storage systems with integrated virtual inertia alongside low-inertia power sources

Hence, energy storage systems are considered as the prime actuator in frequency stability control, which have physical limitations such as: (1) (dis)charge cycles; (2) restricted power reservation; (3) reserved power losses; and (4) individual speed of (dis)charge. Moreover, energy storage control performed by virtual inertia uses power-inverting electronics, which come with physical delays and limitations in frequency measurement and power conversion.[3]

CHAPTRE 2

BACKGROUND ON INERTIA IN POWER SYSTEMS

2.1 Inertia in power systems

Inertia is defined as kinetic energy stored in the rotating masses of generators and motors synchronously connected to a power system which translates into resistance of rotating masses (synchronous machines) to imbalances within the grid.

Kinetic energy is exchanged with the power system (released or absorbed) whenever there are instantaneous imbalances between generation and load. This is referred to as an inertial response.[10, 11]

Changes in load profile can greatly impact the stability and resilience of the grid.

Nonsynchronous devices interfaced to the system via power electronic inverters such as photovoltaic inverters have zero inertia.[1]

Fixed speed induction generators wind turbines are also inertially coupled and provide an inertia response.

Table 1: Comparison between machines that are inertially coupled to the grid and those which have no inertia coupling to the grid

Inertially coupled	No inertia coupling
○ Synchronous machines(generators, motors)	Static converters like P.V inverters
○ Fixed speed induction generator wind turbines	Variable speed wind turbine generators

The moment of inertia for a generator shaft is proportional to its mass and the square of its radius therefore machines that are bigger and heavier in size possess more inertia than smaller and lighter machines.

Consider a rotating cylindrical mass, for example a generator shaft,

Length of an arc of a circle L= $\theta\, r$ in metres

Rotational velocity of rotating mass V = $\frac{\theta r}{t}$

Or V = $\omega\, r$ where ω is angular velocity

KE (general form): KE = $^1/_2\; m\, v^2$ in joules or kg $^{m^2}/_{s^2}$

Rotational inertia /kinetic energy

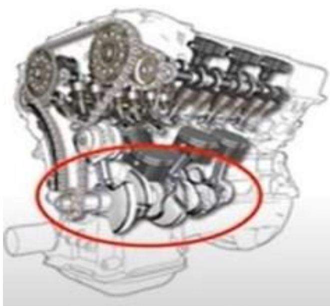
$$KE = \; ^1/_2\; m\, (\omega\, r)^2 \qquad (1)$$

$$KE = \frac{1}{2}\, \mathrm{j}\;\; \omega \qquad (2)$$

Where J (moment of inertia) = $m\, r^2$

For synchronous machines operating at nominal frequency (fn): $\omega = \omega n$ = 2 $\pi\, fn$

Steam turbine Gas turbine



Hydraulic turbine Combustion engine (Crankshaft)

Figure 2.1: Different examples of Mechanical prime movers used in electricity generation for Power Systems: Steam turbine, gas turbine, hydro turbine and internal combustion engine.

The inertia of a generator can also be expressed as a nominal quantity known as the constant of inertia.

Inertia of a generator;

$$H = \frac{1}{2}\frac{J\,\omega^2}{Sn} = {KE}/{Sn} \qquad (3)$$

Where Sn is the nominal apparent power of a generator in VA.[12,13]

2.2 High and low inertia systems

Steam/gas units have higher inertia, hydro and coal fired steam power generating units have relatively high inertia and diesel engines have low inertia

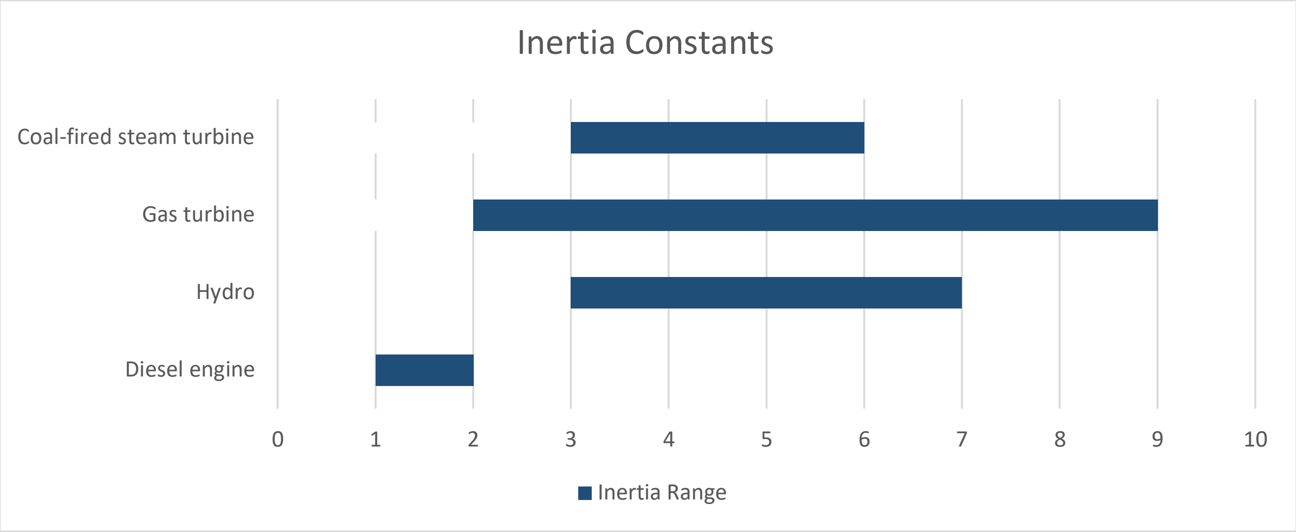


Figure 2.2: Typical inertia constants of different turbines used in generator units

Total inertia in a power system is the addition of all individual inertia components coupled to the system at a given time.[12]

$$KE\ syst = \sum_1^N KEgen + \sum_1^M KE\ load \qquad (4)$$

KE load is the inertia contributed by rotating loads like motor loads.

However, taking a sum approach for the kinetic energy of a power system is not practical as connection status and inertia parameters for all connections need to be known.

2.3 Inertia and System Frequency

In synchronous power systems, inertia is the energy exchanged with the system when there is a mismatch in generation and load.

When the load is greater than generation, kinetic energy from the inertia supplies the energy deficit but rotating masses slow down and thus system frequency reduces

When generation is greater than the load, the excess load is converted into kinetic energy and the rotating masses speed up thus system frequency rises

If generation is suddenly removed, energy from inertia supplies the load but rotating masses start to slow down, and frequency drops down/declines.

When generation is equal to the load there is no inertia exchange and system frequency is stable (50Hz) [1, 4]

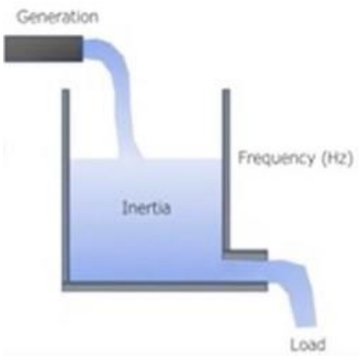


Figure 2.3: Physical representation of effect of generation and load increase or decrease on inertia and system frequency

Lower inertia is equal to less energy stored in rotating masses and frequency declines more rapidly, higher rate of change of frequency (RoCoF).

; The implementation of a virtual inertia control is based on the emulation of the typical swing equation of a synchronous generator (SG) in the control of inverter. The typical swing equation of an SG can be written as;

$$Pm - Pe = Pa \qquad (5)$$

$$\frac{d\Delta f}{dt} = \frac{fn}{2\,KEsyst}\,(Pm - Pe) = \frac{fn}{2\,KEsyst}\,\Delta P \quad (6)$$

$$Pm - Pe = Pa = \frac{2\,H}{\omega 0}\,\frac{d^2\,\delta}{dt^2} \quad (7)$$

$$Pm - Pe = Pa = \frac{2\,H}{\omega 0}\,\frac{d\,\Delta\,\omega r}{dt} \quad (8)$$

When the damping component is also included, the equation above becomes

$$Pm - Pe = Pa = \frac{2\,H}{\omega 0}\,\frac{d\,\Delta\,\omega r}{dt} + K_D\,\frac{\Delta\ \omega r}{\omega 0} \quad (9)$$

Represented in frequency (Hz) as

$$Pm - Pe = Pa = \frac{2\,H}{f0}\,\frac{d\,\Delta\,f}{dt} + K_D\,\frac{\Delta\ f}{f0} \quad (10)$$

Where;

$\frac{d\Delta f}{dt}$; Rate of change of frequency

KEsyst; system inertia

Pm; *Power produced by generating units* (pu)

Pe;Power of the loads (pu)

Pa; Acceleration Power (pu)

fn ;Nominal frequency

H; Inertia Constant

$\omega 0$; rated angular velocity of the rotor(rad/s)

ωr ; angular velocity of the rotor (rads/s)

ΔP; *Genrator and load imbalance*

K_D; Damping coefficient

f0; Rated frequency of the power system

f; frequency of the power system

The swing equation shows the relationship between active power and the angular rotor velocity of an SG and is also correlated to the system frequency.[9 , 10]

Based on the swing equation the system frequency can increase or decrease depending on the balance between the mechanical power input and electrical power output. When (Pm-Pe) is positive, the acceleration power Pa is positive and system frequency increases and vice versa.[9]

Considering.

- The disturbance is instantaneous and can be measured accurately e.g. a generator contingency
- The system frequency and its first derivative can be measured accurately and with high resolution
- The onset of the disturbance can be accurately determined
- The method is only valid for a small period after the onset of a contingency thus effects of load relief and primary frequency response are neglected.

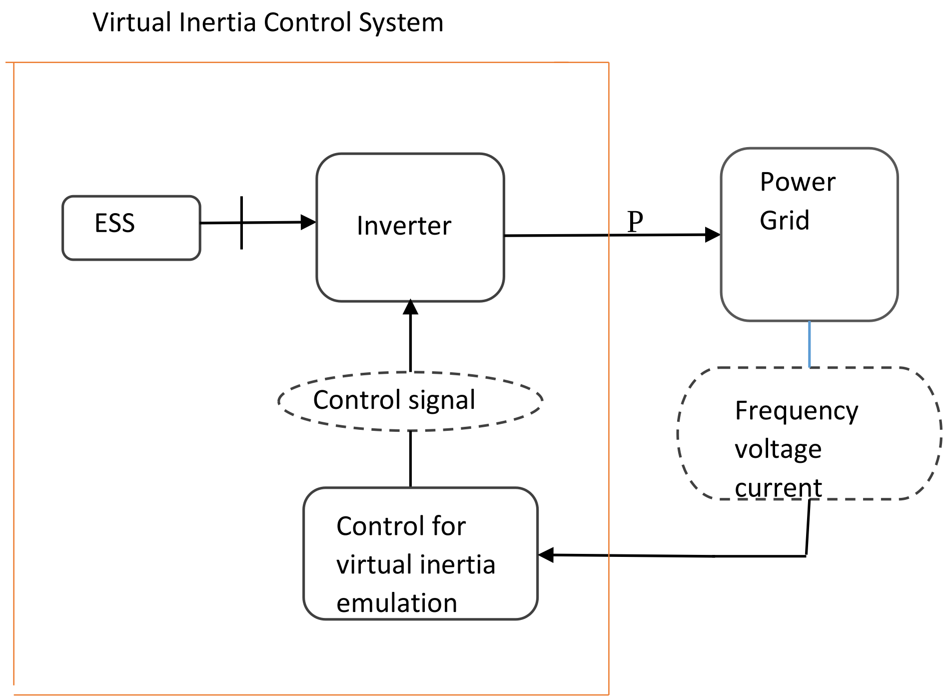


Figure 2.4: Basic Diagram of virtual Inertia Control System

2.4. Existing solutions and technologies of virtual inertia

Numerous control techniques have been implemented to virtual inertia control to solve micro grid frequency control problems, improving frequency stability:

1. **Virtual Synchronous Generator (VSG)**

The VSG concept emulates the dynamics of a synchronous machine using control algorithms integrated within power electronic converters. These systems emulate inertia by controlling active power based on frequency deviation and its rate of change (RoCoF). VSGs typically use swing equation-like control laws:

$$P = -M \frac{dw}{dt} - D \, \Delta \mathrm{w} \tag{11}$$

VSG-based systems have been widely studied for grid-forming inverters, enabling them to provide both frequency support and voltage regulation.[11]

2. **Droop-Based Virtual Inertia**

Some controllers implement virtual inertia through modified droop control, where a frequency derivative term is added to the traditional power-frequency droop equation. This approach allows inverter-based sources to contribute to both inertial and primary frequency response using:

$$P = -Kp \, \Delta \mathrm{f} - Kd \, \frac{d\, \Delta \mathrm{f}}{dt} \tag{12}$$

This is simpler to implement than full VSGs.[9]

3. **Energy Storage-Based Inertia Emulation**

Battery Energy Storage Systems (ESS) are often coupled with virtual inertia controllers to provide fast and controlled active power injections. [7] ESS has the following advantage:

- React instantly to frequency changes
- Absorb or inject power to stabilize frequency
- Be used in both grid-connected and islanded micro grid environments

Technologies include; Flywheel energy storage, Super capacitors, Lithium-ion battery systems

In energy storage systems like for micro grids;

- Flywheels store energy by spinning a heavy wheel at high speeds in a vacuum, the energy type is kinetic and fast acting. When energy is needed, the flywheel slows down and the rotational energy is converted back into electricity. Used for grid frequency regulation reducing short power interruptions and stabilizing renewable energy systems.

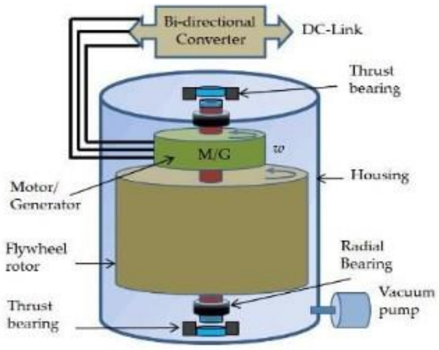


Figure2.5; Flywheel energy storage

- Lithium-ion batteries store energy in chemical bonds through chemical intercalation of lithium ions, this type of battery handles the bulk energy -storing energy from solar/wind and supplying it steadily.

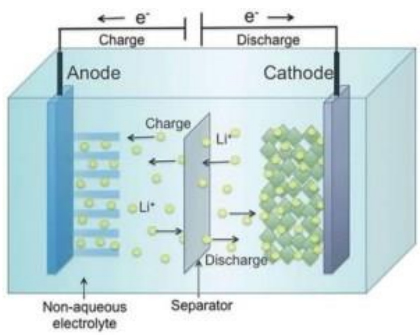


Figure2.6; Lithium ion battery storage

- Super capacitors store energy in electrostatic fields (electric double layer) through charge separation is fast acting and helps with fast response -like handling sudden power drops or spikes (e.g. frequency support).

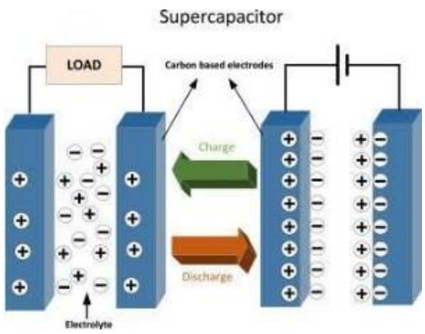


Figure2.7; Super Capacitor energy storage

4. **Model Predictive and Robust Control Techniques**

More advanced control strategies such as Model Predictive Control (MPC) and H-infinity control have been applied to virtual inertia problems, particularly where robustness against uncertainty or constraints is important.

These methods design a controller that minimizes frequency deviation under worst-case disturbances or forecasted trajectories, often requiring more computation and system modeling.

5. **Grid-Supportive Inverters**

Some inverter manufacturers have begun integrating inertia emulation directly into their products. These "grid-supportive" or "grid-forming" inverters include built-in logic to provide: Synthetic inertia, fast frequency response, voltage support during transients

Standards like *IEEE 1547-2018* and *EN 50549* encourage or require such features for grid-connected RES.

Current virtual inertia solutions range from basic droop-modified control to highly advanced optimization-based methods.

2.5. Characteristics of low inertia days include.

Weekends: Lower loads on weekends are experienced due to reduced commercial and industrial activity

Sunny days: Leading to increased rooftop PV outputs

Days with mild temperatures: hence forth no need for heating and cooling appliances reducing residential loads while being optimum for PV performance

Clear skies: This translates into maximum rooftop PV output

2.6. Frequency control during a contingency

Frequency regulation is related to the energy balance of load demand and generation, which is of great significance and recognized as a high priority area by most operators. Any disturbance that leads to the unbalance between generation and load can cause an abrupt change in system frequency, resulting in frequency oscillations. Frequency oscillations may affect system stability, operation, and resiliency. Large frequency oscillations can damage equipment, deteriorate load performance, overload transmission lines, trip protection relays, and in the worst case, lead to system collapses and wide-area power blackouts. [12]

The frequency of the system is proportional to the rotating speed of the generator. Thus, the frequency control issue may be directly transformed into a speed control issue of the generator-turbine units. This problem is solved by applying a governing system, which can track the generator speed and adjust the input value to change the mechanical power output to follow the load variation and reduce the frequency deviation. After that, the secondary control action will restore the frequency back to its nominal value. Based on the frequency oscillation (deviation), the natural response called inertia power compensation, along with primary control, secondary control, tertiary control, and emergency control may be needed to regulate system frequency. [12 15]

1. Inertial Response (IR)

A rapid and automatic injection of energy to suppress rapid frequency deviations, slowing the rate of change of frequency.

2. Primary Frequency Response

Immediate response within 10s involving droop control of governors on generators.

Reacts to frequency deviation due to sudden disturbances like loss of generation unit by adjusting power output of the remaining generator units.

The governors detect frequency changes and adjust their power output to stabilize frequency.

3. Secondary Frequency Response

Response is slower within minutes after primary control.

Automatic Generation Control (AGC) signals act to restore frequency to nominal frequency and relieve providers of primary frequency response.

4. Tertiary Frequency Response (Redispatch)

Active power controls, such as the start-up of new units or set point changes on operating units, act to replace depleted secondary frequency control resources to ensure the system continues to remain within its normal operating band.[2]

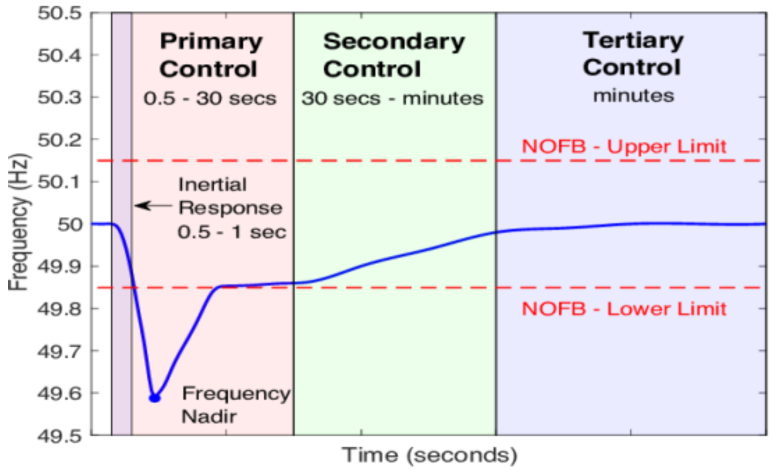


Figure 2.8; Hierarchal representation of frequency control [2]

CHAPTER 3:

SYSTEM FREQUENCY RESPONSE AND SYSTEM MODELLING

3. System frequency response and modeling

This chapter presents a simplified mathematical model of an isolated micro grid taken from recent publications as shown in the figure. This model includes simplified domestic load that is comprised of both residential and industrial loads, energy sources (thermal power plant, wind farm and solar power plant) and energy storage systems. The thermal power plant is composed of a governor with a generator rate constraint (GRC) and a turbine with a frequency rate limiter, which restricts the valve opening/closing (VU, VL). The dynamic model of the micro grid utilizes hierarchical architecture with primary and secondary control loops. The primary control loop has a droop coefficient of 1/R, and the secondary loop has an area control error (ACE) system with the second frequency controller, a gain of KI and a first-order integrator. The regulation of frequency is performed by the virtual inertia controller. [7]

The balancing system is performed by first-order transfer function with micro grid damping coefficient D and system inertia H. The power generation by variable energy sources is modelled as random signals. The hierarchical control of frequency includes the primary control loop (PCL) and secondary control loops (SCL). The modelling parameters of the micro grid are summarized in Table 2.

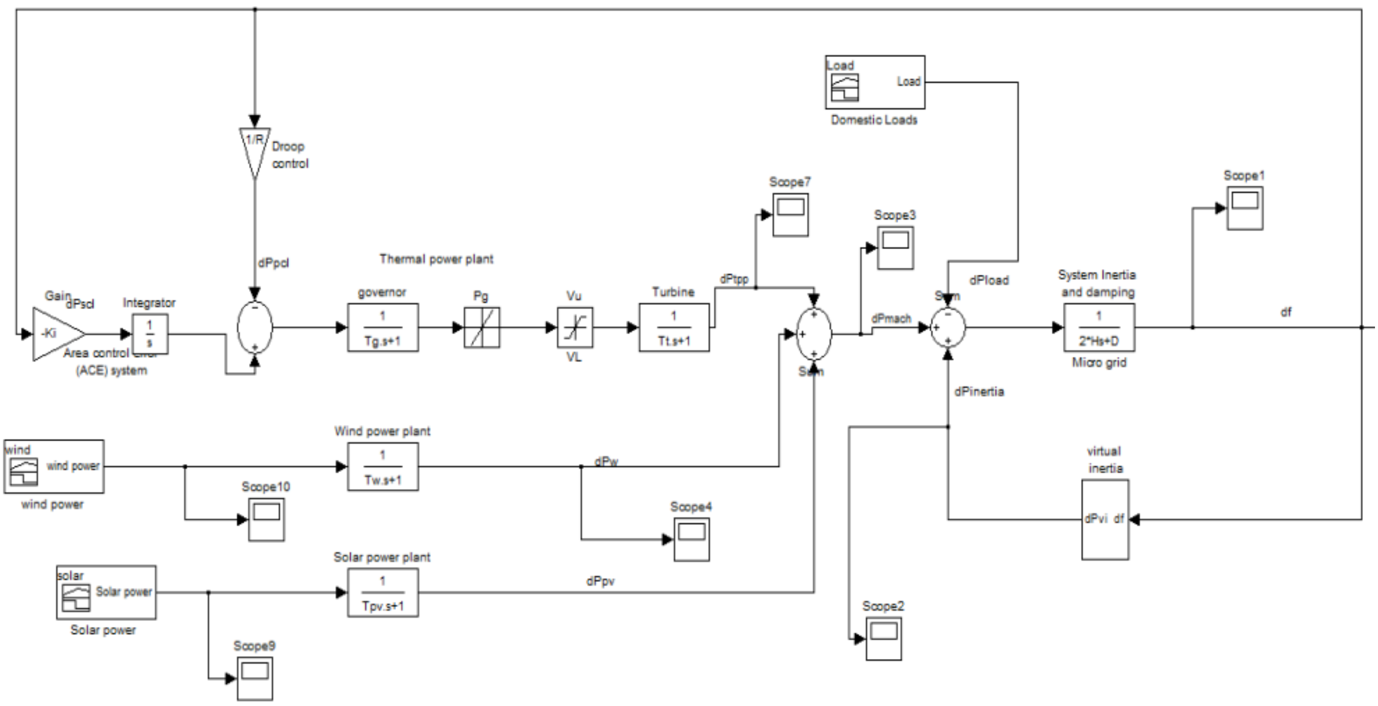


Figure 3.1: Mathematical model of isolated micro grid with hierarchical control loop and frequency support provided by virtual inertia controller, including renewable energy and domestic loads.

3.1 Thermal power plant

This is the major power supplier with a large synchronous generator, which has high rotational inertia. In the mathematical model to control the frequency deviation Δf and preserve stability under various disturbances, two main frequency control methods are responsible for balancing and restoring the system, which is the PCL and SCL.[15]

Table 2: Parameters of the isolated micro grid

Parameters	Value
System inertia, H, p.u. s	0.083
Damping coefficient, D, p.u./Hz	0.015
Virtual damping coefficient, D_{VI} , p.u./Hz	0.3
Virtual inertia droop coefficient, R_{VI} , Hz/p.u.	2.7
Droop coefficient, R , Hz/p.u.	2.4
Virtual inertia time constant, T_{V_I} ,s	10
Turbine time constant, T^t ,s	0.4
Governor time constant, T^G ,s	0.1
Integral controller gain, K^I ,s	0.075
WTG time constant, T_{WTG} ,s	1.85
PV time constant, $T^P{}_V$,s	1.5
Governor valve limiter $V^U, V^L,$ p.u.	±0.5
Governor dead band limits ΔPg_{min}^{max} ,p.u. MW/min	±0.12
Virtual inertia valve limiter ΔPvi_{min}^{max} , p.u.	±0.25

These two loops are applied to the thermal power plant (TPP) governor to generate power from the turbine system provided as

$$\Delta P_G = \frac{1}{1+s\,TG}\,(\Delta P_{SCL} - \Delta P_{PCL}) \qquad (13)$$

in which $\Delta P_{PCL} = R^{-1}\Delta f$ and $=\Delta P_{SCL}\ S^{-1} - KI\Delta f$ are the control and ACE action changes from PCL and SCL, respectively; R is the droop constant; and KI is the integral controller gain.

Finally, its output is defined as:

$$\Delta P_{TPP} = \frac{1}{1 + s\,Tt}\ \Delta P_G \tag{14}$$

Where ΔP_G is limited by valve opening/closing constants V_U and V_L

3.2 Variable renewable energy sources

In traditional power plants the rotational speed of the generator depends on controllable steam flow, which is easily controlled by closed-loop methods.

However the kinetic energy of wind turbines is defined by wind velocity, which is not controllable.

With solar panels, photoelectric panels have zero inertia and energy generation depends on the daily intensity of solar radiation.

Therefore, in modelling, variable renewable energy is considered as a source with unstable power generation and decreased inertia, where solar panels ΔPPV and wind turbines ΔPWTG are random signals with a transfer function that simulate natural transfer delay power flow.

Renewable energy sources do not participate in frequency management. Hence, these simplified models of the renewable energy power sources:

$$\Delta P_{RES} = \Delta P_{WTG} + \Delta P_{PV} = \frac{1}{1 + s\,T_{WTG}}\ \Delta P\ \text{wind} + \frac{1}{1 + s\,T_{PV}}\ \Delta P\ \text{solar}. \tag{15}$$

where ΔP wind and ΔP solar are signals with random defined values, where T_{WTG} and T_{PV} are transfer delays of wind turbine and solar panels, respectively.

3.3 System inertia and damping

In many power systems, the inertia model has a predefined constant of system inertia H whose nominal value is 0.083 (i.e. 100% inertia) and can be changed to simulate the dynamics scenario with decreased inertia, e.g. with 80% nominal magnitude, damping coefficient D has a nominal value of 0.015. By defining the damping D and inertia constant H, the frequency deviation Δf can be represented

$$\Delta f = \frac{1}{2\ Hs + D} + \Delta P_E \tag{16}$$

Where ΔP_E is the general power deviation resulting from all power sources and loads and can be calculated

$$\Delta P_E = \Delta P_{TPP} + \Delta P_{WTG} + \Delta P_{PV} + \Delta P_{VI} - \Delta P_L \quad (17)$$

The system and damping function are based on a swing equation, which in the common form is represented as

$$\frac{2\ H}{f}\frac{df}{dt} = P_M - P_L \quad (18)$$

3.4 Energy Storage

Energy Storage is energy holding for a certain time.

The most common types of energy storage are batteries like super capacitors, flywheels, pumped hydro storage and superconducting magnets.

Energy storage is essential in power systems as they allow the smoothness and balancing of unstable energy sources by accumulation for later dispatch. [15]

Energy storage can be directly added into frequency response and activated, supporting RoCoF during a contingency, it is stored during overproduction and utilized during the underproduction of power in the grid.[7]

The simplified model of energy storage can be represented as:

$$\Delta P_{VI} = \{ \begin{array}{c} \Delta P_{VI}\,\text{max},\ \Delta P_{VI} < \Delta P_{VI}\text{max} \\ G(s)\text{RoCoF}, \Delta P_{VI}\,\text{min} < \Delta P_{VI} < \Delta P_{VI}\text{max} \\ \Delta P_{VI}\,\text{min}, \Delta P_{VI}\,\text{min} > \Delta P_{VI}\,\text{min} \end{array} \quad (19)$$

Where G(s) is represented as a first order function:

$$(s) = {}^{1}/{T_{IV}s + 1} \quad (20)$$

The energy storage model (low pass transfer function) limits how fast the storage can react to frequency changes to inject power into the system.

Where, T_{VI} is time delay that simulates energy storage speed and ΔP_{VI} represents the power injection limits.

3.5 Domestic loads

Domestic loads simulate the behavior of regular electricity consumers, including residential (residential buildings, civil institutions, private houses, schools) and industrial loads (factories, chemical plants, manufactures, and mining institutions).

The loads are represented by variable signals ($\Delta P v_L$) to imitate real life variable nature of such loads. One signal is used to represent the summation of domestic and industrial type load.

CHAPTER 4

Analysis of Virtual Inertia Control in isolated micro grid

4.1. Virtual inertia control (derivative method)

A virtual synchronous generator is a power converter-based device that produces power as a real synchronous machine. Thus, the virtual inertia control system imitates the inertia characteristic, contributing to the total inertia of the islanded micro grid and improving the frequency stability and resiliency. It is designed to compensate for the lack of inertia by power injection. [8 16]

Usually applied in systems with a high level of fluctuating renewable power to improve the frequency stability.

Traditionally, a virtual inertia control setup consists of a derivative component, virtual inertia variable gainK_{VI}, an energy storage system and a power limiter (ΔP_{VI}max, ΔP_{VI}min). The main concept used in virtual inertia control is the Rate of Change of Frequency (RoCoF), which can be calculated as:

$$RoCoF = {}^{d(\Delta f)}/_{dt} \qquad (21)$$

The RoCoF defines the time derivative of the frequency signal, which is used to calculate the inertia response of the system as

$$\Delta P_{VI} = {}^{K_{VI}}/_{T_{VI}\, s + 1} * {}^{d(\Delta f)}/_{dt} \qquad (22)$$

Where K_{VI} virtual inertia constant is usually defined as

$$K_{VI} = \frac{2\ H\ P_{inv}}{f0} \qquad (23)$$

Where $f0$ is the nominal frequency, P_{inv} is the power of the inverter and H is the calculated inertia

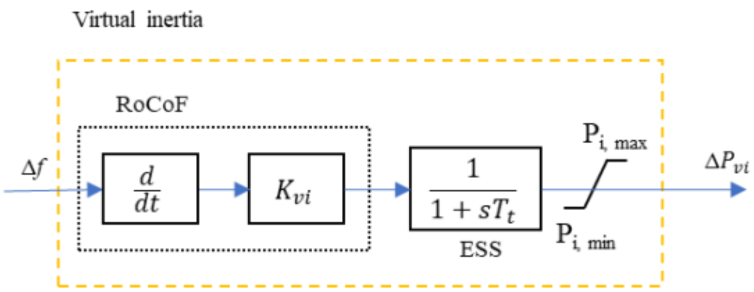


Figure 4.1: Structure of virtual inertia controller with constant K_{VI} described as virtual inertia gain

4.2. Enhanced virtual inertia controller

$$\Delta P_{VI} = \frac{s\ Kvi + Dvi}{1 + s\ \ T\,vi}\ \frac{\Delta f}{Rvi} \tag{24}$$

The enhanced VIC proposed decreases the influence of decreased inertia which provides an illustrative comparison between versions of virtual inertia controller proposed by [7, 9]

Afterwards, the wind power, solar irradiation power, and load demand are considered as the disturbance to the islanded micro grid and micro grid damping (D), micro grid system inertia (H) considered as uncertain parameters[16]

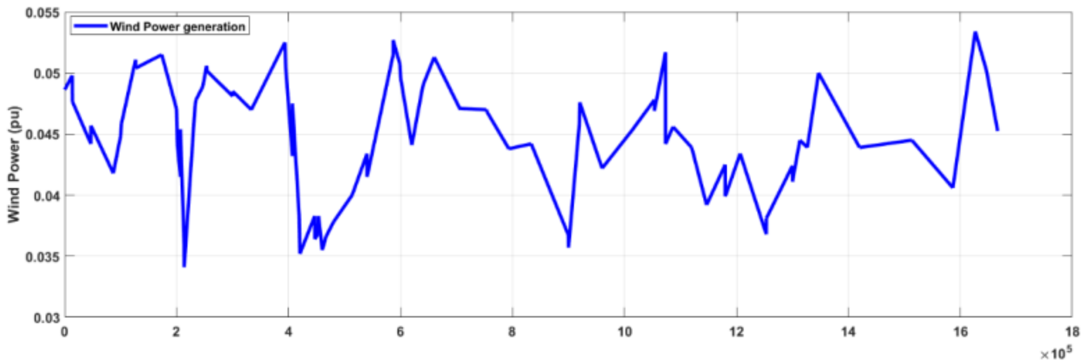


Figure 4.2; Illustration of variable wind generation in pu

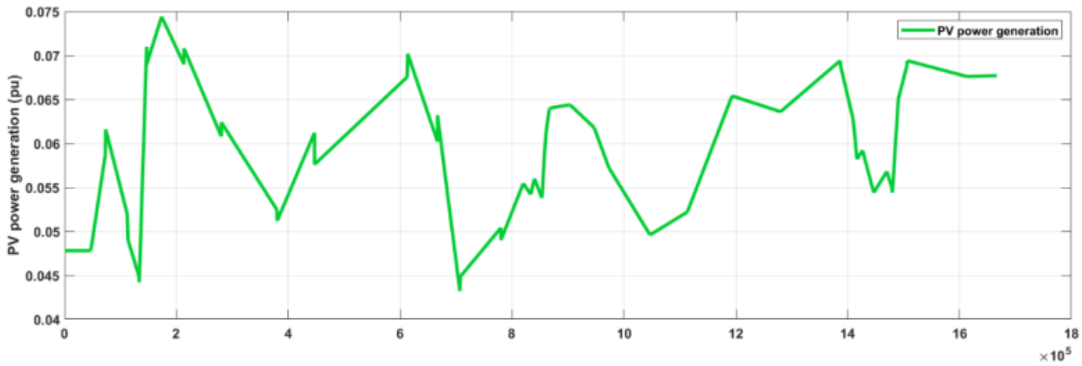


Figure 4.3; Illustration of variable solar power generation in pu

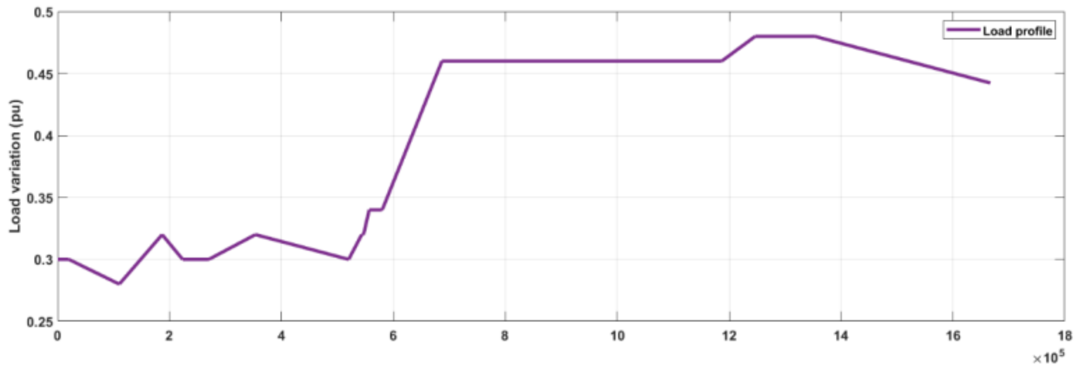


Figure 4.3: Load profile scenario used for simulation

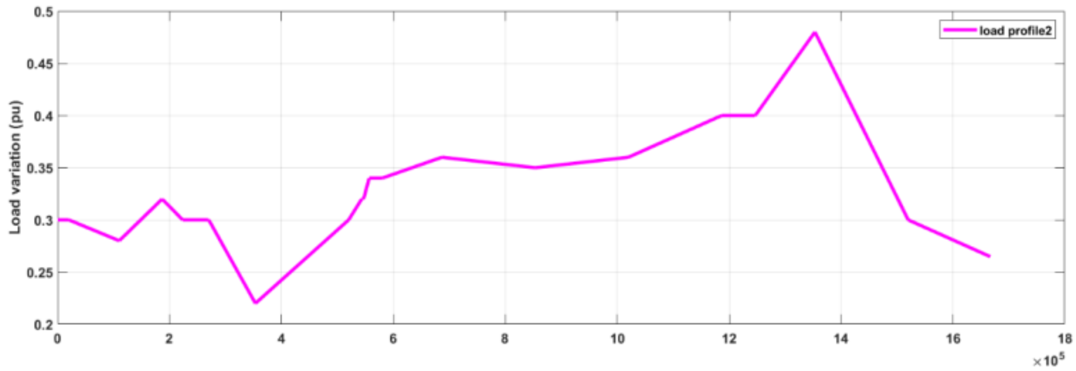


Figure 4.4; Second load profile used for simulating additional industrial load

System Disturbances/frequency disturbances consist of sudden load increases and decreases, renewable generation fluctuations that is wind /solar output drop or increases.

When the system inertia is reduced due to distributed generation's penetrations, the constraint nadir/overshoot (lowest point of frequency after disturbance) of the micro grid significantly increases, resulting in an unstable system.

The enhanced Virtual inertia controller proposed decreases the influence of decreased inertia of the micro grid by

- Lowering nadir/overshoot
- Improving system stability through faster recovery after a disturbance,
- Reducing system oscillations thus improving system frequency compared to the case without virtual inertia controller.

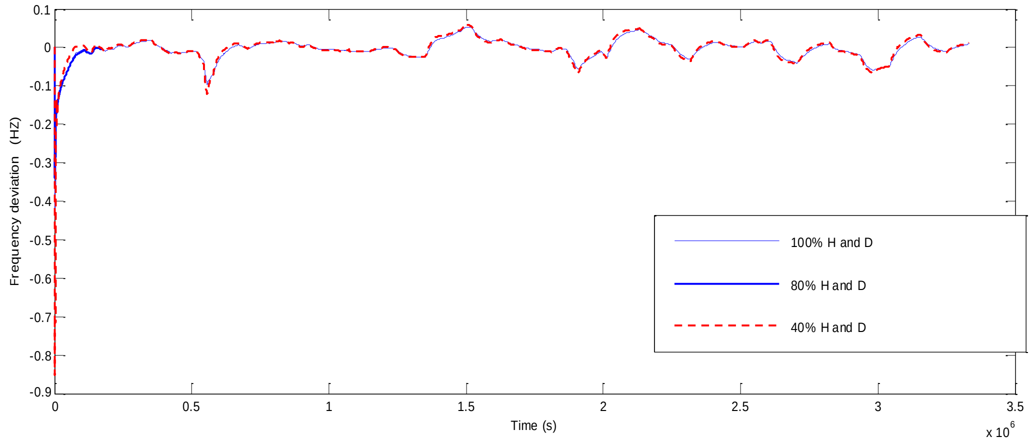


Figure 4.5; System frequency response without virtual inertia

Figure 15 investigates the system frequency response without virtual inertia operation against the degraded circumstances of system inertia and damping (reduction from 100% to 40%). With the reduction in system inertia and damping properties due to RESs/DGs penetration, it is obvious that the frequency nadir/overshoot of the system significantly increases with longer stabilizing time. These problems would be greater in the system with a high share of RESs/DGs.

By applying the virtual inertia control unit, the system frequency nadir/overshoot under the critical situation of low H and D (40%) could be effectively arrested.

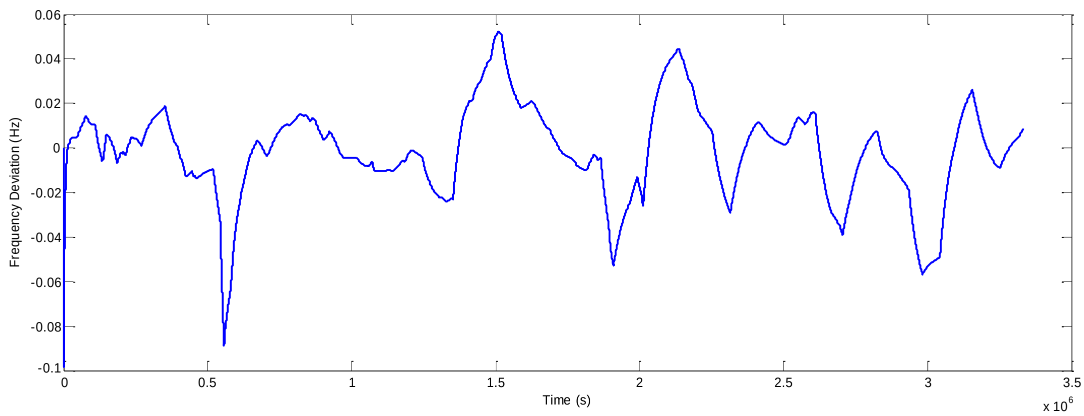


Figure 4.6: Illustration of decreased inertia effects with variations of virtual inertia controller: full scheme with constant Kvi;

The system with virtual inertia control can obtain a better performance than the system without virtual inertia control. The system can reach an optimal response in cases of numerous disturbances, especially under the critical situations of low system inertia and damping triggered by a high share of DGs/RESs.

The virtual inertia control unit provides significant properties for handling a high share of RESs/DGs penetration without compromising the system stability and resiliency. Unlike a real synchronous machine, the parameters of virtual inertia control can be adjusted to enhance the dynamic frequency response of the system [1, 3].

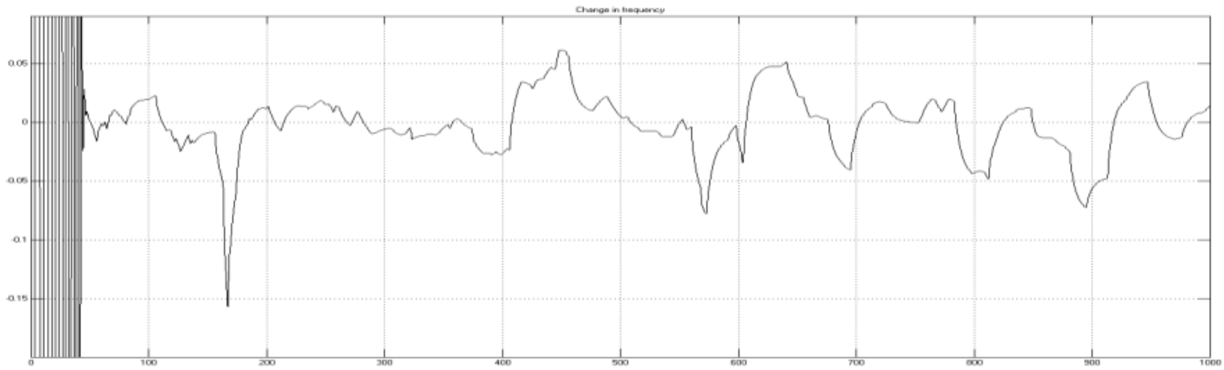


Figure 4.7: Illustration of decreased inertia effects with variations of virtual inertia controller—without 1/Rvi and Dvi.

The RoCoF of the system increases, this creates a less stable system, with longer stabilizing time meaning that a system operator has less time to respond to disturbances. In this case, following the disturbance, the generated power fluctuates more, leading to stress in this unit.

4.3. PI controller

Proportional Integral controller is one of the most used control strategies in power systems and engineering in general to regulate frequency deviations caused by load variations and renewable energy fluctuations in a micro grid.

This control strategy is simple to implement and proven to be effective in secondary frequency control. The PI controller provides a corrective power signal to balance the mismatch between generation and demand.

The PI controller adjusts its output based on;

1) . Proportional (P) -reacts to the current error
2) . Integral (I)-reacts to the accumulated error over time

Together: They help the system react quickly to changes that is by the Proportional part and eliminate steady state error that is by the Integral part.

The PI controller was integrated into the micro grid control loop where it receives the frequency deviation signal (df) as input. The controller aims to minimize changes in frequency by adjusting the control input to the system, thereby restoring the frequency to its nominal value.

The output of the controller represents the required power adjustment, which is used to command an energy storage system (ESS), this helps support system stability.

I. Mathematical representation

Include the standard PI transfer function:

The controller is expressed in the frequency domain as:

$$(s) = K_p + \frac{K_i}{s} = \frac{K_p s + K_i}{s} \quad (25)$$

Where K_p is the proportional gain and K_i is the integral gain. These parameters were tuned to achieve fast dynamic response with minimal overshoot and steady-state error.

In Simulink, the PI controller was implemented using the built in PID controller block configured in PI mode. The frequency deviation signal was connected to the input of the block. The output was passed through a transfer function representing energy storage system, then finally a saturation block was added to limit the maximum and minimum power injection, reflecting real ESS constraints.

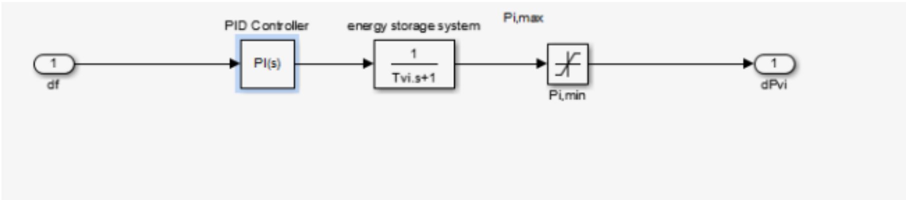


Figure 17; Representation of PI controller for virtual inertia control

The PI controller integrates and scales the change in frequency to compute an appropriate energy storage response.

II. Tuning process

Initial gain values were chosen as

Kp=2 and Ki=0.3

These values were tuned through trial and error method based on disturbance simulations to ensure acceptable overshoot. Further refinements were made to reduce oscillations and improve steady-state behavior. A saturation block was used to prevent excessive control effort.

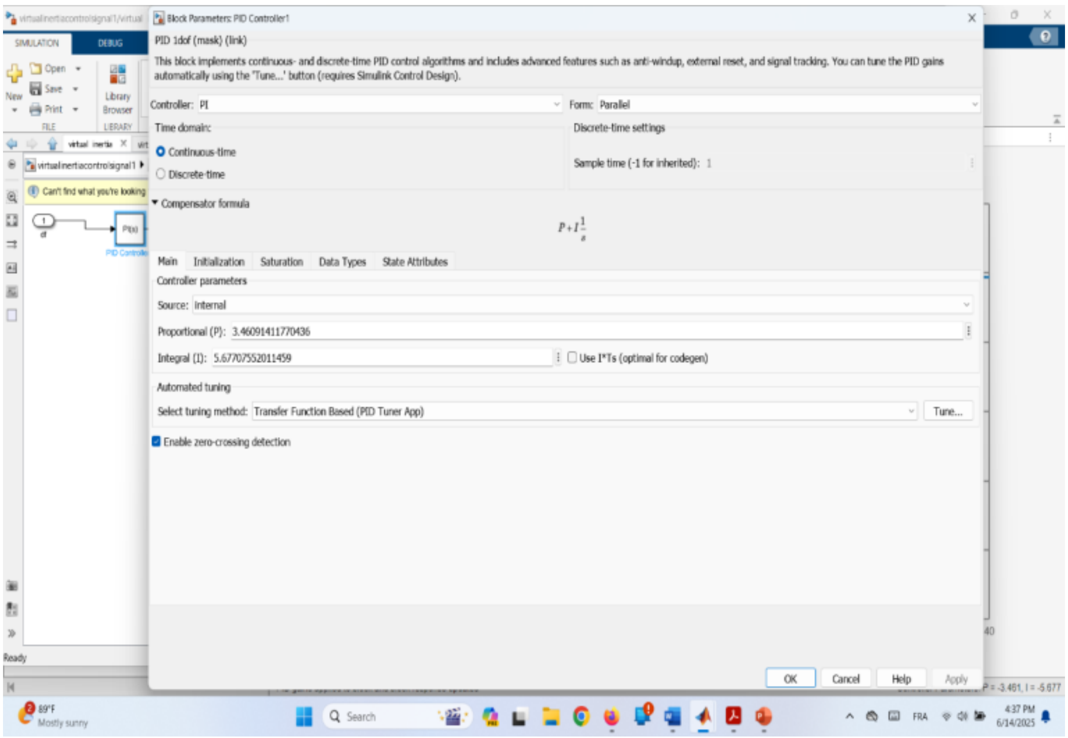


Figure 4.9; MATLAB interface for tuning the PI controller

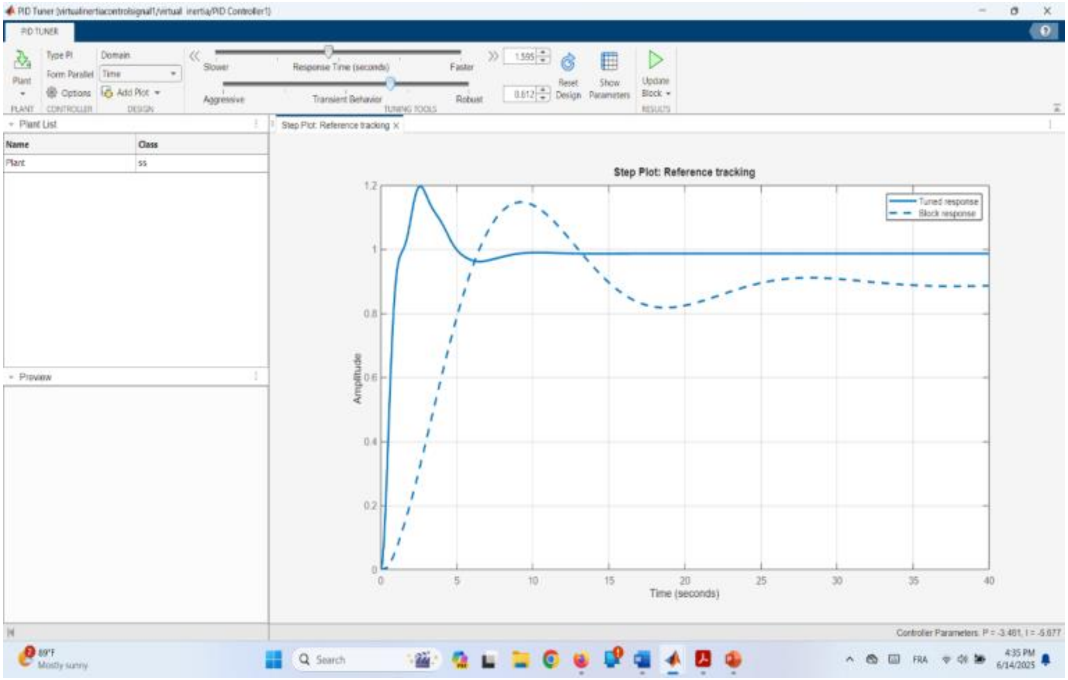


Figure 4.10; PI performance tuning

Results of simulation with pi controller

It is observed that PI based controller improves the influence of decreased inertia of the micro grid compared to traditional vertical inertia controller that is there is an obvious reduction in frequency drop and reduced system oscillations thus improving system frequency.

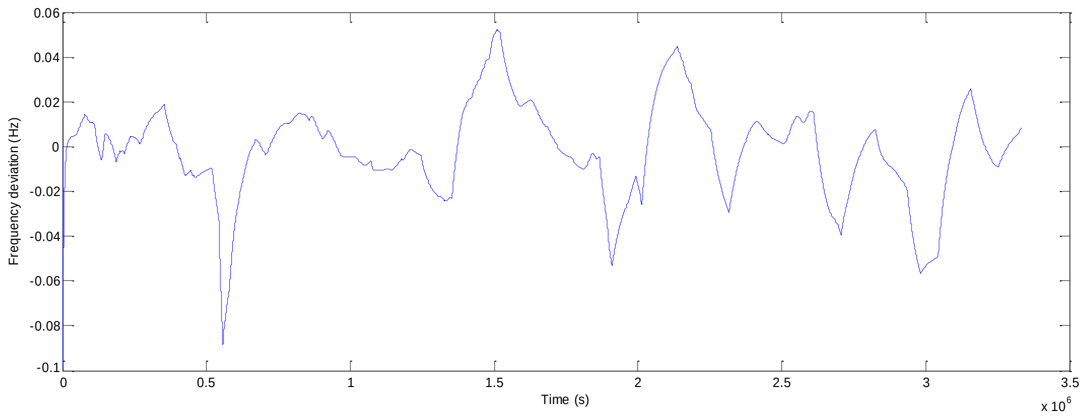


Figure 4.11; Frequency Response of system with pi controller.

4.4. Fuzzy logic-based controller for virtual inertia

A fuzzy logic controller (FLC) is composed of several key functional blocks that together allow it to handle imprecise, nonlinear, or complex systems such as virtual inertia emulation in power systems. The general structure includes the following components:

1) Preprocessing

The preprocessing block prepares the raw input signal (e.g., frequency deviation, RoCoF) by filtering, normalizing, or scaling it into a form suitable for fuzzy logic analysis. This ensures the input is compatible with the expected operating range of the controller.

2) Fuzzification

Fuzzification converts the crisp numerical input into fuzzy linguistic variables using predefined membership functions. For instance, a frequency deviation may be classified as “low,” “medium,” or “high.” This step allows the controller to process uncertainty and vague information.

3) Inference Mechanism

The inference engine applies fuzzy logic rules from the rule base to the fuzzified inputs. It evaluates these rules using logical operations (e.g., AND, OR) to produce fuzzy outputs. This step essentially mimics expert decision-making under uncertainty.

4) Fuzzy Rule Base

The rule base contains a collection of IF–THEN statements that describe the system behavior. For example:

IF frequency deviation is high AND RoCoF is positive, THEN increase virtual inertia.

These rules are usually designed based on expert knowledge or system modeling.

5) Defuzzification

Defuzzification converts the fuzzy output of the inference mechanism back into a crisp numerical value. This step is crucial to generate a usable control signal. Common methods include the centroid or weighted average approach.

6) Post processing

Post processing adapts the crisp output to the system's specific requirements. This may include rescaling, limiting, or combining it with other signals to produce the final control signal (e.g., a virtual inertia injection command to an inverter or synchronous emulator).

A. Application to virtual inertia control

In the context of fuzzy-based virtual inertia control, the FLC interprets grid frequency behavior and determines how much synthetic inertia to provide. Its ability to manage uncertainty makes it ideal for systems with high renewable penetration, where grid dynamics are fast-changing and nonlinear.

Fuzzy logic control has been credited with being a remarkable-accepted technique for designing controllers that can provide satisfactory performance under the presence of imprecision and uncertainty [7]

The fuzzy logic mechanism is created in the form of a rule base. Fuzzy rules are considered as an important tool for forming portions of knowledge in a fuzzy system.

The rules are applied within a fuzzy system to evaluate the outputs based on the inputs.

The most important rule is represented by the "if-then" statement as [7]:

$$I\ \ , hen\ B\ . \qquad (26\ )$$

The important logical operators, which have been often used in fuzzy relations, are the intersection (and), union (or), and complement (not).

For a complex control system, the compound rule base can be added and represented as:

$$\text{If A, and B, then C} \qquad (27)$$

Alternatively, the "or" logic often uses in the compound rule base as:

$$\text{If A or B, then C} \tag{28}$$

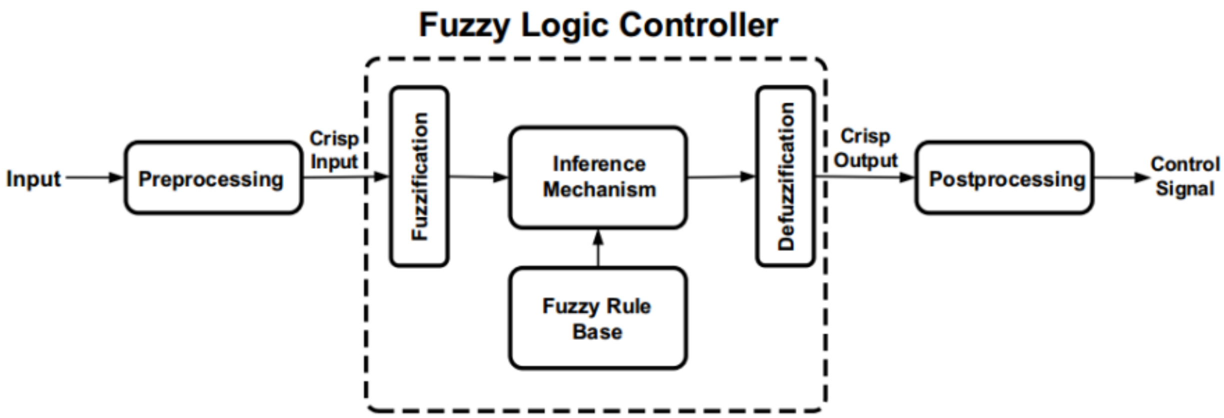


Figure 4.12: General scheme for a fuzzy control system

The proposed fuzzy system contains four processing units; that is the fuzzification, inference mechanism, fuzzy rule base, and defuzzification, as shown in Fig 15.

The active power changes of RESs/DGs (ΔPRES) and system frequency deviation (Δf) are used as the crisp inputs of the fuzzy controller. The output is a crisp (normalized) value of the virtual inertia constant (KF). Thus, this fuzzy system contains two inputs and one output. Firstly, the scale factors (i.e., the preprocessing) is implemented to adjust the size of scale inputs. Later, the fuzzification process is performed to alter the actual inputs to the fuzzy values. The Mamdani inference model is used in the inference process. The Input 1 and Input 2 are formed as:

$$Input\ 1 = df * K_1 \tag{29}$$

$$Input\ 2 = df * K_2 \tag{30}$$

Where K1 and K2 are scale factors of the fuzzification system, where $K_1 = K_2 = 1$

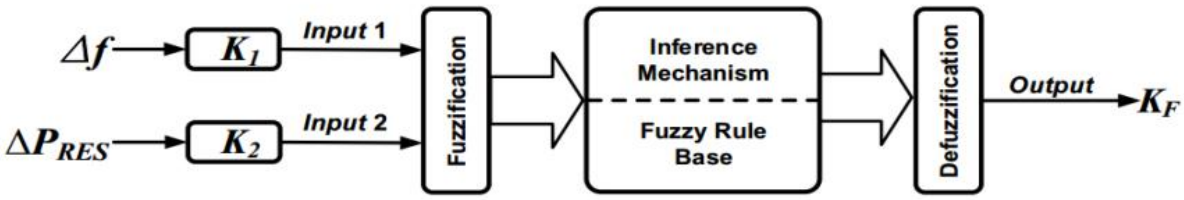


Figure 4.13 : Dynamic scheme for the fuzzy logic in scheduling virtual inertia constant

Next, the fuzzy values of Input 1 and Input 2 are progressed to the fuzzy inference mechanism with a fuzzy rule base. The fuzzy rules are the fundamental fuzzy operations for mapping the input signal to the output signal. To determine an optimal KF value, the fuzzy rules are implemented by merging the input signals of Δf and ΔPRES.

From Table 3, fifteen fuzzy rules are used based on the practical experiences and knowledge of the virtual inertia control regarding RESs/DGs penetration and frequency deviation as follows:

1. When ΔPRES and Δf are quite small, a zero value of KF is applied to regulate the system frequency, distributing fast damping of deviations.

2. When ΔPRES and Δf are quite large, a medium KF value (in cases of large negative Δf) or very big KF value (in cases of large positive Δf) should be applied to diminish the deviations with high amplitude driven by the lack of system inertia and damping regarding high RESs/DGs, preventing system instability and failures.

3. When Δf is quite small, and ΔPRES is quite large, a medium KF value (in cases of small negative Δf) or very big KF value (in cases of small positive Δf) should be implemented to reduce the system frequency deviations with high amplitude driven by the lack of system inertia and damping regarding high RESs/DGs, preventing system instability and failures.

4. When Δf is quite large, and ΔPRES is quite small, a zero value (in cases of large negative Δf) or medium value (in case of large positive Δf) of KF should be applied to regulate the system frequency, delivering fast damping with low frequency deviations.

By using Table 3, the fuzzy rules are expressed in terms of "if-then" expression as follows:

If Input 1 is x and Input 2 is y, Then JF is z.

Where x, y, and z are the fuzzy set on the corresponding sets.

Due to the characteristics of simplified calculation and outstanding control performance, the triangle and trapezium membership functions have been chosen. In this study, the range of fuzzy variables are ΔPRES= [−1, 1] p.u., and Δf = [−0.5, 0.5] Hz. The output range of KF is selected as [−1, 3]

Table 3: Fuzzy rules of fuzzy-based virtual inertia control for linguistic variables

Control variable		Δf				
		NL	NS	ZO	PS	PL
ΔP_{RES}	L	ZO	ZO	ZO	ZO	M
	M	S	S	M	B	B
	H	M	M	M	VB	VB

The μ represents each membership grade. The inputs and output are separated into fuzzy subsets and expressed using linguistic variables. By defining linguistic variables, the linguistic words are defined by words that we use in our daily life with respect to the penetration levels and deviations as follows. PL is positive large, PS is positive small, ZO is zero, NS is negative small, NL is negative large, VB is very big, B is big, S is small, L is low, M is medium, and H is high.

The fuzzy inference mechanism alters the rule base to the fuzzy linguistic output, as shown in Table 3.

However, the linguistic output is unavailable for the signal of equalization control. To resolve the issue, the defuzzification process is demanded.

In this study, the center of the area (centroid) technique is applied for defuzzification.

Lastly, the obtained results from the fuzzy rules are forwarded to the defuzzification, and transformed to the crisp values as:

$$K_F = \frac{\sum_{j=1}^{n} x_j * (x_j)}{\sum_{j}^{n} (x_j)} \quad (31)$$

By implementing the proposed fuzzy controller, the virtual inertia constant is automatically modified to follow the variations in numerous integration levels of RESs/DGs (i.e., disturbances), allowing self-adaptive inertia response. [7].The dynamic equation of the fuzzy-based virtual inertia control is obtained as:

$$\Delta P_{VI_{Fuzzy}}(s) = \frac{K_F * s + D_{VI}}{1+sT_{INV}} \left(\frac{\Delta(s)}{R_{VI}}\right) \qquad (32)$$

Thus, the proposed fuzzy-based virtual inertia control is not only to offer sufficient inertia response with the self-adaptive ability but also to provide low-frequency deviation with fast damping, reducing high-frequency overshoots/drops driven by different penetration levels of RESs/DGs.

B. MATLAB-based fuzzy logic control

A fuzzy logic technique is integrated into a virtual inertia control loop to enable the self-adaptive ability of virtual inertia constant against the different levels of RESs/DGs penetration regarding frequency control. As a result, the virtual inertia control unit can automatically adjust itself in emulating different amounts of inertia and damping responding the integrated levels of RESs/DGs at the specific time.

MATLAB-based fuzzy logic control

This section presents the implementation procedures for designing a fuzzy logic controller using MATLAB/Simulink® software [7]. A fuzzy logic controller block in Simulink® called "Fuzzy logic toolbox" offers an application with control functions for designing, analyzing, and simulating systems based on fuzzy logic. The toolbox allows to model complex system behavior using simple logic rules, the rules are applied in a fuzzy inference system. The control input/output data, membership functions with several shapes, inference systems, and rule base can be specified and designed in this toolbox via a function called "Fuzzy logic designer". Once a fuzzy inference system has been created, the evaluation and visualization can be modified. After completing the design process, use the fuzzy controller in Simulink and simulate the fuzzy systems within a comprehensive model of the whole dynamic system then generate structured text for a fuzzy system applied in Simulink using the fuzzy logic controller block.

The proposed fuzzy-based virtual inertia controller has involved five steps as follows:

1. Determine the input/output control variables, states, and their variation ranges. Then, open a "fuzzy logic designer" function by typing "fuzzy" in the MATLAB command window.

2. Define suitable fuzzy sets and membership functions. The input/output fuzzy set can be added by clicking an Edit' tab and select an 'Add variable' tab. Then, conduct the degree of membership functions for each input/output variable and complete the fuzzification process. The membership functions and its control ranges can be adjusted by double-clicking an 'input' or output section,
3. Select an appropriate inference mechanism by clicking a 'File' tab and 'New FIS' tab. select either Mamdani inference model or Sugeno inference model. Next, create the rule base using the control rules, in which the system will operate under a desirable condition. By clicking an 'Edit' tab and 'Rule' tab, the fuzzy rules can be defined with linguistic variables, Then, decide how the action will be examined by adjusting strengths (i.e., red line) to the rules, this process can be done by clicking a 'View' tab and 'Rule' tab. 5. Select a suitable defuzzification technique by clicking 'Defuzzification' tab. Then, perform the defuzzification and obtain the output as a control signal.
4. Finally, implement the obtained fuzzy controller [7]

4.5 Results from simulations

Simulations and results of controllers under key disturbances

This chapter evaluates the performance of different control strategies, no control (base line), virtual inertia droop control, PI control, and Fuzzy logic based virtual inertia control in an islanded micro grid environment. The main objective is to assess how each control strategy influences frequency stability, specifically in terms of frequency nadir, RoCoF and dynamic settling behavior. All simulations were performed in the MATLAB/Simulink environment, and the different parameters were previously described. In this section, we perform simulations for three different scenarios: the case with connection of RESs (Scenario 1), and the case with smooth (dis) connection of Solar (Scenario 2) and the case with smooth connection of load (Scenario3).

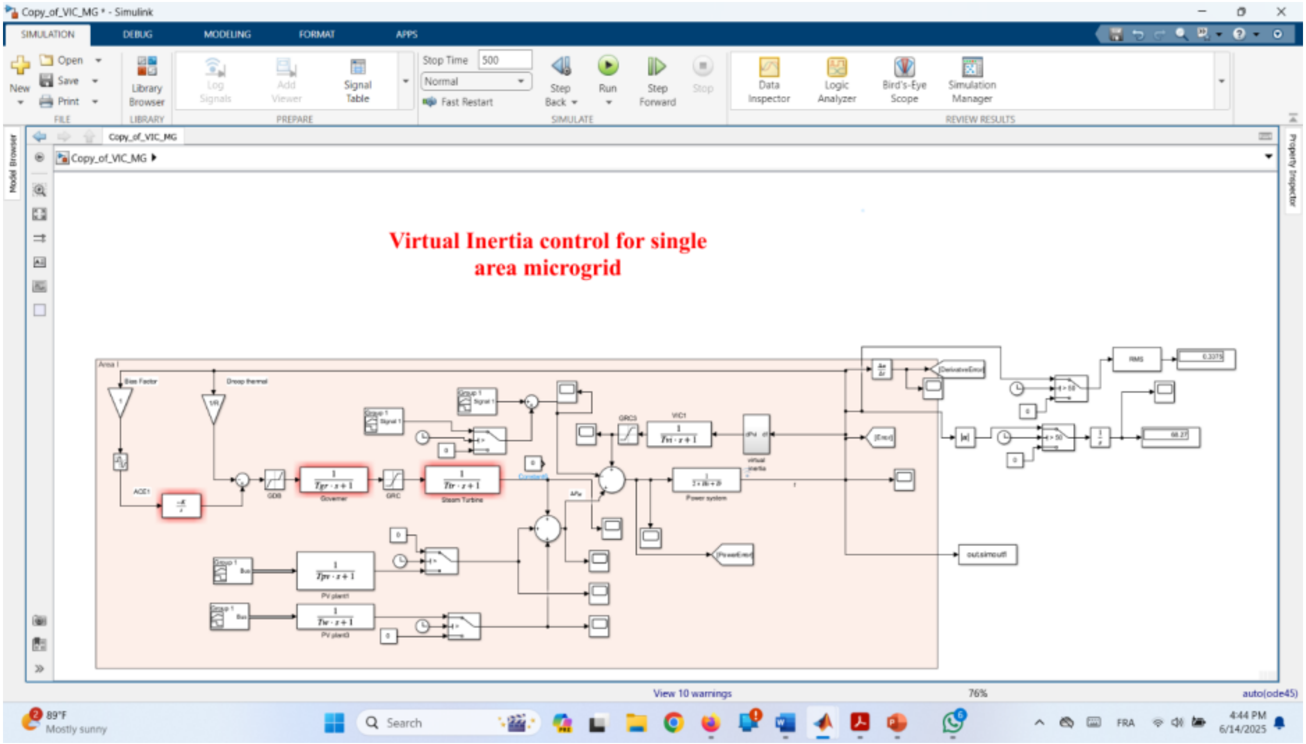


Figure 4.13 : Representing simulation for virtual inertia control for single area microgrid

Controllers tested:

- No virtual Inertia
- Derivative based virtual inertia control
- PI based virtual inertia control
- Fuzzy logic based virtual inertia control

Disturbance types:

- Sudden load increase
- Renewable generation variability

Performance Metrics

1. Frequency Nadir: Minimum frequency after a disturbance
2. RoCoF (Rate of Change of frequency) Peak Value of change in frequency after a disturbance VIC reduces peak value of df acting as synthetic inertia
3. IAE: Integral Absolute Error
4. RMSE: Root Mean Square Error

Table 4: Summary results from controller simulations under normal working conditions without disturbances.

	Without VIC	Traditional VIC	PI based VIC	Fuzzy logic based VIC	What is observed
Frequency nadir	Very high Worst frequency nadir -0.158	Lower Better frequency nadir -0.148	Low Improved frequency nadir -0.09	Lowest Better improved frequency nadir -0.05	Less frequency drop with virtual inertia controllers Fuzzy logic controller offering best response
ROCOF (df/dt) Peak df/dt Value	Very high 0.06	Low 0.054	Lower 0.05 Smoother df curve	Lowest 0.035 Smooth df curve	Controllers dampened ROCOF especially Fuzzy logic controller
P_VIC response to controllers	None	Injection	Fast power injection	Fastest power injection	Power injection with the support rocof
Sensitivity to disturbance	Unstable	Better	Offers good stability	Offers very good frequency stability	Controllers improve system stability

Table 5: Numerical values

Approach	Without	Initial Proposed controller	PI based controller	Fuzzy logic based controller
IAE	4.382	4.377	1.086	1.035
RMSE	0.01366	0.01365	0.00854	0.00643

Scenarios tested:

1. Connection of industrial load at t=400 ms
2. Connection of wind power at t=100 ms
3. Disconnection of solar generation at t=250 ms

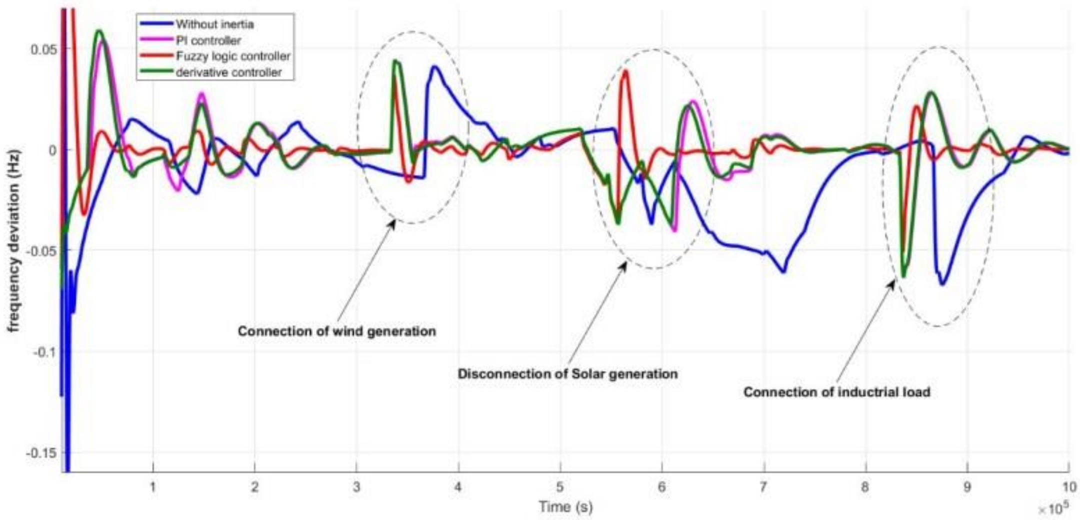


Figure 4.14 : Frequency deviation response of different inertia control strategies

This figure shows the impact of different virtual inertia controllers on system frequency stability following disturbance

Scenario 1; Wind power connection at t=100ms

- At 100ms ,wind power was suddenly introduced into the system
- This caused a sudden power surplus
- System frequency rose sharply due to excess generation

Explanation

The Generators in the system are still operating to meet load, now wind adds extra power. This caused temporary power surplus.

With low inertia, the system can't absorb the extra energy, leading to frequency overshoot.

How controllers support

a. No control

Without virtual inertia control, the system exceeds nominal frequency, there is high overshoot, then frequency oscillations and the system takes time to stabilize.

b. Derivative virtual inertia control

The controller detects increasing frequency (positive df/dt) and tried to absorb the energy using damping. The system slowed down the rise restoring stability but offered limited damping

c. PI controller

Proportional Integral controller reduces quick rise in frequency changes and restores the system quickly

d. Fuzzy logic based controller

The fuzzy logic based controller offers the best frequency support during the disturbance quickly arresting overshoot and offering frequency stability. The controller recognizes overshoot and change in renewable energy that is connection of wind generation and smoothly minimizes the overshoot.

Scenario 2; Solar Generation Disconnection at t=250ms

- At 250 ms a solar generator was disconnected from micro grid (for example due to fault or cloud cover)
- A power deficit occurs and the system has to supply more energy suddenly to meet constant load demand
- The sudden reduction caused frequency drops due to mismatch

Explanation

Sudden loss of generation leads to increased load /generation imbalance and since this is a low inertia system there is no time for primary units to react immediately to fast RoCoF and frequency decline

Controller support

a. No Control

The uncontrolled system showed high RoCoF, a steep frequency drop below -0.05 and very unstable behavior

b. Derivative Virtual Inertia Control

This controller reacted instantly to RoCoF by injecting power via synthetic inertia and slowed down the frequency decline

c. PI controller

There was better correction of frequency deviation with tuning and the controller helped eliminate error after the frequency drop

d. Fuzzy logic based control

Based on fuzzy rules, the controller calculated inertia needed in the system and injected power which quickly improved frequency deviation and ensured a stable recovery

Scenario 3; Industrial load connection at t=400 ms

- At t = 400 ms, a large industrial load was connected to the micro grid, simulating a sudden demand spike**.**
- This resulted in a sudden increase in power demand without an immediate increase in generation
- The imbalance caused a drop in system frequency

Explanation

The mechanical power (Pm) in the system does not equal the electrical power (Pe) and the system gets energy from the rotating masses that is the inertia

In low inertia systems, this energy is too small and frequency drops sharply.

Controller support

a. No Control

The system without virtual inertia showed a deep frequency nadir below nominal value High lighting its vulnerability

What was observed is a sharp frequency drop, high RoCoF and a relatively long recovery time

b. Derivative VIC

Detected RoCoF using df/dt, injected synthetic inertia quickly and reduced the speed of frequency drop.

c. PI controller

Measured frequency deviation and integrated over time to correct it. Provided both fast and long-term correction.

There was improved nadir and reduced frequency oscillations.

d. Fuzzy Logic Controller

The fuzzy logic based controller offered the best response to disturbance with faster virtual inertia injection. It provided better, smoother, and faster recovery to frequency deviation by using input df to calculate the optimal inertia injection dynamically.

Discussion

The baseline case (without virtual inertia): This experienced a deep frequency nadir and very slow recovery.

Derivative based inertia control: This case reduced the rate of change but still experienced some oscillation

The PI controller: This controller improved the frequency response even more, reduced overshoot and steady state error

The fuzzy logic based controller: Provided the most stable response achieving minimal frequency deviation and rapid convergence

The results demonstrated that traditional virtual inertia alone via derivative based control partially improve d system response by mimicking physical inertia, but it lacked regulation capabilities to eliminate steady state error or damp oscillation

The PI controller has a structure that includes proportional action for fast response and integral action for steady state correction, which made it an effective method for virtual inertia control in islanded micro grids with high renewable energy penetration

ABRUPT LOAD CHANGE AND VARIABLE RESs: the scenarios showed that the virtual inertia controllers can improve the frequency performance compared with the islanded micro grid without virtual inertia controller.

Without Virtual inertia control, frequency deviation is high and unstable.

These results confirm the effectiveness of fuzzy logic control in high Renewable energy penetration micro grids

Conclusion

Conclusion

This memoir sets out to understand how to improve frequency stability in micro grids that rely heavily on renewable energy sources like wind and solar. These resources are environmentally friendly and essential for the future of power systems, but they come with a major drawback, they don't have the physical inertia that traditional power plants provide.

Without this inertia, frequency in the grid can become unstable, especially when there are sudden changes in load or generation.

To help solve this problem, I explored virtual inertia control methods, which are essentially ways of emulating inertia using control strategies and energy storage systems. Three types of controllers were studied and tested using a simulated micro grid model in MATLAB/Simulink: a basic derivative-based controller, a proportional-integral (PI) controller, and a fuzzy logic controller.

Each method was tested under realistic disturbance scenarios, including a sudden load increase, the sudden connection of wind generation, and the disconnection of solar power. These events were chosen because they represent real challenges that modern grids face with high levels of renewables.

The results showed clear differences between the controllers. That virtual inertia controllers significantly improved frequency stability by emulating the inertial response traditionally provided by synchronous generators. The derivative-based method effectively reduced the initial Rate of Change of Frequency (RoCoF) but introduced sensitivity to high-frequency noise. The PI-based controller provided robust steady-state performance but required careful tuning to avoid excessive overshoot. Meanwhile, the Fuzzy logic-based controller exhibited superior adaptability to varying operating conditions, offering a balanced trade-off between dynamic response and damping. However, the absence of a virtual inertia controller led to severe frequency deviations and prolonged settling times, confirming the necessity of VIC in RES-dominated micro grids.
Despite the advantages of Fuzzy Logic control, its computational complexity may limit real-time implementation in certain applications, suggesting a need for further optimization.

Future work could explore hybrid control strategies, advanced machine learning-based VIC, and hardware-in-the-loop validation to enhance robustness under different micro grid configurations.

Additionally, the impact of communication delays and distributed energy storage systems on VIC performance warrants further investigation.

In conclusion, virtual inertia control is a critical enabler for stable micro grid operation with high renewable penetration, and the choice of control method should be tailored to specific system requirements, balancing performance, complexity, and reliability.

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