Chapter 3: Research Methodology

3.1 Introduction

The integration of renewable energy sources (RES) into main power grids is a transformative step towards achieving a sustainable and resilient energy future. Since there is a huge transition towards cleaner energy options, the integration of different renewable resources for example solar and wind power has become pivotal in dropping reliance on conventional fossil fuels. However, this transition brings forth a set of technical challenges, one of which is the virtual inertia issue in power systems. The issue of virtual inertia occurs due to the integration of RES with the grid. It mainly refers to the challenge of preserving system constancy and resilience in the absence of traditional rotating mass-based inertia, characteristic of conventional power plants. Unlike traditional power generation, many renewable energy sources lack inherent inertia due to the nature of their generation mechanisms, such as inverter-based photovoltaic systems and wind turbines. The virtual inertia issue poses a substantial threat to the stability of power systems, as it affects the ability to respond to sudden variations in load or generation, leading to frequency instability and potential grid failures. As such, the mitigation of the virtual inertia issue is a critical research area, needful innovative techniques to safeguard the seamless integration of renewable energy with existing power grids. This chapter outlines the research methodology employed to investigate and address the virtual inertia issue.

3.2 Overview of the proposed methodology

The main objective of this research is to offer a comprehensive empathetic of the challenges posed by the lack of inertia in renewable energy systems and to propose effective mitigation techniques. The research methodology presents a systematic approach that combines theoretical analysis, modeling, simulation studies, and practical experimentation. A novel virtual inertia control (VIC) method is employed in this research for addressing the issue of virtual inertia. The proposed VIC method is combined with a multi power level controller (MPLC) approach for RES integrated microgrids. Due to the high level penetration of RES there are certain issues wherein the stability of the system might get affected and this is due to the dynamic variation in the load and frequency. To overcome this problem, this research employs a supercapacitor which acts as an energy storage device. The supercapacitor helps in obtaining a high power density and thereby emulates the inertia of an inverter. The dynamic variations in the grid system is effectively handled using the proposed MPLC. In addition to the variations, the proposed approach is also designed to address the problem of frequency instability and thereby maintain the level of inertia for sudden disconnecting loads. The MPLC system is designed to achieve a maximum inertia and frequency support through the sudden changes in the load. The grid is integrated with RES through the DC converter which helps the system to find maximum power from the RES sources for example wind and solar energy. The solar energy is acquired from the photovoltaic (PV) system and a maximum power point tracking (MPPT) algorithm is utilized for extracting the maximum power from the PV system. A Perturbation and Observation (P&O) based MPPT technique is utilized for maximum power extraction.

3.3 Modeling of Grid system with RES

A solar power plant and wind turbines are the electricity production components of the electrical grid. The goal of this study's management technique is to regulate the electricity flow among the grid, electric demand, and renewable energy sources. The following is a discussion of square element simulation:

- ***Modeling of PV systems***

The PV scheme harnesses the photovoltaic effect, where certain materials generate an electric current when exposed to sunlight. The primary component of a photovoltaic organization is the planetary cell, which is the basic building block responsible for converting sunlight into electricity. Photovoltaic modules, also known as solar panels, consist of an array of interconnected solar cells and the planetary PV system is analyzed as per the corresponding circuit as shown in figure 3.1.

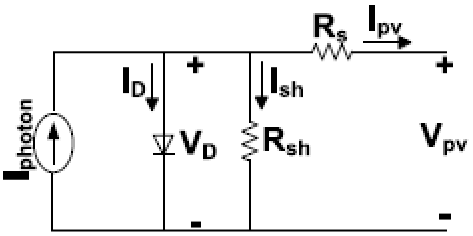

Figure 3.1 A single-diode photovoltaic cells corresponding circuit

The initial equation may be used to figure out the voltage and current parameters of solar power systems.

$$I = I_{pv} - I_s\left[e^{\frac{(V+R_sI)}{nkT}} - 1\right] - \frac{(V+R_sI)}{R_{sh}}$$
....(1)

where V is the system's starting voltage, Rs and Rsh are series and shunt resistances, accordingly, Is is a diode's saturating electricity, Ipv is the amount of current flowing through the photovoltaic system, k is the Boltzmann's characteristic (1.38 × 10 − 23 J / K), V is the voltage above the load being converted, and η is the conversion effectiveness.

Grid-tied PV systems are connected to the electric grid. They generate electricity during daylight hours, and any excess power can be fed back into the grid.

- ***Modeling of wind turbine***

Wind turbine models or wind energy generation systems are crucial for studying power generation, control strategies, and overall performance. The wind's motion energy is captured by the turbine's blades that rotate. According to the kind and dimensions of the wind turbine, the quantity and style of propellers may change. The main shaft and rotor blades are connected by the central location. Additionally, it contains the pitch structure, which enables the generator's electrical power to be controlled by varying the blade angles. A permanent- magnet synchronous generator (PMSG) transforms the movement energy of the wind turbine into electric power, which is then represented. Here is the mathematical formula for the energy of kinetic friction:

$\boldsymbol{E = \frac{1}{2} mv^2}$.....(2)

The blades of the wind turbine's inputs and its output speeds are indicated by the letters va and vb, correspondingly. The wind turbine's output of electricity is expressed as follows:

$$P_{w(in)} = \frac{1}{2} A_s \rho_{air} V_a^{\,3} \quad .....(3)$$

$$P_{w(out)} = \frac{1}{2} A_s \rho \left(\frac{v_a + v_b}{2} \right) \left(v_a^{\,2} - v_b^{\,2} \right) \quad ....(4)$$

wherein vw is the direction of the wind the voltage, ρair is the weight or that constitutes the air, and As is the area where the blade sweeps. The blades of the wind turbine's possible power input is denoted by Pw (in) and output power by Pw (out).

- ***Modeling of supercapacitor***

Supercapacitors, also known as ultracapacitors or electrochemical capacitors, store electrical power by separating particles electrostatically. The equivalent circuit consists of a Series Resistance (ESR) for the internal resistance of the supercapacitor, which causes energy losses during charge and discharge. The capacitor represents the capacitance of the supercapacitor, typically denoted as C. Supercapacitors have much higher capacitance values than traditional capacitors, often in the range of farads. The voltage characteristics of the supercapacitors are analyzed with respect to the variations in the capacitance especially at high voltages. Further, the capacitance of the double layer (C_dl) is modeled which defines the charge stored at the electrode-electrolyte interface. The double layer capacitance is one of the important parameters which helps in distinguishing supercapacitors from fundamental capacitors. A Ragone plot is used for representing the energy and power density attributes of the supercapacitor. The Ragone plot defines the balanced trade-off between energy storage capacity and the rate at which energy can be delivered or absorbed. While modeling the capacitor, the voltage limit has to be defined in such a way that a safe operating voltage is defined in order to prevent overcharging of the capacitor or excess discharging. In addition to the operating voltage, the effect of temperature on the performance of the supercapacitor is also determined. It is observed that the parameters of the supercapacitor and the capacitance value varies with respect to the temperature. Hence, the temperature effect must be analyzed thoroughly. The capacitance is modeled considering the state of charge (SOC) and state of health (SOH) in order to regulate the energy storing capacity and the health of the supercapacitor over time. SOC can be estimated by monitoring the voltage of the supercapacitor. However, due to the relatively flat voltage profile of supercapacitors during charge and discharge, other methods are often needed for accurate SOC estimation. By integrating the current flowing into or out of the supercapacitor over time provides an estimate of the charge (or discharge) that has occurred, helping to determine the

SOC. However, SOC estimation can be challenging due to factors such as self-discharge rates, voltage hysteresis, and temperature dependencies. On the other hand, SOH represents the overall health or condition of the supercapacitor over its operational life. It reflects the degradation or aging of the supercapacitor and is often expressed as a percentage relative to its initial performance. By integrating aging and degradation models to simulate the gradual loss of performance over the supercapacitor's life cycle can be determined. Factors such as cycling frequency, temperature, and voltage stress contribute to aging. Modeling supercapacitors accurately is crucial for optimizing their use in various applications, including energy storage.

3.4 Proposed Virtual Inertia Control (VIC) Strategy with MPLC

Virtual Inertia Control (VIC) is a control strategy that uses sophisticated control methods to mimic the actions of physical inclination in electrical systems. Synchronization generator' natural motion, which prevents shifting frequencies during disruptions, is provided by their rotating weight in conventional energy systems. The cumulative proportion of renewable energy sources (such solar and wind) used to power networks, which have little to no resistance, makes alternative solutions crucial for improving system reliability. In this study, the concept of virtual adjustment is one such method that is used.

The primary goal of VIC is to enhance the stability and reliability of power systems with a significant share of renewable energy sources by mimicking the inertia response traditionally provided by conventional generators. In this research, VIC relies on power electronic converters and supercapacitors to provide rapid and controllable responses to the variations in system frequency. The VIC approach is used for cultivating the performance of the system by addressing the issue of frequency instability caused due to the increased penetration of RESs. In this research, VIC is implemented in a decentralized manner, wherein each RES, power converter and supercapacitor autonomously contributes to the overall inertia emulation. This decentralized approach enhances scalability and adaptability. The system model and circuit diagram of the proposed VIC approach are exposed in figures 3.2 and 3.3 respectively.

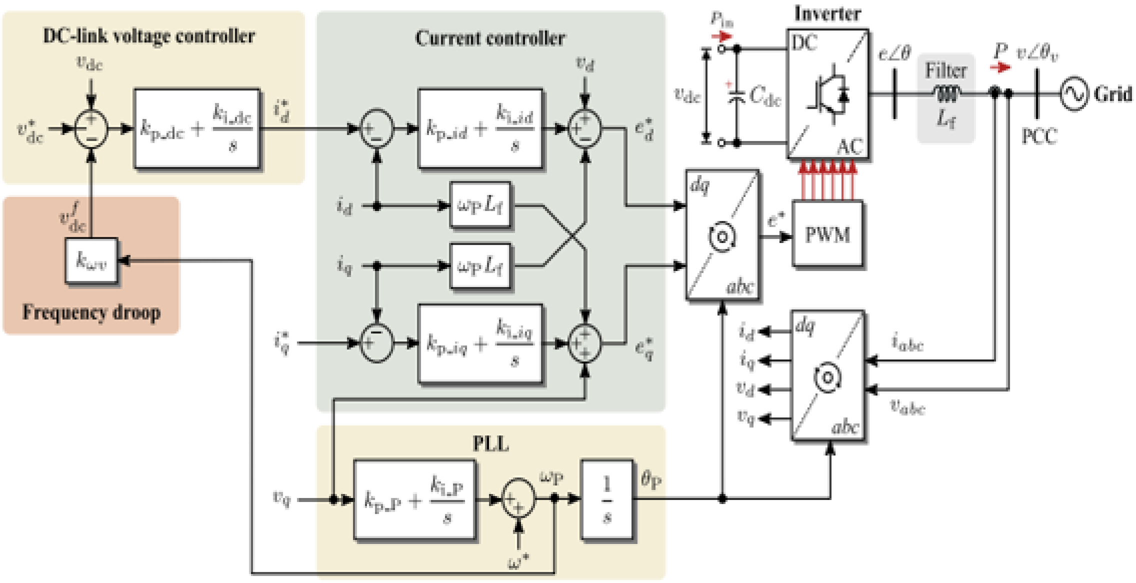

Figure 3.2 Schematic of the proposed VIC controller

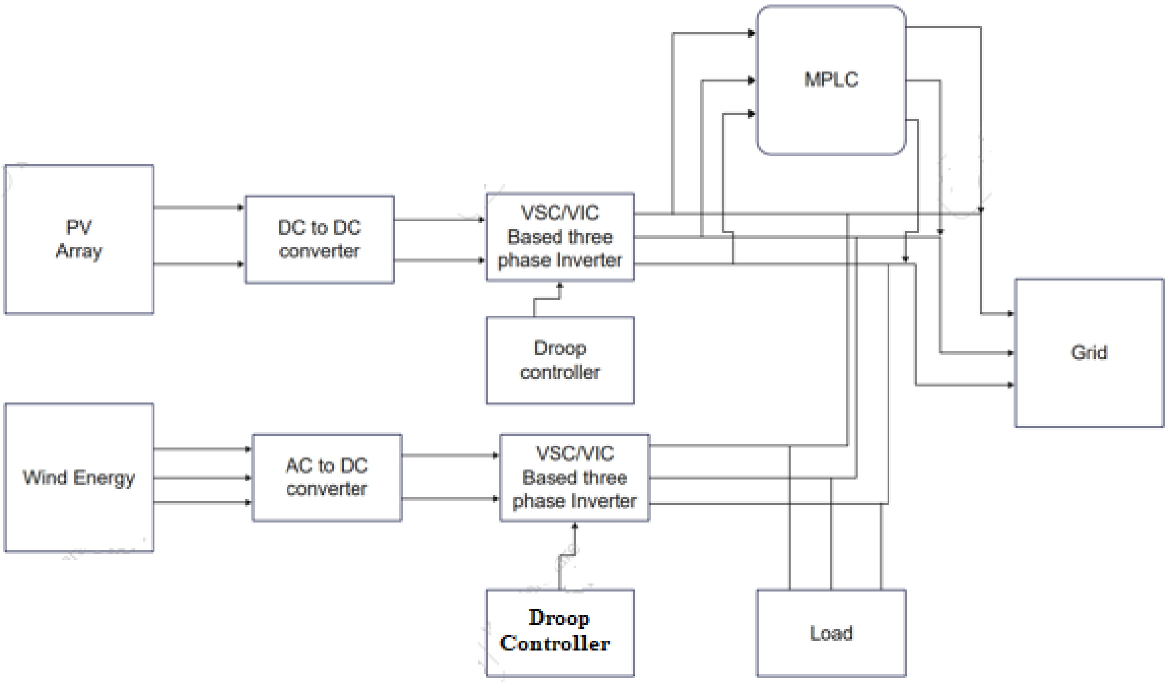

Figure 3.3 Circuit diagram of the proposed controller approach

In the present investigation, an MPLC regulator is employed to provide sufficient artificial inertia. Depending on the load and demand for electricity, the control system feeds electricity into the electrical network and pulls electricity out of it. In order to determine frequency of the grid and maintain it amid system disruptions, the MPLC conversion is built as a nine-level converter. By controlling the grid frequency and transferring electricity from the A super capacitor to the grid, the VIC approach is used to regulate the switch-over activity of the MPLC. The converter consists of 9 half cycles including 9 positive and 9 negative half cycles and is assumed as a control signal. A IGBT is used as a soft switch to decrease switching losses and progress overall effectiveness. Soft switching technique is utilized in this research to minimize the impact of switching transitions, particularly during turning on or off the MPLC, to reduce power losses and stress on the components. When implementing soft switching techniques with IGBTs, the circuit is effectively designed and the control strategy is formulated to ensure optimal performance. Factors such as the application, operating frequency, and specific necessities of the control system will influence the implementation of the soft switching technique and the design parameters.

For controller operation, a half cycle of the control signal is considered as an energy pulse and in this case, the energy is transferred in terms of both positive and negative cycles, which is controlled using IGBT. By controlling the control signals, the differences in the grid occurrence is also controlled. In this research, the MPLC controlled by the VIC strategy is deployed as a derivative control to measure the quantity of change of frequency (RoCoF). By accurately measuring RoCoF, the additional active power required by the grid during disturbances can be determined and this helps in preserving the equilibrium among the energy source and request.

However, it was observed during the experimentation process that the MPLC is highly sensitive to the uncertainties observed during the frequency analysis such as additive noise. This is eliminated by including a pass filter with the controller which also helps in improving the energy storing capacity of the supercapacitor. The proposed strategy is considered in such a technique that it exhibits a similar behavior to the traditional grids. In this way, the inertia characteristics of the VIC contributes to the complete inertia of the DG system. The main objective is to improve the robustness and stability of the system and this is achieved by the VIC strategy which is exposed in figure 3.4.

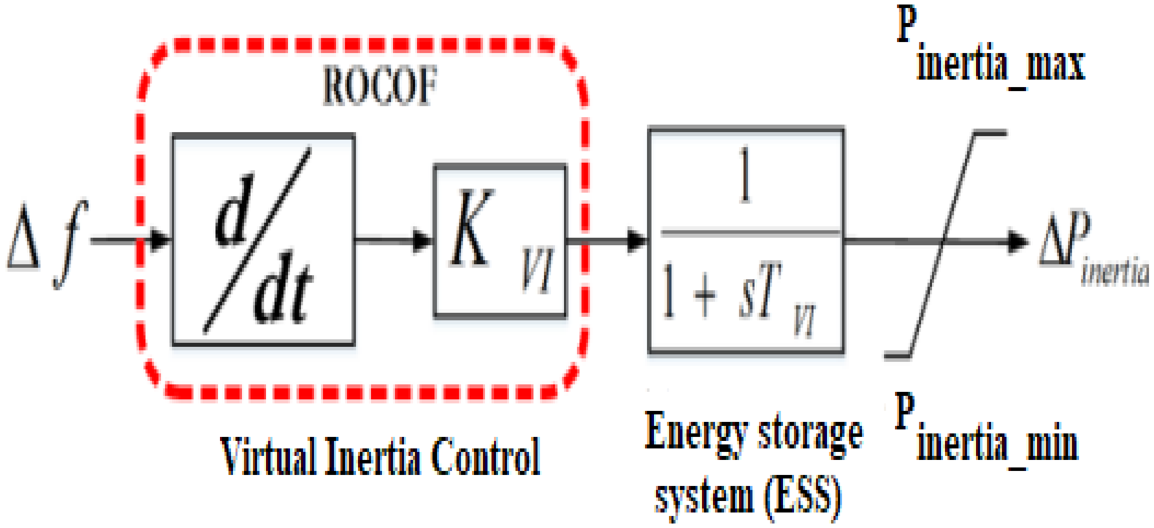

Figure 3.4 The dynamic model of VIC

The overall simulation diagram is shown in figure 3.5.

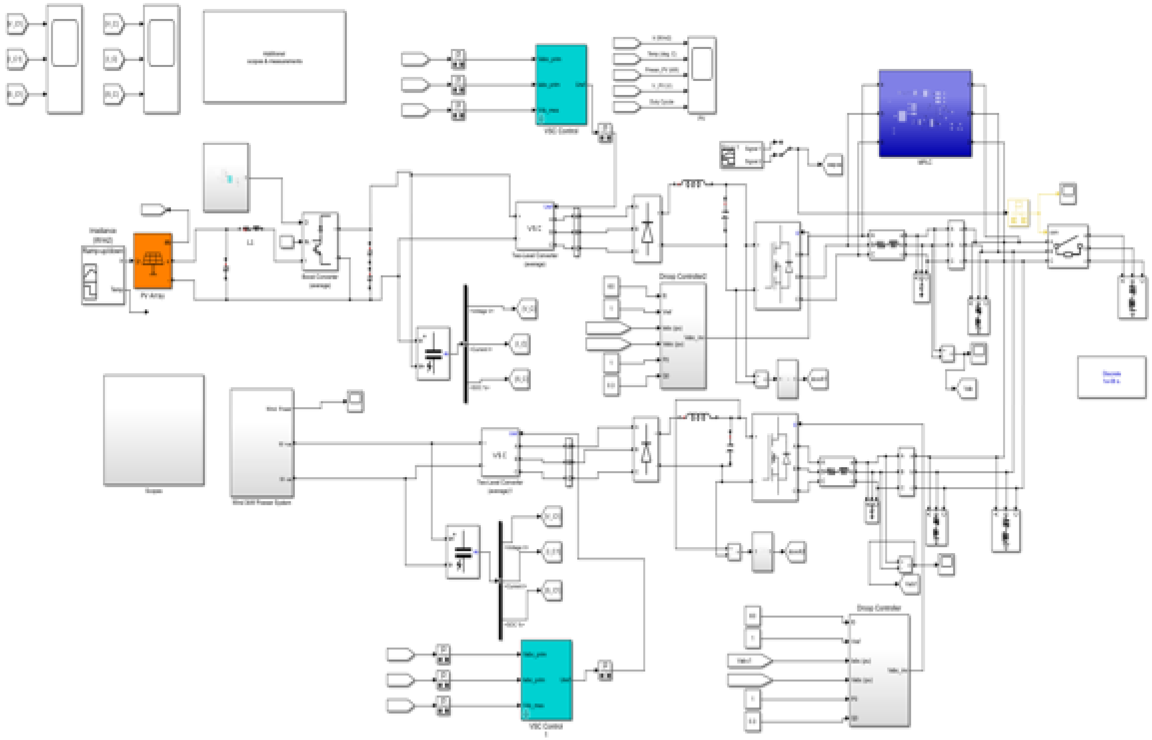

Figure 3.5 Simulation diagram

3.5 MPPT Technique for Maximum Power Extraction

In order to collect the greatest amount of power from PV systems and guarantee that the system is functioning at its maximum power point (MPP), the Maximum Power Point Tracking (MPPT) technique is used in conjunction with the VIC controlled MPLC. The MPP is the operational point where, in light of the current situation, the DG system's output power is maximized. In this study, a Perturb and Observe (P&O) MPPT technique is applied, which involves periodically perturbing (changing) the DG method's operational point and tracking the subsequent shift in power production. The P&O algorithm then modifies the point of operations in accordance with the change that was seen, consistently advancing in a manner of increased power. The following stages can be used to define the P&O procedure's operating principle:

(i) Perturbation: The method consists of slightly altering (stirring) the PV method's operational point. The disturbance basically consists of a tiny adjustment to the voltage point of operation or duty cycle of a DC-DC converters, which is utilized in photovoltaic systems.

(ii) Observation: Immediately prior to and following the disturbance, the power output of the photovoltaic system is monitored. Increases in power production cause the system to perturb in the same way that is, toward increased duty cycle or voltage. Precisely opposite modification is made (in the direction of lower voltage or duty cycle) if the electrical output decreases.

(iii) Iteration: The process is repeated in a continuous loop, with the operating point being perturbed and observed at regular intervals. The objective is to zero in on the MPP, where further perturbation in either direction would result in a decrease in power output.

The P&O algorithm is included in this work since it is a straightforward and simple algorithm to implement. In this research, the perturb value is fixed to generate reference signals for both MPLC and VIC controllers. The reference voltage for the algorithm is set based on the voltage of the PV system. For larger perturb values, the tracking speed of the controller increases which in turn increases the power extracted by the PV system. For smaller perturb values, tracking response of the system is reduced which also minimizes the power of the PV system. To achieve this, the controller is provided with a fixed perturb value, and fixed duty ratio.

The process involved in the operation of the P&O technique is described using the governing equations given below:

The voltage and current from the photovoltaic system, which are represented as VPV (n) and IPV (n), correspondingly, are first absorbed by the PV system; the letter "n" designates the sample occurrence. Equation 5 illustrates how the filtered values of VPV (n) and IPV (n) are used to calculate the power of the PV system.

$P_{PV}(n) = V_{PV\_filtered}(n) \times I_{PV\_filtered}(n)$ ….(5)

The variations observed in the power of the PV system will be high in the initial stages and it slowly declines until the system reaches zero at steady state. The P&O based MPPT controller is designed to manage such huge variations in power and thereby helps in maintaining the power system stability. The algorithm is suitable for real-time operation, and responds quickly to the variations in the environmental conditions. Furthermore, the implementation of the P & O algorithm is cost effective since it doesn't require complex mathematical models.

The advantages of the MPPT techniques are as follows:

- ***Better Energy Control:*** MPPT controllers maximize the energy extracted from solar panels by continuously adjusting the operating point of the panels to the MPP under varying conditions such as temperature changes and shading. This optimization results in increased energy production compared to conventional controllers.
- ***Higher Efficiency:*** By operating the solar panels at their maximum power point, MPPT controllers enhance the overall efficiency of the solar power system. This efficiency boost can be significant, especially in situations where environmental factors fluctuate frequently.
- ***Adaptability to Varying Environmental Conditions:*** Solar panels usually experience changing weather conditions, shading, and temperature fluctuations, which can affect their performance. MPPT controllers dynamically adapt to these changes, ensuring the panels operate at their most efficient level despite varying environmental factors.
- ***Compatibility with Multiple Panel Configurations:*** MPPT controllers are versatile and can work efficiently with various types of solar panels, including different voltage and

current configurations. This flexibility makes them suitable for a wide range of solar power systems.

- ***Remotely controlled and Observation:*** The MPPT controllers come with monitoring functions that let users keep an eye on the operation of the solar panels from a distance. Certain types also allow for remote modifications and management, which improves the efficiency and simplicity of operating the solar energy system.
- ***Reduced System Losses:*** MPPT controllers minimize power losses in the system by ensuring that the maximum power from the solar panels is effectively converted and utilized, reducing wasted energy.

The advantages mentioned above make MPPT controllers a preferred choice for solar power systems, especially in scenarios where optimizing energy production and system efficiency are paramount.

3.6 Proposed Model of Multi-Region Power Framework with Virtual Inertia Control

The distinct layout and regulation anticipated to produce enough virtual inertia-based power electronic converters are depicted in Figure 3.6. The subordinate control strategy, which can calculate the rate of progress of recurrence (ROCOF) to shift an additional capacity to a predetermined location in area I during RESs entrance and possibility, is the main idea underlying virtual inertia control. However, the subsidiary control strategy is exceptionally helpless to recurrence estimation clamor.

A low pass channel is utilized to control the framework to get around this issue. Moreover, the low-pass channel could introduce the ESS's dynamic ways of behaving. Thus, virtual inertia control can help an interconnected power framework by causing the RESs in that framework to have inertia power equivalent to simultaneous generators utilized in conventional power frameworks. Thus, the recommended virtual inertia the executives delivers the inertia trademark, adding to the interconnected power framework's complete inertia and upgrading recurrence dependability and execution. In this work, we proposed that the ESS could produce virtual inertia power in the two areas.

Figure 3.6 shows the control regulation for reenacting inertia power in the Laplace space in view of a for each unit framework. The recommended virtual inertial control will supply the expected capacity to the I^{th} region during the recurrence deviation in the way portrayed underneath:

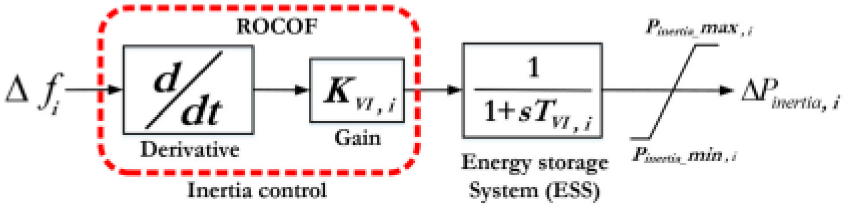

Figure 3.6 dynamic model of the controller that was created to simulate virtual inertia.

Ultimately, ROCOF will be established by the suggested inertia control system through the subsidiary control process; the inertia power will be recreated by the virtual inertia gain (KVI) modifying the ESS's dynamic power reference. Consequently, the special model of a multi-region framework with virtual inertia control is addressed by modifying to include virtual inertia (also known as imitated power). The recurrence deviation for region I should be determined using the preceding recipe, taking into account the age/load power signals, inertia power signals, and tie-line power signals is represented in equation (2):

$$\Delta f i = \frac{1}{2H_{is}+D_i}\left(\Delta p_{mi} + \Delta p_{wi} + \Delta p_{si} + \Delta p_{inertial,i} - \Delta p_{Li} - \Delta p_{Tie,i}\right)$$

(2)

where the recurrence deviation in region I is addressed by Δfi. In region I, Hello addresses the consistent of inertia, while Δ Pmi addresses the power created by the warm creation unit. Di is the region I's damping coefficient. Δ PWi is the region I's created power from the breeze ranch. Δ PSi is the region I's created power from the sunlight-based ranch. Δ Pinertia,i is the region I's copied inertia power from the ESS unit. ΔP Li is the region I's heap changes. Δ PTie,i is the region I's general tie-line AC power changes.

3.7 Summary

The thesis delves into the pressing challenge of virtual inertia in power grids resulting from the integration of renewable energy sources. Acknowledging the significance of inertia in traditional power systems for stability, the research focuses on proposing and validating a mitigation technique to enhance grid resilience amid a growing share of renewable energy. This research aims to achieve better system performance of the grid integrated with RES. Considering the high level penetration of the RES, the chances of virtual inertia issue increases which majorly affects the performance of the system. The study mainly focuses on obtaining an efficiency control strategy for controlling the flow of active and reactive power between load and the grid using a VIC controller approach. In the proposed control approach along with a 9 level converter based-power control methodology is employed which is capable of optimizing the power flow between the grid and the load. It controls the power flow thereby minimizing the active power loss in the system. The effectiveness of the VIC based MPLC controller was evaluated using two different case analyses namely; sudden connection of loads and sudden disconnection of loads. The methodology states that during variations in the load the output power of different sources was almost constant and the stability of the system was sustained. The core contribution of this thesis lies in the proposal and validation of a novel mitigation technique tailored to mitigate virtual inertia challenges. Drawing from theoretical foundations and innovative control strategies, the proposed technique demonstrated promising results in simulation studies and experimental setups which will be discussed in the next chapter. The output of the proposed system was analyzed with respect to the frequency variation, load variation and voltage. It can be inferred from the case analysis that the proposed controller was highly effective and it reduces the distortion significantly compared to existing strategies. In light of these findings, this research methodology contributes not only to the theoretical understanding of virtual inertia but also offers tangible solutions for the sustainable integration of renewable energy into existing power infrastructures. The proposed mitigation technique, with its innovative approach and demonstrated effectiveness, holds promise for the evolving landscape of modern power systems.