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VIRTUAL INERTIA BASED INVERTERS FOR FREQUENCY MITIGATION BY INCORPORATING VIC AND MULTI-POWER LEVEL CONTROLLER IN GRID CONNECTED RENEWABLE ENERGY

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Abstract: The penetration of Renewable Energy Sources (RESs) into microgrids is gaining huge significance in recent times. RESs are integrated with conventional grid systems to meet the growing energy demand and to enhance the power quality. The increasing penetration of RES into the grid system affects the stability of frequency in microgrids due to the stochastic nature of photovoltaic (PV) and wind energy generation. Unlike in traditional power generation systems, the lack of rotational inertia in microgrids is one of the critical concerns which affects the integration of RES with the grid system through power electronic converters. This introduces more uncertainties into the system and hence the operation and control of such a system becomes more complicated. In order to maintain the stability of microgrids and to effectively utilize RESs and distributed generation (DG) systems, it is essential to control virtual inertia. Proper inertia control improves the flexibility of microgrid operation and as a result various controlling strategies have been proposed in the past to control the virtual inertia. This paper presents a new virtual inertia control (VIC) approach with a multi power level controller (MPLC) for RES integrated microgrids. Considering the high level penetration of RES, the proposed approach is designed to enhance the system performance under sudden load variations and frequency variations. The efficiency of the proposed control approach is validated with and without MPLC. Results show that the controller achieves better frequency stability with MPLC.

Keywords: *Renewable Energy Sources, Virtual inertia control, Multi Power Level Controller (MPLC), Frequency Instability, Frequency Control*

1. Introduction

There is a growing interest in the integration of Renewable Energy Sources (RESs) into power grids to reduce the emission of toxic greenhouse gas released by traditional fossil fuel-based power plants and to prevent the harmful environmental consequences (Rácz et al., 2018) [1]. The distinguished advantages of grid integration with RES has led to the emergence of Distributed Generators (DGs) which emphasizes the combination of different energy sources such as solar photovoltaic (PV) energy, wind energy, fuel cells with energy storage systems such as batteries and supercapacitors, small thermal power plants and microturbines.[51] The renewable energy based power generation sources such as PV systems and wind turbines are connected near to the DG sites.[47] The incorporation of grid-connected RES systems has several advantages such as reduction in the power transmission losses, improvement in the voltage droop characteristics, enhancing system stability, and effective control of active and reactive power (Li et al., 2019). However, it can have some adverse effect on the performance of the grid-connected RES systems in terms of inertia deficiency, power grid security issues, and frequency instability issues (Mehrasa et al., 2019) [3] (Fang et al., 2018a) [4] (Fang et al., 2018b) [5]. These issues can be elaborated as follows:

1. RESs show low or poor inertial responses which results in frequency instability (Rakhshani & Rodriguez, 2017) [6].
2. During fault occurrences or due to sudden variations in the load, the frequency of the grid deviates from the nominal frequency (Rakhshani et al., 2019) [7].
3. The rate of change of frequency (RoCoF) and frequency nadir is higher due to fault occurrences and dynamic load change. This enables the controller to disconnect the frequency relay (Shi & Zhang, 2018) [8].

Integration of RES with a grid using a conventional inverter deteriorates the stability of frequency due to lack of rotating masses (Kerdphol et al., 2018) [9]. In general, RESs are characterized by their intermittent behavior and hence by integrating RES to the grid through a fast switching inverter, a fast dynamic system for grid-connected RES can be developed (Pagola et al., 2019) [10]. This fast integration affects the stability of different grid parameters such as voltage, phase angle, and frequency (Chen et al., 2017) [11]. The stability concerns get more worse during fault occurrences by increasing transient power transmission and frequency deviations.[37] To overcome the challenges caused by grid-connected RES, several researchers have suggested the application of virtual inertia or synthetic inertia control strategies.[38] Virtual inertia imitates the inertia response of conventional synchronous machines through pulse width modulation (PWM) technique.[52] Virtual inertia based control strategies are effectively implemented in several applications such as high voltage direct current (HVDC) transmission (Amin & Molinas, 2016) [12] (Zhang et al., 2016) [13], virtual inertia machine (VIM) and power electronic based DC systems (Li et al., 2019) [14], DC microgrids (Wang et al., 2017) [15], and grid connected RES systems (Gloe et al., 2019) [16] (Chandrakar et al., 2018) [17] to maintain frequency stability and to assist systems with flexible loads.[39]

As discussed previously, the increased penetration of RESs affects the inertia of the system significantly.[40] The RESs connected to the grid system via power electronic converters or inverters can reduce the inertia which is directly related to the stability of the system.[41] Unlike conventional power generation systems, the inverter based grid tied RES causes more fluctuations in the system frequency (Babahajiani et al., 2018) [18]. Hence, the penetration level of RES must be controlled to avoid the stability, flexibility and efficiency of the grid system.[56] It must also be noted that, with the increasing level of RES can also increase the complexity of frequency control.[42] Hence, it is more challenging to control the frequency if there is any conflict or discrepancy in the load demand and power generation (Ali et al., 2019) [19]. Besides, grid integration of RES through power electronic converters can decouple the source from the load without providing inertia.[48] As a result, inertia of the power grid decreases, resulting in undesirable load.[43]

One of the feasible solutions to stabilize the frequency of such grids is to imitate the behavior of synchronous generators (SGs) virtually into the grids in order to improve the robustness, and stability of the system.[57] Virtual inertia control (VIC) is the most effective controlling strategy which can provide sufficient support to improve the frequency stability.[58] In this context, this research employs a VIC based control strategy to evaluate the inertia and to mitigate the frequency instability issues by providing additional power to the system.[45]

The main contributions of this paper are as follows:

- This paper presents the design of a virtual inertia based controller (VIC) for evaluating the effect of virtual inertia and to mitigate the issue of frequency instability in RES integrated grid system.
- The proposed design implements a supercapacitor as an energy storage device to obtain high power density and to emulate the inertia of an inverter.
- The VIC is integrated with the proposed multi power level controller (MPLC) to control the dynamic variations in the grid system.
- The proposed approach is designed to overcome the frequency instability problem and To maintain the inertia levels for sudden disconnecting loads. Therefore, the proposed control scheme provides the maximum inertia and frequency support while the system experiences changes in the load, which is the main contribution of this research.[53]

The rest of the paper is structured as follows: Section II discusses the existing works related to frequency instability mitigation techniques based on virtual inertia control.[54] Section III discusses the virtual inertia control strategy and Multi-power level Controller based virtual inertia evaluation for frequency mitigation.[59] Section IV discusses the results of the experimental analysis and Section V concludes the paper with prominent research observations.[44]

2. Literature Review

Several control strategies have been proposed in the last few years for VIC to overcome the frequency stability issues in grid systems (Nguyen et al., 2016) [20] (Magdy et al., 2019) [21] (Gouveia et al., 2021) [22]. Among different controller proposed in the past, traditional controllers such as Fuzzy Logic Controller (FLC) (Rajesh et al., 2021) [23] (Yap et al., 2021) [24], proportional Integral Derivative (PID) controller (Khamies et al., 2021) [25], Model predictive control (MPC) (Yang et al., 2019) [26] have been used to achieve robust control over frequency in grid connected RESs.[60] In addition to these techniques, several other robust control strategies have also been introduced to overcome the problems related to system uncertainties during adverse scenarios (Xia et al., 2019) [27] (Khudhair et al., 2022) [28] (Ali et al., 2021) [29]. A comprehensive analysis on the virtual inertia based inverters in advanced power systems is presented in (Yap et al., 2019) [30]. The reviews outline the recent advancements, progress, challenges, and different prospects of virtual inertia based control strategies, which is essentially important to transform the operation of conventional power plants.[54] Since the virtual inertia based inverter technology is a new technique, the research related to its adaptation in power grids is still in the infant stage and there is a great scope of research in this field. Based on the observations, the authors in (Yap et al., 2021) proposed a novel adaptive VIC control strategy with varying moment of inertia (J) and damping factor (D_p). The proposed strategy is designed to achieve a fast frequency recovery against the fluctuations with high stability, and less overshooting under fault occurrences and extreme weather conditions.[49] Experimental evaluation is conducted with different case studies in the MATLAB/ SIMULINK platform to exhibit the effectiveness of the proposed approach.[55] Results show that the frequency nadir was increased by 1.9 % with a value of 0.95 Hz compared to traditional PI based synchronverter and inverter.[61] The results are validated through real-time simulation and hardware implementation.[46] It can be inferred from the results that the proposed VIC strategy can effectively regulate the grid frequency and voltage with varying temperature, solar irradiance, frequent load variations, and overloading conditions. (Chang et al., 2021) [32] proposed a forecasting based VIC strategy with coordinated reserve technique. The FB-VIC allows the photovoltaic systems to act as an alternative system to supply required inertia to the system without using any energy storage system (ESS). The PV system is used for predicting the energy availability for different conditions such as shaded, partially shaded or unshaded conditions and PV plants providing virtual inertia. The coordinated reserve technique is used to estimate the amount of energy that has to be reserved by the selected PV system. This approach increases the robustness of the system and makes it resilient to forecasting errors.[62] Simulation results show that the proposed FB-VIC strategy can increase the system inertia and control the variations in the frequency with a faster response time.[63] A VIC based frequency regulation of microgrids with RES and power system stabilizers (PSS) is proposed in (Asokan, 2021) [33]. The PSS employed in this research is to reduce the effect of oscillations and to maintain the stability of the system. The main objective of this research is to improve the dynamic response of the system along with frequency regulation. The performance of the proposed approach is evaluated in the MATLAB environment and the VIC strategy exhibits better results in terms of frequency regulation and power system stability. Although several control strategies have been developed, the dynamic and intermittent behavior of RES and its penetration into the grid makes it challenging to regulate the frequency and maintain the system stability. This problem motivates this research to design a novel strategy for mitigating the effects of frequency instability in grid connected RES using a VIC based control strategy.[64]

3. Proposed Research Methodology

A RES connected grid system is considered as a test system to design the proposed VIC strategy using a Multi-power level Controller (MPLC) for mitigating the frequency instability issues. The grid system consists of renewable energies such as a solar PV system and wind energy with supercapacitors as an energy storage element. This research considers a low-order dynamic response model for RES since it is appropriate for analyzing the frequency stability of the grid system as mentioned in the references (Magdy et al., 2019) [21] (Kerdphol et al., 2017) [34]. The variation in the wind energy, solar energy, and variation in the load are considered as the disturbances or uncertainties in the system that affect the performance of the grid system. Super capacitors (SC) are implemented as electrical energy storage devices that provide high power density.[50] The supercapacitors used in this research provide initial inertia support to the system and have a fast response time, high-power density, and larger cycle life. In addition, the supercapacitor will also supply power to the grid when required. A Virtual

Inertia based Droop controller is incorporated with the system and virtual inertia is determined using the voltage and current controller. Based on the obtained values and the PWM signals generated the required power supplied to the inverter and inertia support obtained by the grid via inverter are determined. Power electronic converters such as DC converters are used for connecting the RES with the grid. A proper controlling of the power electronic converter is essential in order to obtain maximum power from the varying energy resources such as wind or solar energy. In PV systems, an effective control of the converters is provided for maximum power point tracking (MPPT) ensuring that maximum power is extracted from PV systems. A Perturbation and Observation (P&O) MPPT technique is employed in this research. It is assumed in this research that the supercapacitor implemented in study can handle a maximum power of about 9 kW with a voltage range of 35-65 V. The supercapacitor model makes a better use of storage technologies and helps the grid system to achieve high efficiency.

3.1 Modeling of Grid system with RES

The grid system is modeled with different energy sources such as PV system, wind energy, and supercapacitors. The control strategy in this research is designed for controlling the power flow between RES, utility load and grid. The modeling of grid components are discussed as follows:

- ***Modeling of PV systems***

The solar PV system is analyzed as per the equivalent circuit as shown in figure 3.1.

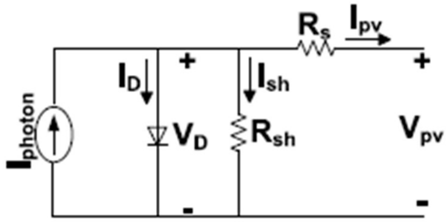


Figure 3.1 Equivalent circuit of a single-diode PV cell

The current and voltage characteristics of the PV systems can be determined using equation 1.

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

....(1)

Where I_s is the saturation current of the diode, and I_{pv} is the current through the PV system, V is the system voltage, R_s and R_{sh} are series and shunt resistance respectively, k is the Boltzman's constant (1.38 × 10 − 23 J / K), V is Voltage across load and η is the efficiency of the converter.

- ***Modeling of wind turbine***

Wind turbine or wind energy generation system is modeled in terms of its kinetic energy which is converted into electrical energy through a permanent magnet synchronous generator (PMSG). The kinetic energy equation is given as:

$$\boldsymbol{E = \tfrac{1}{2} mv^2} \ldots\ldots (2)$$

The input and output speed of the wind turbine is given as v_a and v_b respectively. The power generated by the wind turbine is given as:

$$P_{w(in)} = \frac{1}{2} A_s \rho_{air} V_a^3 \qquad \ldots\ldots (3)$$

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

Where A_s is the area swept by the rotor, ρ_{air} is the mass density of the air and v_w is the wind voltage. $P_{w\,(in)}$ and $P_{w\,(out)}$ is the available input power and output power of the wind turbine respectively.

- ***Modeling of supercapacitor as energy storage***

Supercapacitors play an important role in supplying power to the grid system in island mode. In general, energy storage elements can be operated in two modes (i) in transient response mode and (ii) energy exchange between grid and energy storage systems in steady state environments. Supercapacitors are proven to be the best to operate in transient mode and batteries are more suitable for steady state operations. While modeling the supercapacitor, the capacitance is assumed to be ideal i.e., its resistance is 0.

3.2 Virtual Inertia Control (VIC) Strategy with MPLC

The VIC control strategy is used to emulate the inertia provided by the synchronous generators in conventional power generation systems. The VIC strategy employed in this research aims to mitigate the effect of frequency instability issues in grid-tied RESs during high-level penetration of RESs. A Virtual Inertia based Droop controller is designed in this research.
The schematic of the proposed VIC strategy is illustrated in figure 3.2.

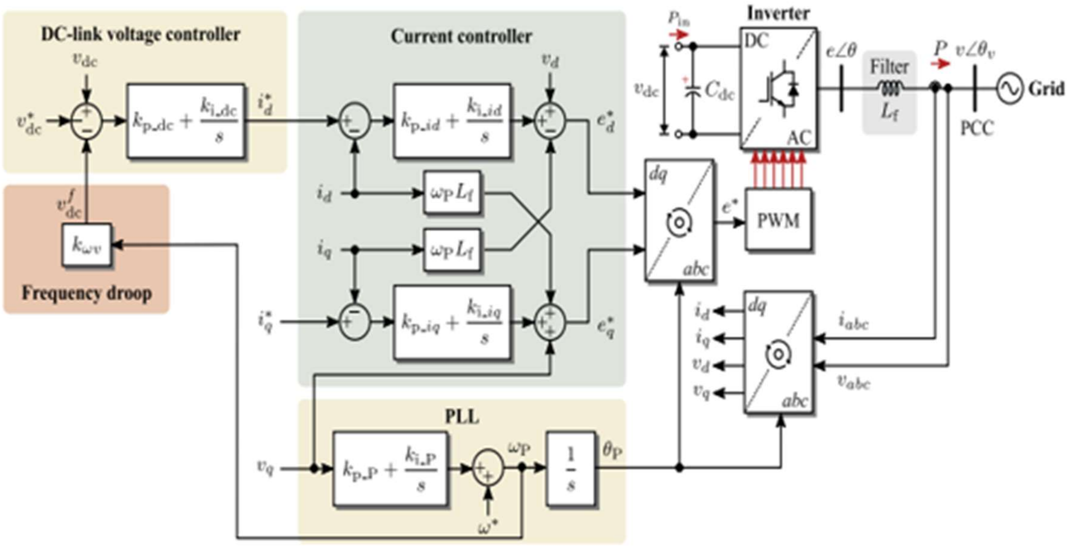


Figure 3.2 Schematic of the proposed VIC controller

The VIC control is an integral part of the virtual synchronous generator (VSG) wherein the prime mover in the VSG is emulated to provide required support to maintain the frequency stability (Zhao et al., 2017) [35] (Li et al., 2016) [36]. To provide enough virtual inertia, this research employs a MLPC controller which provides energy to the grid or absorbs the energy from the grid based on the energy demand and load conditions.

The MPLC converter is implemented as a nine level converter which generates pure sinusoidal signals. The MPLC converter measures the grid frequency and provides online support to the grid.. Using the proposed VIC, the switching cycles are controlled and as a result, the power transfer from the super capacitor to the grid can be regulated in response to the grid frequency change. The proposed MPLC converter is designed with nine level half cycles including 9 positive and 9 negative half cycles and is assumed as a control signal. Considering each half-cycle of the control signal as one energy pulse, power can be transferred either in the form of positive or negative energy pulses. The control signal is given to the soft-switch IGBT. Based on the control signals, the respective changes in the frequency of the grid can be controlled.

The VIC based on the MPLC is implemented as a derivative control which measures the ROCOF to supply additional active power to the grid during contingencies. Since the controller is sensitive to the noise caused due to the frequency measurement, a low pass filter is added which also simulates the fast response of the ESS. Correspondingly, the VIC also emulates the behavior similar to conventional SGs and as a result, the VIC exhibits the inertia characteristics which also contributes to the total inertia of the grid system and thereby improving the resilience and frequency stability of the system. In this research the inertia is emulated through the supercapacitor which is added in the form of ESS as shown in figure 3.3 (Kerdphol et al., 2017) [34].

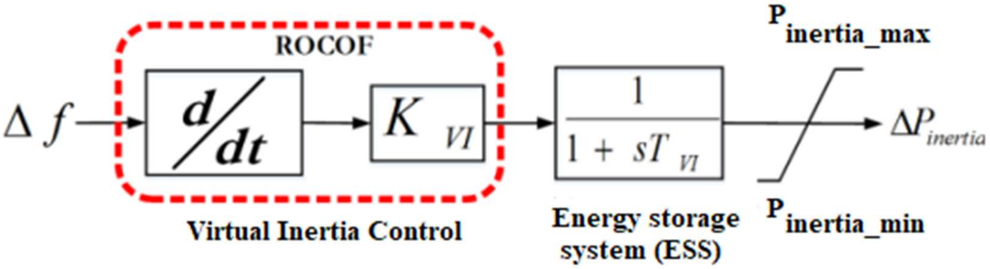


Figure 3.3 Dynamic model of VIC

A Maximum power point tracking (MPPT) technique is used to extract maximum solar energy from the PV system. MPPT is one of the most effective techniques used in solar PV modules which ensures the maximum extraction of solar energy from the PV modules to supply the maximum power to the load to enhance the efficiency of the grid connected RES. The P&O technique used in this research to overcome the perturbations in the energy generation systems and to obtain maximum input energy. P&O is simple to implement in grid connected RES. Initially, the input voltage is considered for analyzing the perturbations in the PV system which also analyzes the perturbations in all possible directions. If the power obtained from the PV system increases beyond the specified value then the operation point moves towards the MPP and this also tends the voltage to vary in the same direction. In this research, a fixed perturb value is considered for generating the reference signals for the VIC based MPLC controller and the reference value is decided based on the voltage of the PV system. For smaller values, the tracking response of the system reduces which in turn reduces the power of the PV system. On the other hand, for larger perturb values, the tracking speed increases which also increases the power. Hence, in this research, instead of using a fixed perturb value, the duty ratio of the converter is used. The process involved in the operation of the P&O technique is described using the governing equations given below:

Initially, the PV system absorbs the voltage and current from the PV system which is denoted as V_{PV} (n) and I_{PV} (n) respectively where ‘n’ defines the sample instance. The power of the PV system is determined using the filtered values of V_{PV} (n) and I_{PV} (n) as shown in equation 5.

$$P_{PV}(n) = V_{PV\_filtered}(n) \times I_{PV\_filtered}(n) \quad \ldots(5)$$

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.

4. Results and Discussion

In this section, the proposed virtual inertia control strategy using MPLC controllers is proposed and implemented. The proposed framework is simulated using the MATLAB/Simulink environment. The simulation parameters used for the analysis are tabulated in table 1.

Table 1. Simulation parameters

Parameters	**Values**
Output voltage of PV system	300 V
Output power of PV	10 kW
Operating frequency	60 Hz
Output voltage of wind turbine	300 V
Output power of wind turbine	3 kW

The controller is designed and simulated such that it offers flexibility and adjustability to the parameters of the model. In practical scenarios, it is referred to model a specific behavior of the system and to ignore other insignificant aspects. The main objective of the proposed approach is to obtain an optimal frequency stability analysis in the grid connected RES system. The simulation results are presented in this section.

4.1 Performance Analysis

Simulation was performed for evaluating the performance of different renewable energy resources such as a PV system, and the wind energy system. The outputs of the same are discussed in this section. The MPPT algorithm is implemented with solar energy and it generates power around 10 KW and wind turbines generate 3 KW power as shown in below figures:

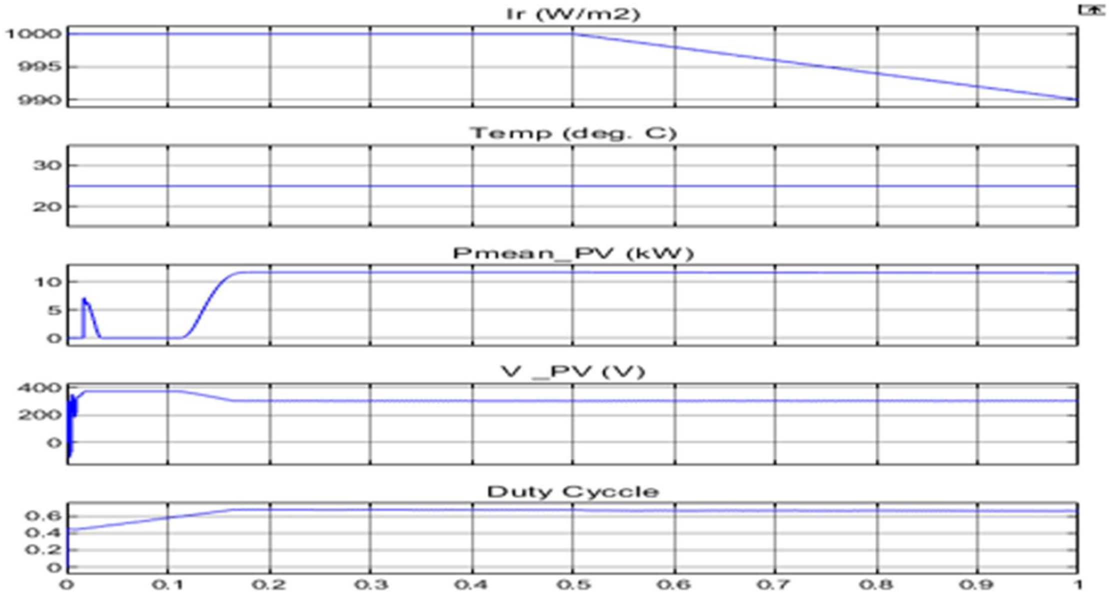


Figure 4.1 Output waveforms of solar PV system

As inferred from figure 4.1, it can be inferred that in the proposed approach a maximum solar irradiance of 1000 W/m^2. The mean value of the power exhibits a steady state performance and the voltage of the system reaches a maximum value of 300 V. The output waveform of the system is shown in figure 4.2.

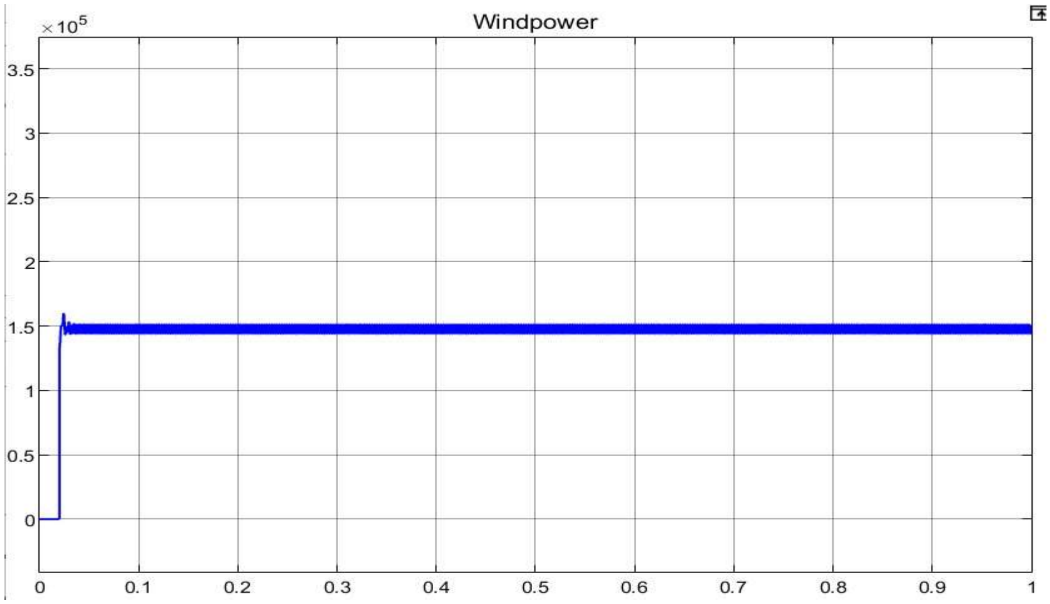


Figure 4.2 Output of the wind turbine

The performance of the VIC with MPLC controller is evaluated to analyze the system's behavior under sudden connecting loads. The simulation is conducted for two conditions: (i) for sudden connecting loads of 75 kW and (ii) for sudden disconnecting loads of 75 kW.

- ***For sudden connecting loads***

For sudden connecting loads a 75 kW load is added to the grid as shown in figure 4.3 and the output current of the inverter is shown in figure 4.3.

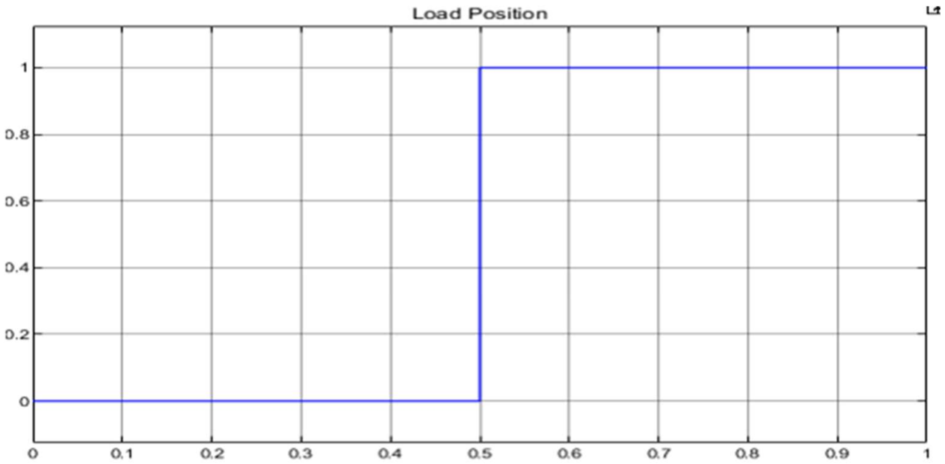


Figure 4.3 Load position with sudden variation in the connecting load

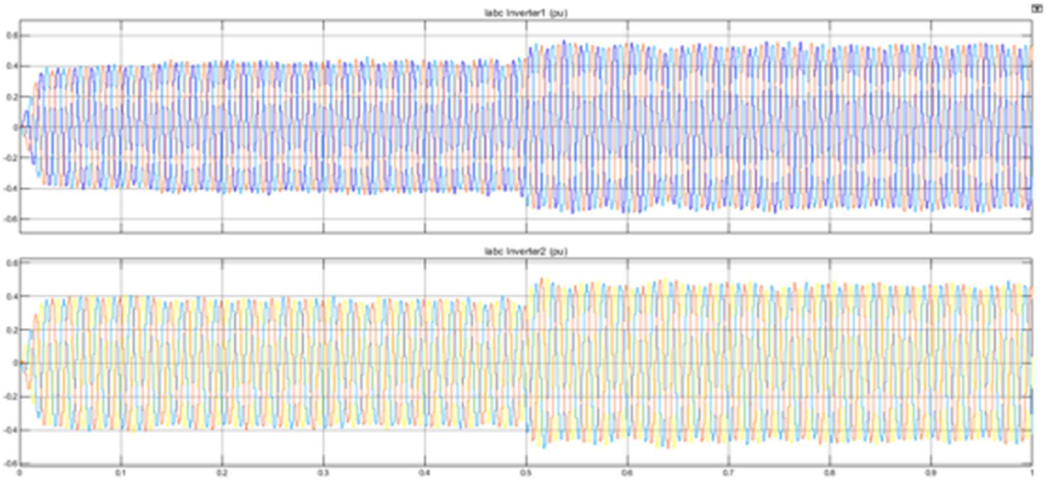


Figure 4.4 Variation of inverter output current with sudden change in the load

It can be inferred from the above figure that the sudden demand in the load is high and hence the inverter output current increases from 0.4 p.u. Hence, the proposed controller enables the exchange of power between grid and the inverter such that the inverter supplies required power to the grid whenever required through RESs. The power sent to the grid is illustrated in figure 4.5.

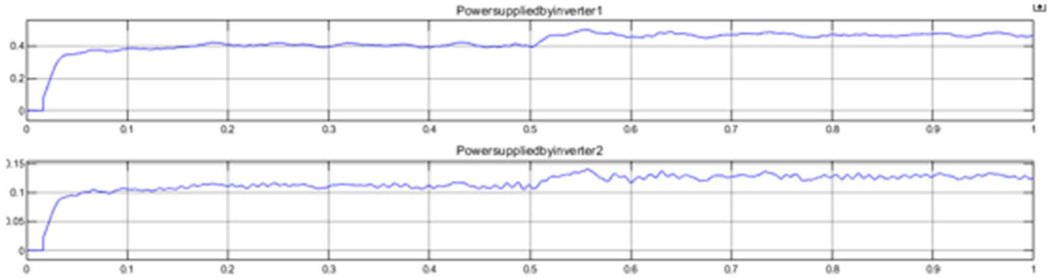


Figure 4.5 Power supplied by the inverter to grid during sudden connection of loads

When the load is added into the grid, there is a variation in the power supplied as observed from figure 4.5. However, the power supplied has constant perturbations and this is due to the variation in the load. The corresponding change in the inverter output voltage and output frequency is shown in figures 4.6 and 4.7 respectively.

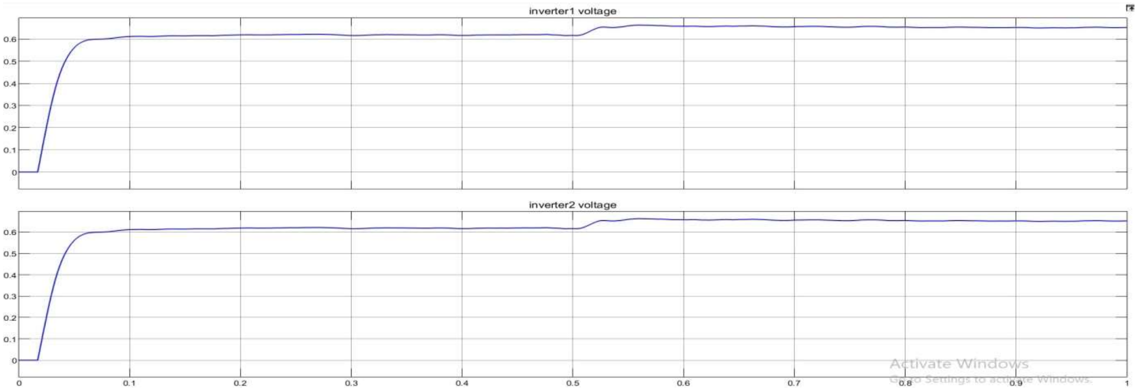


Figure 4.6 Change of inverter output voltage

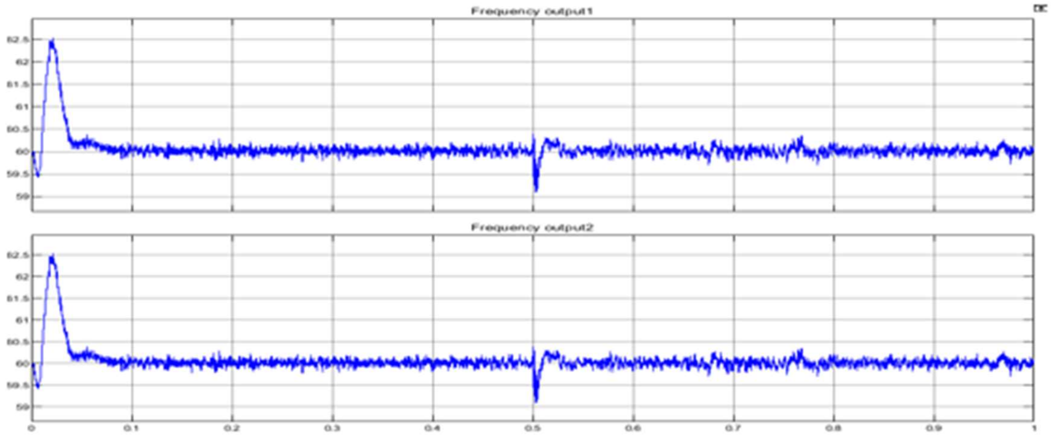


Figure 4.7 Frequency output for sudden connecting loads

The output frequency of the grid system decreases up to 59.2Hz and again maintains the same frequency. This shows that, although there is a change in the load position, the frequency can be stable after sustaining small variations.

- ***For sudden disconnecting loads***

For sudden disconnecting loads a 75 kW load is disconnected from the grid as shown in figure 4.8 and the output current of the inverter is shown in figure 4.9.

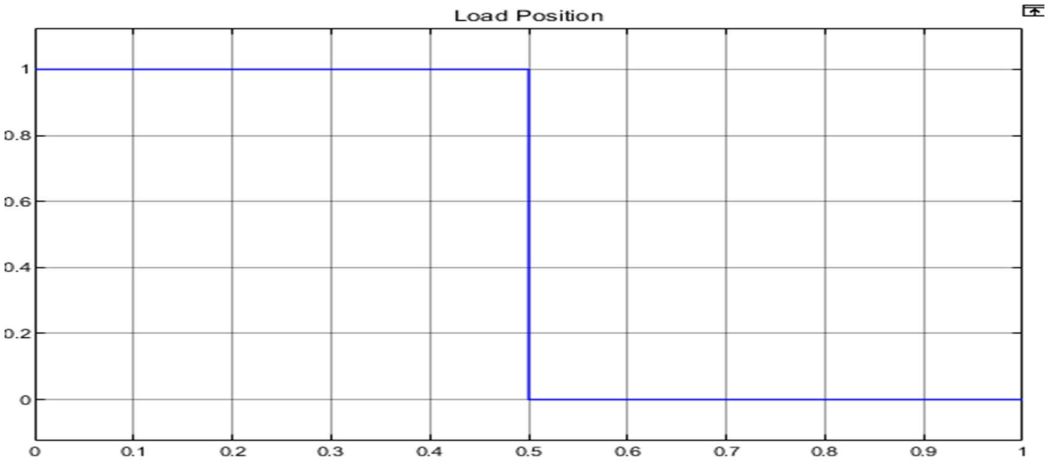


Figure 4.8 Load position with sudden variation after disconnecting the load

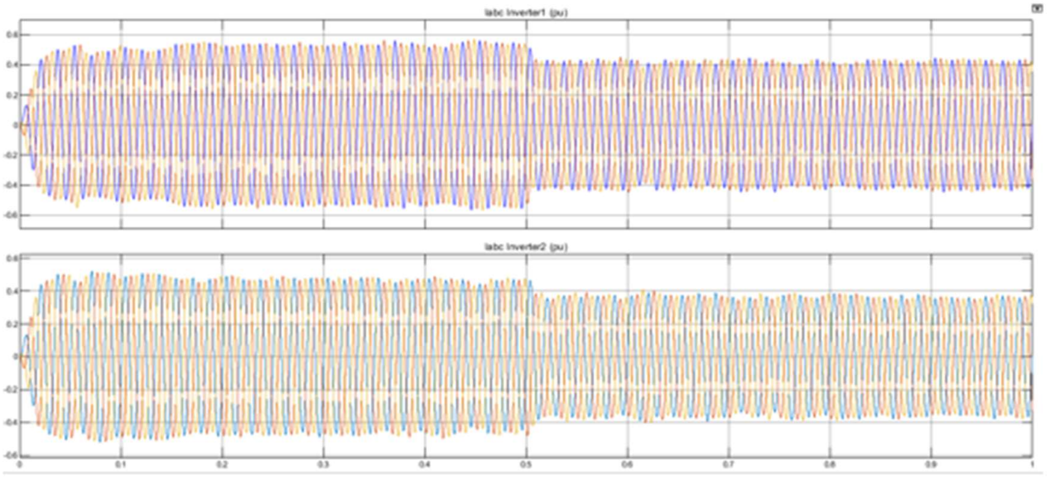


Figure 4.9 Variation of inverter output current after disconnecting the load

It can be inferred from the figure 4.9 that the sudden disconnection of load reduces the inverter output current from 0.5 p.u to 0.4 p.u. In this case, the power from the inverter decreases based on the load demand and power absorbed by the super capacitor. As a result the inertia reduces. The power sent to the grid is illustrated in figure 4.10.

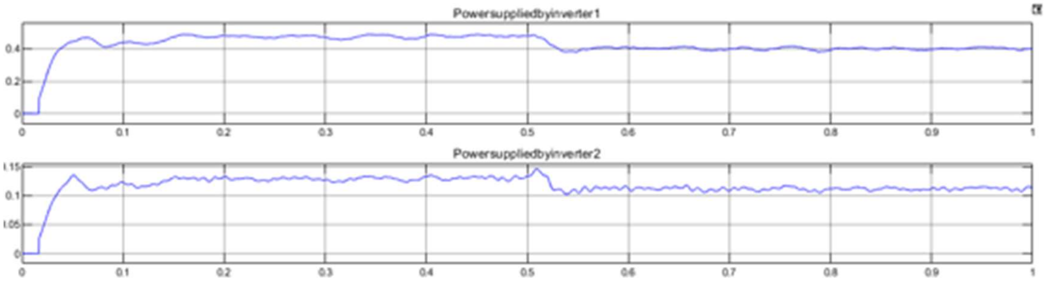


Figure 4.10 Power supplied by the inverter to grid after disconnecting the load

When the load is suddenly disconnected from the grid, there is a variation in the power supplied as observed from figure 4.10. However, the power supplied has constant perturbations and this is due to the variation in the load. The corresponding change in the output frequency is shown in figure 4.11.

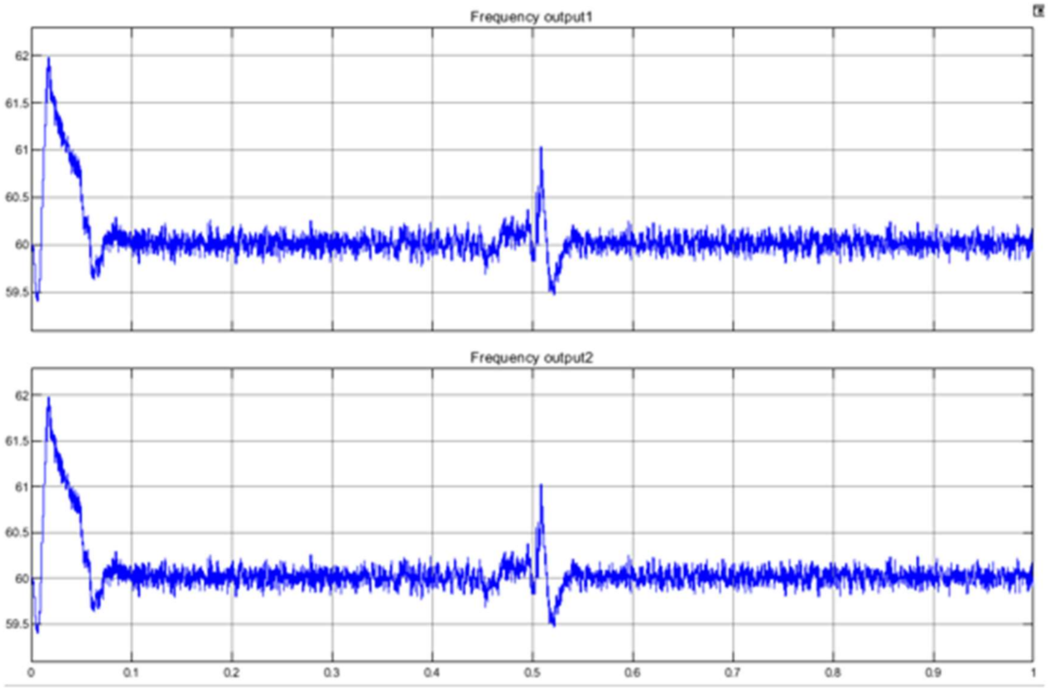
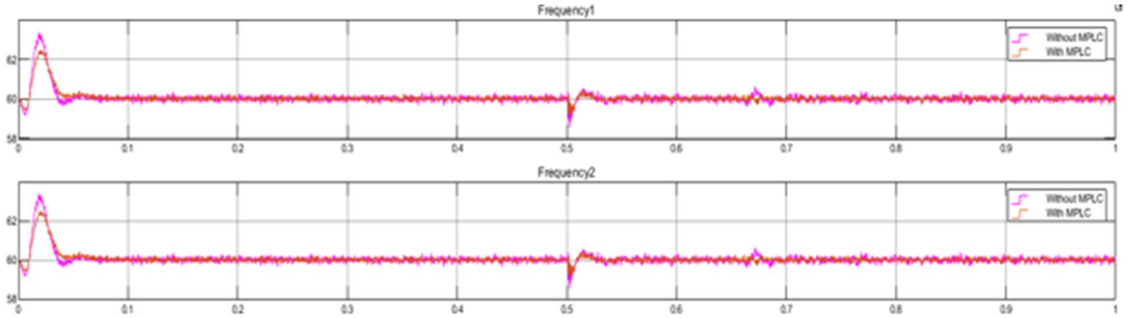


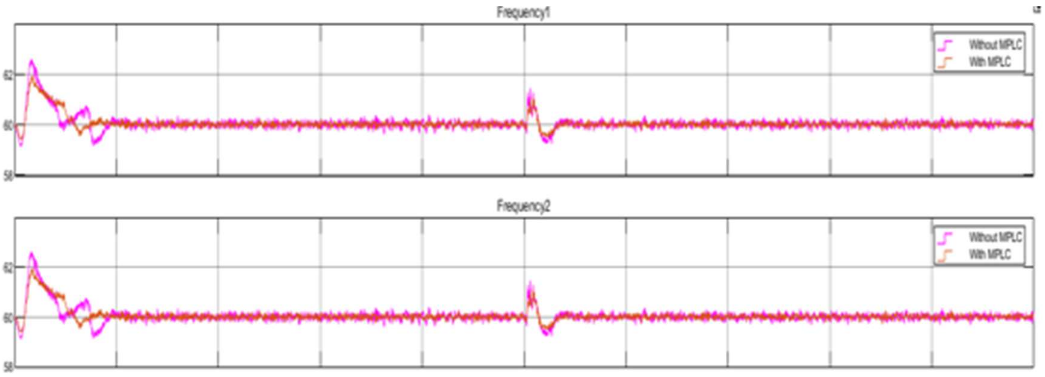
Figure 4.11 Frequency output after disconnecting the load

The output frequency of the grid system increases from 59.5 Hz to 61 Hz and again maintains the same frequency. This shows that, although there is a change in the load position, the frequency can be stable after sustaining small variations. The performance of the proposed approach with and without MPLC for sudden connecting load condition is illustrated in figures 4.12.



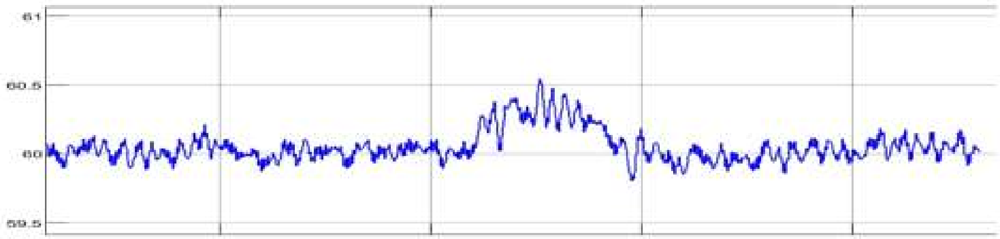
Frequency 4.12 Frequency response for sudden connecting load

For sudden disconnection of load, the performance of the proposed approach with and without MPLC is illustrated in figure 4.13.

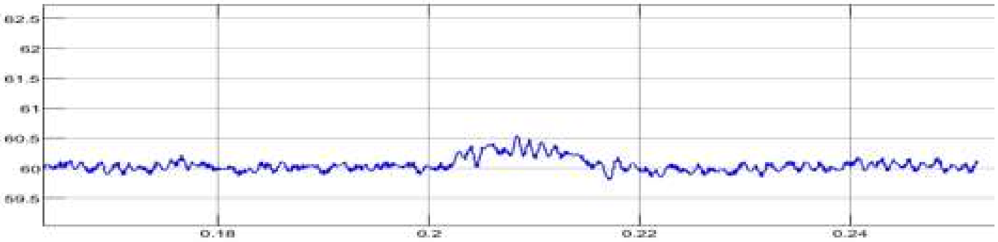


Frequency 4.13 Frequency response for sudden disconnection of load

As observed from figure 4.13, the variation in the frequency is controlled effectively with the proposed MPLC controller. Without MPLC, the frequency changes from 58.5 Hz during the inertia period and the variation in the frequency is greater than 1 Hz. Correspondingly, without MPLC, the frequency changes to below 59 Hz during the inertia period and the frequency variation is controlled below 0.8 Hz. In addition, the performance of the proposed approach is also evaluated with super capacitor and without supercapacitor as shown in figure 4.14.



(a) Without Supercapacitor



(b) With Supercapacitor

Figure 4.14 Performance graphs without and with supercapacitor

It can be inferred from the above the above graphs that the waveforms settle down after the frequency at delay after 0.22sec (without super capacitor) compared to below wave form settle down the frequency at faster before 0.22sec (with Supercapacitor)

5. Conclusion

The study proposed a VIC based MPLC controlling strategy for controlling the frequency variations in the grid connected RES system. The proposed design of the grid system was accompanied with an effective MPLC and MPPT strategy to enhance the performance of the grid system integrated with solar PV system and wind turbine. A P&O based MPPT approach is used for extracting maximum power under partial shading conditions. The performance of the proposed approach was validated from the simulation results which shows a stable control of frequency variation with the proposed control strategy. From simulation results, it can be validated that the better control over frequency with sudden connection and disconnection of loads is observed. For future work, this research intends to analyze the power quality management and compares the proposed control strategy with existing approaches to validate the effectiveness of the VIC based MPLC approach.

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