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A HYBRID METAHEURISTIC-SMC FRAMEWORK FOR SMART NANO-GRID CONTROL AND OPTIMIZATION

Javed Khan Marwat[*1], Salman Anjum[2], Muhammad Taha[3], Kiran Raheel[4], Zaheer Farooq[5], Ali Mujtaba Durrani[6], Shahzad Ahmed[7], Romaisa Shamshad Khan[8], Abdul Aziz[9],

[*1]*Executive Engineer Material Management, PESCO, Peshawar Electric Supply Company Peshawar, Pakistan.*
[2]*Department of Electrical Engineering, CECOS University, Peshawar, Pakistan.*
[3,4,5,6]*Department of Electrical Engineering, CECOS University of IT and Emerging Sciences, Peshawar, Pakistan.*
[7]*Department of Information & Communication engineering, Islamia University, Bahawalpur, Pakistan.*
[8]*Department of Electrical Engineering, NFC Institute of Engineering and Technology Multan, Pakistan.*
[9]*CECOS University of IT and Emerging Sciences, Peshawar, KPK; Pakistan*

[*1]engr.jade@gmail.com, [2]salmanlibra6@gmail.com, [3]m.tahakhan1999@gmail.com, [4]kiran@cecos.edu.pk, [5]zaheer@cecos.edu.pk, [6]ali@cecos.edu.pk, [7]shahzadkhan786123@gmail.com, [8]romaisa1khan@gmail.com,[9]abdulamiruet@gmail.com

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Corresponding Author: *
Javed Khan Marwat

Abstract

A nano-grid represents a compact, self-sufficient power system that integrates both renewable and conventional energy sources to ensure a continuous electricity supply. In this study, the nano-grid incorporates a photovoltaic (PV) array, a wind turbine, and a fuel cell as its primary power generation units. To maintain stability in both active and reactive power outputs, various control strategies are employed, including integral (I), proportional-integral (PI), proportional-derivative (PD), proportional-integral-derivative (PID), fractional-order PI (FOPI), fractional-order PID (FOPID), and sliding mode control (SMC). To enhance the performance of these control methods, advanced optimization algorithms, namely Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), have been applied. These algorithms are guided by the integral square error (ISE) criterion, which serves as the objective function during optimization. Comparative assessments, using both graphical plots and tabulated data, were conducted to evaluate each controller's efficiency and to determine the optimal configuration. Among all the tested controllers, SMC demonstrated the most effective performance in terms of maintaining power stability. It was able to bring the system output within 1.00% of the target power level in under 0.27 seconds. PSO consistently outperformed GA across different controllers in achieving faster convergence and better tuning results. Conversely, the FOPID controller, when optimized using GA, delivered the poorest performance, exhibiting a significant steady-state error of 6072.3W and noticeable overshoot and undershoot issues.

To further improve operational efficiency, an ingenious switching mechanism was introduced. This algorithm dynamically selects the most cost-effective and demand-responsive energy source, enhancing the economic viability of the nano-grid. A case study was also conducted, demonstrating the system's resilience: in the event of a fault in one of the generation units, the smart algorithm automatically rerouted *power from alternative sources to maintain uninterrupted supply to the connected loads.*

INTRODUCTION

Rising environmental concerns and the inefficiencies of conventional power grids drive the growing integration of sustainable energy sources into power systems. Traditional grids rely on long-distance transmission lines to deliver electricity from centralized generation stations to end users, which leads to considerable line losses and reduces the overall efficiency of the system. Another pressing issue is that approximately 1.2 billion people around the world still lack access to electricity. Most of these individuals live in rural or isolated areas, where expanding the traditional grid is typically considered uneconomical [1]. Addressing these societal, environmental, and financial challenges calls for innovative solutions, one of which is distributed generation. A promising approach within this context is the use of nano-grid technology—compact, independent power systems that utilize power converters to directly link renewable sources with distribution networks, forming self-sustaining energy systems.

Nano-grids are generally smaller than micro-grids, with typical capacities ranging from 7 kW to 40 kW, tailored to serve electrically isolated or remote areas. They can operate on both AC and DC systems, utilizing standard grid frequencies like 50 or 60 Hz, and depend on power electronic converters to effectively connect sources and loads. For example, boost converters enable low-voltage sources in a nano-grid to deliver usable power to the network, while bi-directional converters allow energy storage units to charge and discharge as needed [2]. Researchers have proposed various nano-grid architectures, with the core control challenge being the maintenance of power balance within the network, particularly in the presence of fluctuating renewable sources.

When beneficial, nano-grids may even operate at frequencies other than 50/60 Hz. In such cases, network voltage variations can be used to transmit control signals, making rigid voltage regulation unnecessary, as is common in power electronics-based networks. Just as transformers regulate voltage in traditional systems, interfacing converters in nano-grids can maintain desired voltage levels across a wide range of network fluctuations [3]. Maintaining this power balance remains the key challenge due to the stochastic nature of renewable generation. Control strategies are typically divided into demand-side and source-side management. Demand-side control modifies load consumption to align with available generation, disconnecting low-priority loads during shortages. However, relying solely on this method is impractical for nano-grids because the loads depend heavily on the unpredictable output of renewable sources.

Source-side control is therefore preferred, as it independently manages generation and storage. In this method, energy storage systems are charged during periods of excess generation and discharged when renewable sources underperform. Non-renewable generators are engaged only when prolonged shortfalls occur [4]. Some advanced systems combine source-side control with limited demand-side adjustments to reduce peak load demands and prevent non-renewable generators from being triggered unnecessarily.

Centralized control methods are a traditional approach in renewable-based systems, where a single controller gathers data from across the network and issues control decisions. These systems depend heavily on communication links and require redundancy to ensure reliability [5]. However, distributed control systems offer a more resilient alternative by spreading control functions across the network. In distributed systems, voltage levels within a DC grid can serve as communication channels, reducing reliance on external links. Simulation studies have shown that DC bus voltage levels can transmit load-side control data effectively in an optimized transmission network [6]. Nevertheless, implementing source-side control using voltage levels in non-ideal transmission networks is still a developing area.

Renewable technologies such as wind turbines and photovoltaics are particularly valuable in remote and off-grid areas, where connecting to the main grid is either too expensive or not feasible. Nano-grids provide an economical and reliable power solution for such locations by harnessing local renewable resources.

Literature on nano-grids has focused significantly on control strategies and hardware configurations. Various control algorithms and converter topologies have been explored [7][8]. The nano-grid controller enables coordination among multiple power sources and optimizes power production and consumption [2]. The two primary control strategies remain supply-side management (SSM) and demand-side management (DSM), with numerous topologies offering varied degrees of success. One common approach is centralized control, where a central unit collects sensor data and issues commands. This enables fast, system-wide response but suffers from a critical vulnerability: if the controller fails, the system can become non-functional [10][11].

Distributed control models aim to overcome this limitation by decentralizing decision-making. Each node or component includes its own controller and communicates with neighboring nodes, thereby forming a cohesive strategy without depending on a single control point [12][10]. A hybrid approach enhances this model further by using DC supply lines to communicate control data, eliminating the need for additional communication infrastructure [13]. One study presented a partially distributed architecture using GSM-based peer-to-peer electricity sharing through power management units [14]. Another study proposed a PV-battery centralized generation model with distributed storage at the household level [15]. Distributed control combines features of both centralized and decentralized systems and allows each node to execute its portion of a shared control law [16]. This approach ensures system operation even when some nodes fail, enhancing overall resilience [17-18].

Hybrid hierarchical topologies also exist, blending centralized planning with decentralized execution. In such systems, decentralized control manages immediate source-level decisions, while centralized control handles longer-term strategies [19]. Though it involves additional cost due to redundant controllers and communication systems, this method provides a balanced trade-off between performance and reliability [20-21-22]. In contrast, decentralized control is cost-effective and reliable but lacks the capability to schedule generation. Distributed control offers the best potential for supply-side management, combining flexibility with reliability [23][24].

With growing concerns around energy consumption and climate change, energy management systems (EMS) have become vital. Building EMS (BEMS) focuses on large-scale energy use such as air conditioning and lighting, while Home EMS (HEMS) targets efficient control of household devices [25-26]. However, controlling household energy use is difficult due to the variability of consumer behavior. Stand-alone management of individual homes often has limited impact because of the narrow control margin. To address this, integrated multi-household energy management has been proposed [27]. One example is KNIVES, a distributed DSM system developed by Keio University, which utilizes smart circuit breakers and cooperative control algorithms [28]. Other DSM solutions include classification and control strategies for residential appliances aimed at energy savings and cost reduction [29].

Regarding transmission frequency, increasing the operational frequency of nano-grids to 400 or 500 Hz has been proposed due to the advantages it offers in reducing the size and weight of magnetic components. This concept is already applied in aircraft power systems operating at 400 Hz [30]. Such high frequencies can reduce emissions and make the network more economically viable by lowering equipment costs [32]. However, these benefits come with trade-offs. Line reactance increases significantly at higher frequencies, demanding more reactive power support [33]. Moreover, higher frequencies result in greater skin effect and dielectric losses, lowering transmission efficiency. PWM inverters used at 500 Hz also incur higher switching losses compared to 50 Hz systems [34]. To maintain similar performance, the switching frequency must be seven to ten times that of traditional systems. Nonetheless, operating nano-grids at medium AC frequencies retains some benefits of conventional 50/60 Hz systems, such as simplified voltage transformation and improved fault interruption capabilities [35].

All the DC powers are fed to a common point called a DC bus. The DC bus has a constant DC voltage because the inverters operate on a constant input voltage. Therefore, it needs to boost the output voltage of each DC source (battery, SC, fuel cell, and PV) to a standard value (i.e., 700V). The DC-DC converter model is shown in Figure 1.

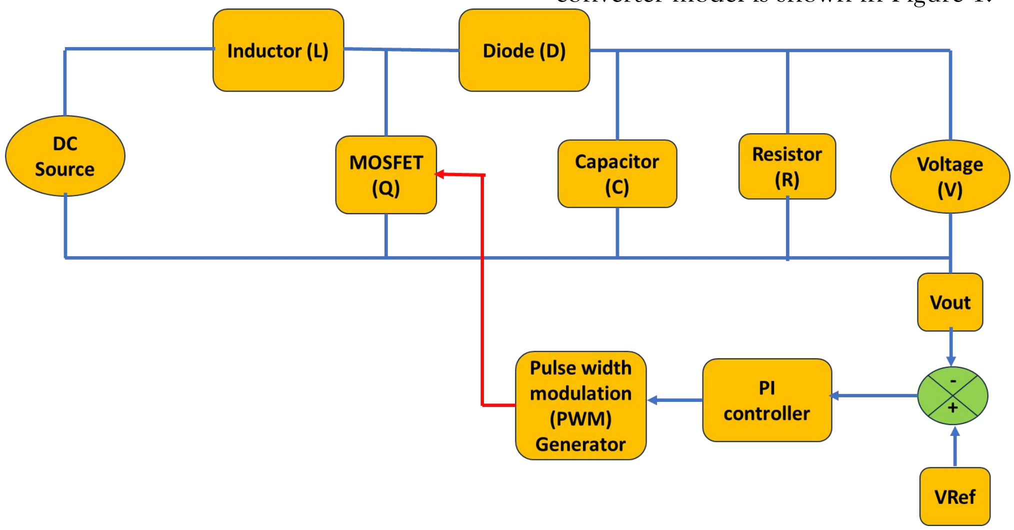

Figure 1: DC-DC Converter Model

The above model can be described with two state space equations [36].

$$\frac{dX_1}{dt} = \frac{1-k}{LX_2} + \frac{k}{LU}$$
$$\frac{dX_2}{dt} = \frac{k-1}{CX_1} - \frac{X_2}{RC} \quad (1)$$

The output voltage converter is measured and compared with a reference voltage. An error is given to the PI, and then the pulse generator generates the desired PWM signal.

The primary challenge addressed in this research is the delivery of uninterrupted power from a nano-grid to local loads while ensuring high power quality and system stability. This requires the optimization of various controllers using intelligent algorithms that can effectively regulate voltage, current, and frequency through diverse control strategies. Given the increasing integration of renewable energy sources and the need for decentralized, efficient energy systems, nano-grids offer a promising solution for isolated or rural regions where traditional grid expansion is not economically feasible. The aim of this research is to satisfy the energy demand reliably by designing and implementing an optimized control system that employs intelligent algorithms to enhance the stability and reliability of the nano-grid. Using Simulink/MATLAB, the proposed system is developed to be more robust, efficient, and capable of intelligent energy management compared to conventional systems. The effectiveness of the system is demonstrated through comparative analysis with multiple controllers, validating its improved performance in meeting load demands under varying conditions.

1. Literature review

1.1 CONTROL OPTIONS OF NANO-GRID

The main challenge in nano-grid systems is maintaining energy balance amid variable loads and fluctuating renewable energy sources. Supply-side control plays a key role in this by managing generation sources to ensure reliable power delivery. This involves scheduling power sources to minimize operating costs and maximize renewable energy usage, which is cost-effective due to its negligible fuel cost. Surplus renewable energy is stored in backup systems, and when renewable supply falls short, energy is drawn from these storages. If both are insufficient, backup generators are activated. Various control topologies manage these energy sources, with their suitability based on modularity, reliability, and economic efficiency. The core topologies are centralized, decentralized, distributed, and hybrid.Centralized control relies on a single controller that monitors the entire system, performs calculations, and adjusts all sources accordingly. It simplifies implementation and supports dynamic changes in operation. However, it is vulnerable to single-point failures and requires high-bandwidth communication, making it less reliable. Decentralized control allows each source to operate independently based on local data, enhancing speed and reliability by eliminating dependency on a central unit. In DC systems, it uses voltage droop control to manage power sharing, while AC systems use frequency and voltage droop for active and reactive power sharing. However, this method can introduce steady-state errors and lacks coordination between sources, making it unsuitable for supply-side energy management. Distributed control blends centralized and decentralized approaches. Each local controller communicates with others to coordinate operations, enabling supply-side management without relying on a single controller. Although it offers improved flexibility and reliability, it still requires external communication links, which can add cost and complexity. Hybrid control combines the advantages of different topologies. Hybrid centralized control uses a hierarchical system where decentralized control manages local sharing, while a central controller handles broader network management. It improves performance and supports source-side management but still depends on communication links and a central controller. Hybrid distributed control distributes control among sources, using the power bus for communication instead of external links. It provides the reliability of decentralized systems while enabling coordinated energy management. This method reduces implementation costs and avoids the need for extra hardware, though it may suffer from signal degradation due to line impedance. Applications include PLC-based systems and DC networks with built-in droop-based load prioritization.

When comparing topologies, no single method offers all the ideal traits. Centralized control delivers high performance but lacks reliability. Decentralized control is reliable and cost-effective but poor in coordination. Distributed control balances both but depends on communication links. Hybrid centralized control achieves performance and flexibility at a higher cost, while hybrid distributed control emerges as the most practical option—offering coordination, reliability, and cost efficiency without external communication or central controllers. Thus, it is preferred for nano-grids, especially in systems where dynamic changes in control strategy are not frequent.

Optimization and Its Role in Real-Life Applications

Optimization is a branch of mathematics that aims to determine the conditions that provide the extreme value (minimum or maximum) of a function or multiple functions. In simpler terms, optimization is about finding the best possible solution in a given scenario. This concept is crucial across many fields, including mathematical programming, scientific operations, economics, management science, business, medicine, life sciences, and artificial intelligence. Optimization seeks to improve efficiency, performance, and decision-making, addressing real-life challenges in these domains.

Find X = (x1; x2; . . .; xn) which minimizes fi(X) i=1; 2; . . .; no

subject to: (or maximizes)

$$g_j(X) \le 0, \qquad j = 1,2,3\ldots., n_g$$
$$H_k(X) \le 0, \qquad k = 1,2,3\ldots., n_e$$
$$H_m^1 \le x_m \le x_m^u, \qquad m = 1,2,3\ldots., n_s$$

The velocity and position of the particles within the search space are calculated as follows [106, 109]:

$$V_{ij}(t+1) = \omega x_{ij}^k(t) + c_1 r_1 \left(p_{ij}^k - x_{ij}^k\right) + c_2 r_2 \left(g_{ij}^k - x_{ij}^k\right)$$
$$x_{ij} = x_{ij} + v_{ij}(t+1)$$

Increasing the PSO convergence factor could be stated as follows:

$$v_{id} = X(v_{id} + c_1 * \text{rand} * (p_{id} - x_{id}) + c_2 * \text{rand} * (p_{gd} - x_{id}))$$
$$x = \frac{2}{\left|2 - \varphi - \sqrt{\varphi^2 - 4\varphi}\right|}$$

The block diagram as shown in figure 2 shows a closed - loop system with such a direct-path PID controller which is the normal relation. The output for the system would obey the reference signal (setpoint) as closely as possible. The PID controller, as shown in figure 3, is characterized by three gains

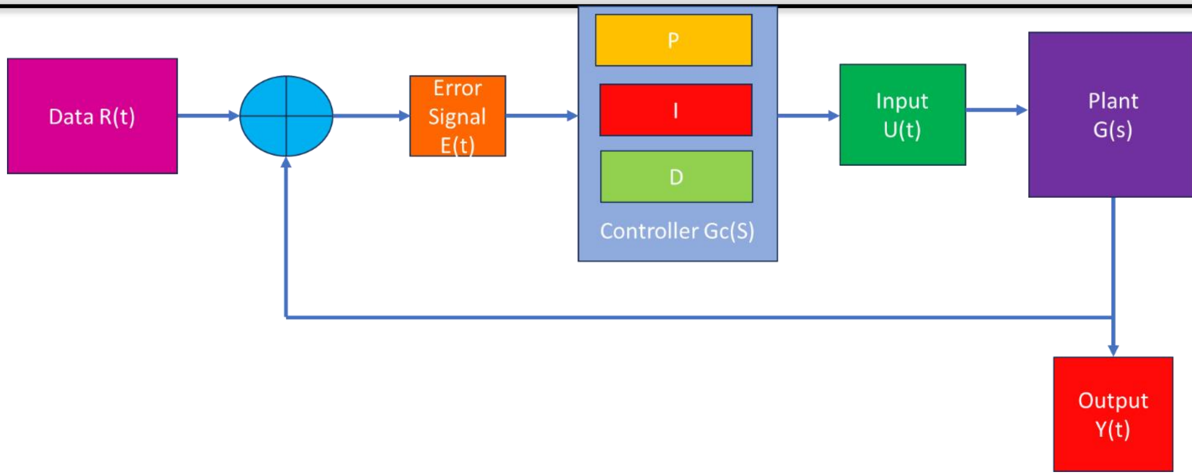

Figure 2: PID control

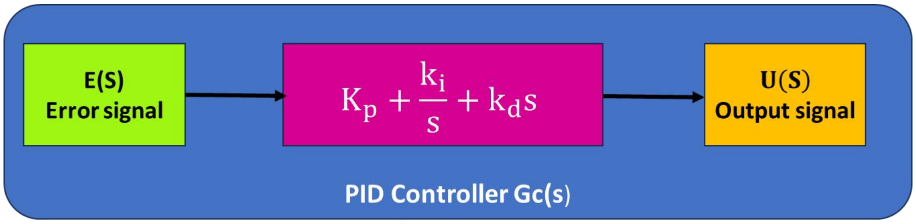

Figure 3 PID controller internal structure

The relationship between the PID controller input E (error signal) and output U (input to the plant) can be expressed in the frequency domain by means of the following transfer function:

$$G_c(S) = \frac{U(S)}{E(S)} = K_p + \frac{k_i}{s} + k_d s$$

The closed-loop transfer function Gg(s) is given by

$$G_g(S) = \frac{Y(S)}{R(S)} = \frac{G_c(S)\, G(S)}{1 + G_c(S)\, G(S)}$$

2. Mehtodolgy

Market volatility, the unpredictable depletion of fossil fuels, deregulation of electric utilities, technological advancements, environmental concerns, and the availability of electrical power have created a pathway for transitioning the energy landscape towards Distributed Generation (DG) systems powered by renewable energy sources. Nano-grids present an effective solution to address issues associated with deregulation and power instability. A hybrid nano-grid, integrating renewable energy sources such as wind turbines (WTs), fuel cells (FCs), photovoltaic systems (PVs), and biomass, offers a sustainable energy approach for these systems. However, utilizing renewable energy sources and storage systems in nano-grids comes with several challenges. Wind turbines rely heavily on weather conditions and require locations with consistent and strong winds. Photovoltaic systems are highly weather-dependent, failing to generate power at night or during cloudy conditions, and they lack the ability to store energy for later use. Fuel cells have limitations such as slow startup times and insufficient responsiveness to sudden changes in power demand. Batteries, with their low power density, are unable to cope with instantaneous demand changes, while supercapacitors, despite their fast response, offer low energy density and cannot supply power for extended periods, with rapid load fluctuations potentially damaging them. To overcome these challenges, a hybrid nano-grid combining these energy sources is proposed. The primary control challenge of nano-grids is maintaining power balance in the face of fluctuating loads and generation. A supply management system is needed to prevent loads from being disrupted by variations in renewable energy output. This system plans the utilization of available sources in a way that minimizes operational costs, maximizes renewable energy use, and ensures backup storage devices are charged with excess energy. In situations where renewable energy generation is insufficient, backup storage devices are used, and if these are exhausted, backup generation systems come online. Various control strategies can be employed, with the key selection criterion being the system's ability to manage sources based on control laws, while maintaining system modularity, reliability, and cost-effectiveness for a distributed network.

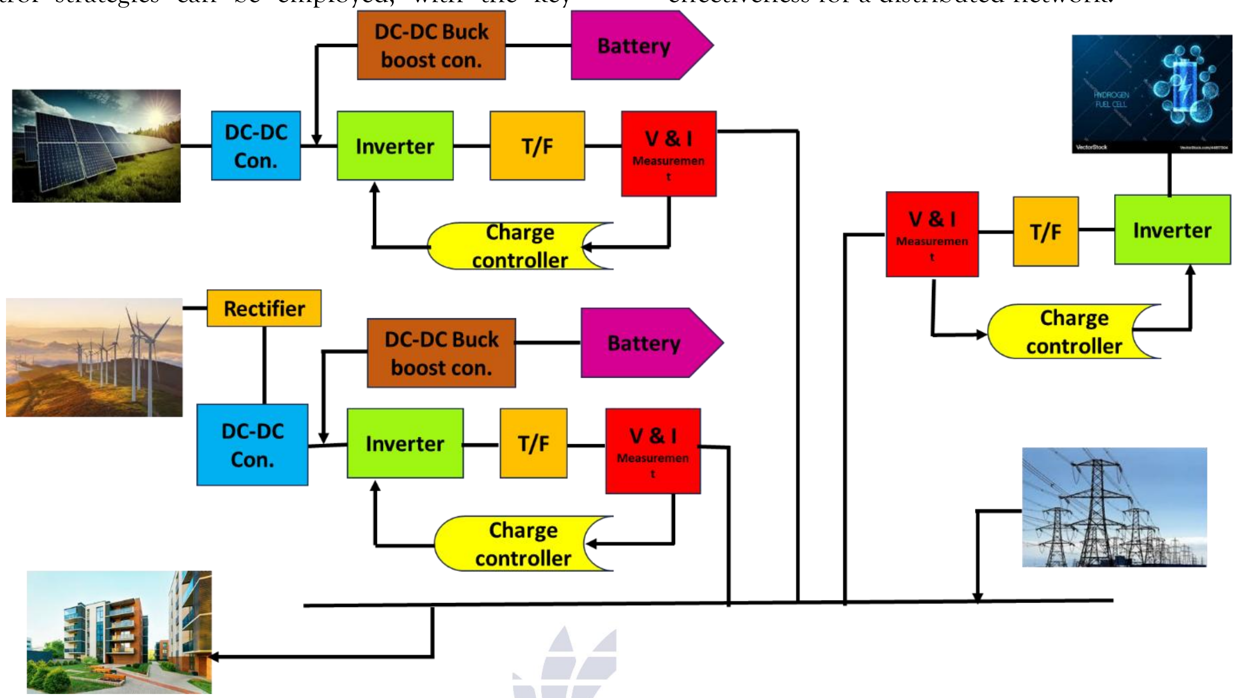

Figure 4: Block diagram of nano-grid

Figure 4 illustrates a system where three sources are interconnected at an AC bus. The photovoltaic (PV) array consists of 23 parallel strings, each with 5 series-connected modules. The maximum power extractable from a single cell is 305.226W, which leads to a total PV array capacity of 35KW. However, only 20KW is being extracted. The PnO Maximum Power Point Tracking (MPPT) technique is applied to the PV array. The system incorporates two types of converters. The first is a Buck-Boost converter, which is connected to the storage batteries. The Buck converter stores power in the batteries when the PV array is not generating power, while the Boost converter extracts power from the batteries and feeds it to the inverter to meet the load demand. The next stage uses a DC-DC Boost converter to step up the voltage from the PV array.

The second energy source in the nano-grid is a wind turbine, generating 20KW with a power factor of 0.8, producing around 12KW of reactive power. The wind speed varies, as in real-world conditions, and a three-phase Permanent Magnet Synchronous Generator (PMSG) is coupled with the wind turbine. The generated AC power is then rectified to DC, smoothing the power for storage in batteries using the Buck-Boost converter, which can be used when the other sources are unavailable.

The third source is a Solid Oxide Fuel Cell (SOFC), selected for its high efficiency of 65%. SOFCs directly convert chemical energy into electrical energy, with the byproduct being high-temperature steam, which can be utilized for other purposes. However, the SOFC has a slow response time. The DC power produced by the fuel cell is fed into a DC bus, which maintains a constant DC voltage to ensure proper operation of the inverters. The output voltage of the fuel cell needs to be boosted to a standard level, typically around 700V.

A Hybrid Power System (HPS) is defined as the integration of multiple renewable and non-renewable energy sources to provide continuous power. The most reliable primary energy source for an HPS is the photovoltaic module. Since each renewable energy source has a different power supply pattern, integrating two or more sources ensures a

continuous and uninterrupted power supply to the load.
Batteries are an effective energy storage solution, providing long-lasting power. When integrated into a hybrid power system (HPS), they enhance the system's reliability. Similarly, the integration of supercapacitors with an HPS improves efficiency during transient load fluctuations. However, relying solely on batteries or supercapacitors as primary sources can be costly, as it requires large storage capacities. It is more economical and practical to use them during peak demand periods, rapidly changing loads, cloud cover in the case of photovoltaic arrays, or when there is no wind for wind turbines. This approach ensures that energy storage systems are utilized efficiently without incurring high costs for large-scale storage.

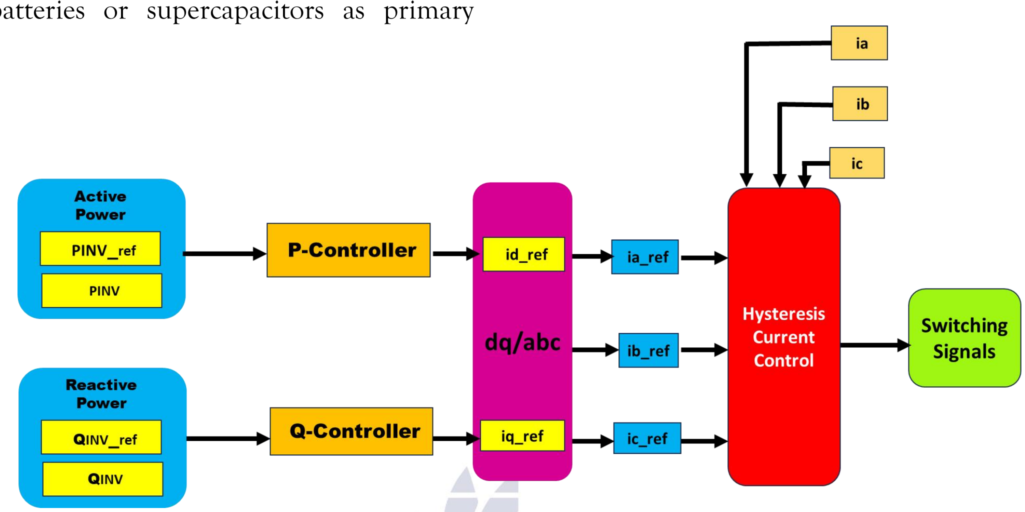

Figure 5: Inverter topology

Figure 5 presents the block diagram of the inverter topology, where various controllers with different algorithms are simulated and compared to determine the most effective controller for optimizing power in the system. In this topology, controllers such as I, PI, PD, PID, FOPID, FOPI, and SMC, along with Particle Swarm Optimization (PSO) and Genetic Algorithms (GA), are implemented. The output results are then compared both in tabular and graphical formats, as shown in the following section.

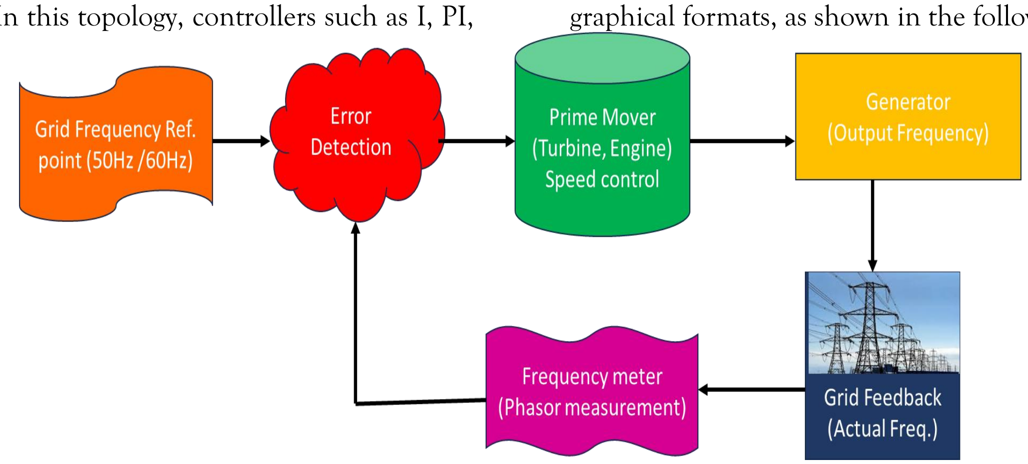

Figure 6: Block diagram of frequency control

Figure 6 illustrates the block diagram of the proposed frequency control system, which integrates a PID controller with automatic gain control to adjust the PID controller's gains over time and varying conditions. The model connects three different power sources to an AC bus, with a variable load, and includes a utility grid. Each primary source is linked to backup storage and a backup line that interconnects the source wings. In case of a fault in any source, the backup line prevents grid overload,

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and intelligent switching ensures that power is supplied from other sources during the maintenance period. Given that renewable energy sources depend on weather conditions, storage devices are in place to provide uninterrupted power to the load. Since this is a grid-connected nano-grid, power management is crucial; if a source cannot meet the load due to adverse conditions, the utility grid will be activated to supply power.

The main challenge in Hybrid Power Systems (HPS) is power distribution. With multiple renewable and non-renewable sources, proper energy distribution is necessary to avoid power quality and stability issues. A reliable Power Management System (PMS) ensures continuous, stable, and high-quality power delivery. Existing literature has proposed PMS for standalone hybrid power systems, with PV and wind as primary sources and fuel cells and battery banks as backups. The hierarchy of power sharing, as shown in Figure 4, prioritizes power from PV and wind turbines, controlled by MPPT. When there is surplus power, it is used to charge batteries and supercapacitors. When there is a power deficit, wind turbines, batteries, supercapacitors, and fuel cells compensate for the shortage, with the utility grid acting as the final backup during peak hours.

This chapter provides an in-depth explanation of the operation and control of each load and source wing in the proposed hybrid nano-grid. Power management is a critical issue in nano-grids, as discussed earlier. The role of each source wing and the interconnection with backup lines are described in detail, explaining their function during faults. Additionally, the power management system is thoroughly discussed to ensure efficient and reliable power distribution across the nano-grid.

3. Results

The proposed hybrid nano-grid consists of three sources, as described in the previous sections. The first source is the photovoltaic (PV) array, with a capacity of 20KW, serving as the primary power source for the hybrid nano-grid. The power generated by the PV array depends on solar irradiance and atmospheric temperature, but in this proposed model, ideal conditions for irradiance and temperature are assumed. Figure 7 shows the reference real power of 20KW along with the output real power generated by the PV array.

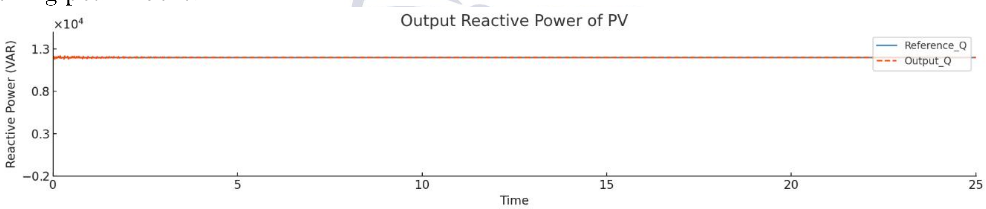

Figure 7: Output reactive power of PV with reference

The peak-to-peak voltage VP-P is the voltage waveform measured from the top of the waveform (called the crest) to the bottom of the waveform (called the voltage drop). Therefore, the peak-to-peak voltage is only the entire vertical length of the top-to-bottom voltage waveform. The Vp-p of PV module is shown in Figure 8.

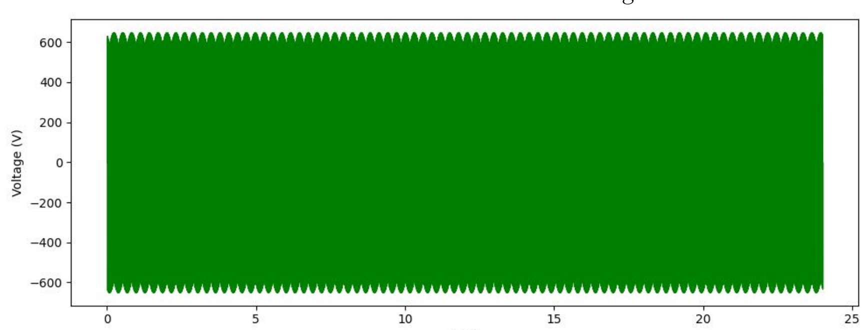

Figure 8: Vp-p of PV source

Peak-to-peak (p-p) mentions to the difference between the highest positive amplitude and the lowest negative amplitude in the waveform. For an alternating current (AC) wave without a direct current (DC) component, the amplitude pk-pk is twice the amplitude of the positive peak. In the case of an AC sine wave without a DC component, the peak-peak amplitude is approximately 2.828 times the mean square amplitude. The peak-to-peak current of the PV source is shown in Figure 9.

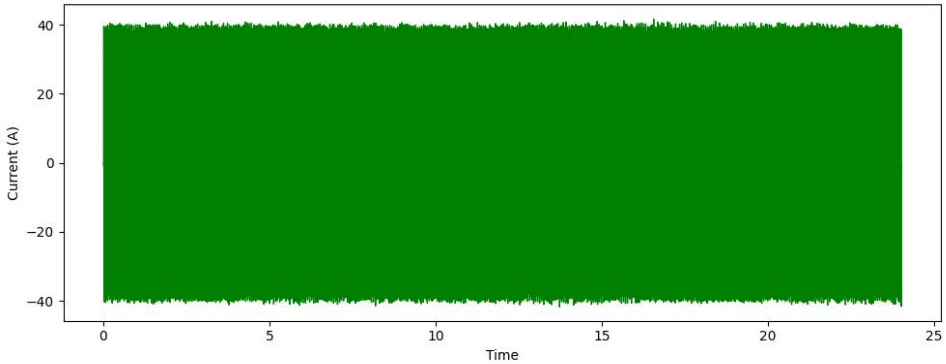

Figure 9: Ip-p of PV source

The second primary source of proposed nano-grid is wind turbine. From the optimized controllers and algorithms sliding mode controller provides the optimized controlled power and having the least steady state error and least settling time in comparison with other controllers there are transients in other controller's output. The wind turbine is secondary source of hybrid nano-grid. It generates the 20KW of real power that is shown in Figure 10.

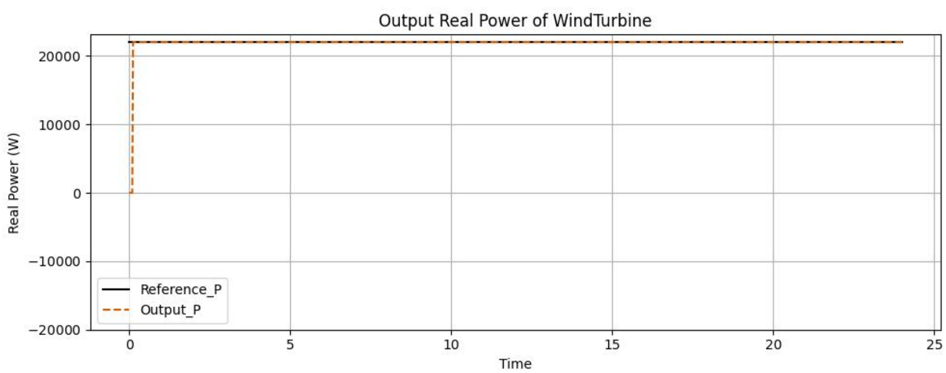

Figure 10: Real output power of Wind with reference

Wind turbine is the secondary source of generation. The inverter control of wind turbine is using the sliding mode control followed by hysteresis current control scheme. The output reactive power of wind turbine is continuous with least settling time and steady state error with reference power of that source which is shown in Figure 11.

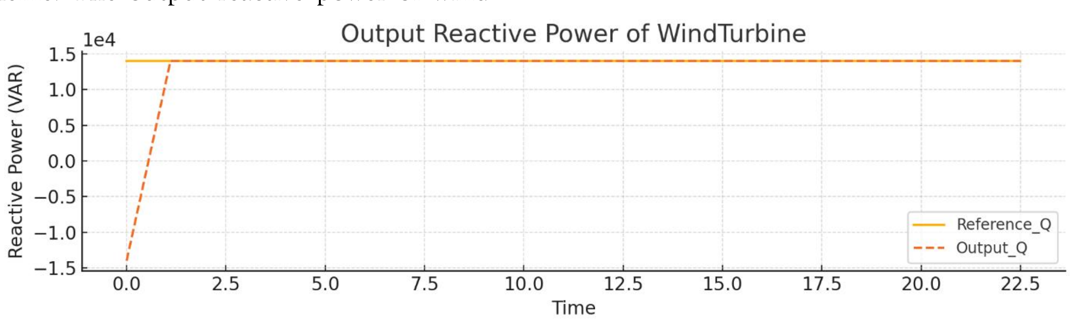

Figure 11:Reactive output power of wind turbine with reference

As peak voltage is one half cycle is called positive half cycle and negative half cycle is another half cycle. The combined positive half cycle and negative half cycle is called one complete cycle. Here the max voltage OR peak voltage at positive half cycle and max voltage OR peak voltage at negative half cycle is called peak-to-peak voltage. The peak-to-peak voltage of wind turbine is shown in Figure 12.

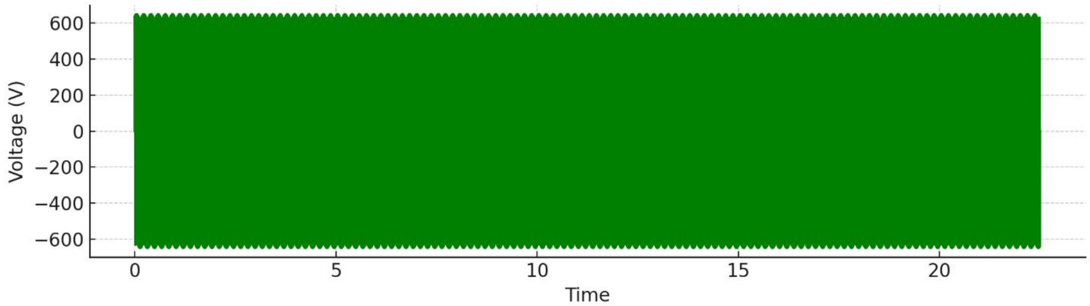

Figure 12: Vp-p of wind turbine

Peak-to-peak values are usually used to measure current, power and voltage. The peak-peak amplitude of the signal is sometimes confused with the peak amplitude. These are two different, because the peak amplitude provides only the highest positive peak of the waveform, while the peak-peak amplitude describes the total difference between the top and bottom of the observed wave. The peak-to-peak current of the wind turbine is shown in the Figure 13.

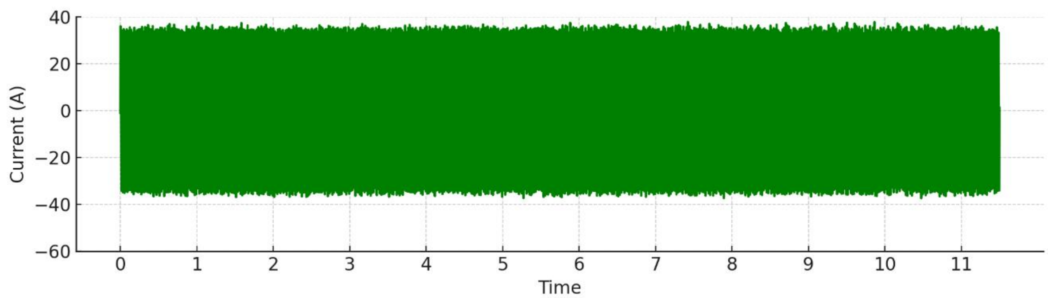

Figure 13: Ip-p of wind turbine

Fuel cell is the third source of proposed hybrid nano-grid. The fuel cell is the tertiary source in switching smart algorithm that if the demand of load is exceeding from the generation of primary and secondary source of wind turbine than the fuel is switched in to provides the power to load. The fuel cell has the fuel flow rate controller having installed PID to controller flow rate of fuel towards the fuel cell by sensing the changing of current. The flow rate of fuel in fuel cell varies from 1ml/min to 81ml/min. Sensing the current and changing flow rate of control can control the transients of the system. The inverter control of the nano-grid has installed a sliding mode control and gives the optimized output power. The generation of real power is 20KW of the fuel cell which is shown in Figure 14.

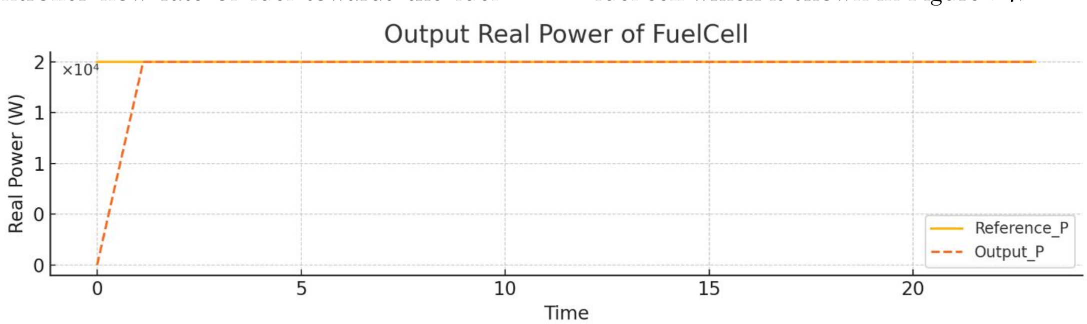

Figure 14: Real output power of fuel cell with reference

The optimized controller which is sliding mode control can minimize the error and control the output power of fuel cell and gives the optimized output power towards the load. The sliding mode controller control the real and reactive power having least steady state error and transient in the output power. The output reactive power of fuel-cell source is 12KW (11973W) shown in Figure 15.

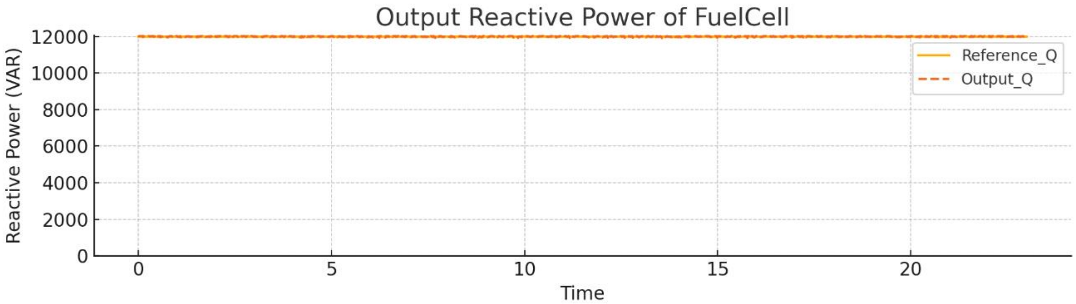

Figure 15: Reactive output power of fuel cell with reference

The peak-to-peak voltage VP-P is the voltage waveform measured from the top of the waveform (called the crest) to the bottom of the waveform (called the voltage drop). Therefore, the peak-to-peak voltage is only the entire vertical length of the top-to-bottom voltage waveform. The Vp-p of PV module is shown in figure 16.

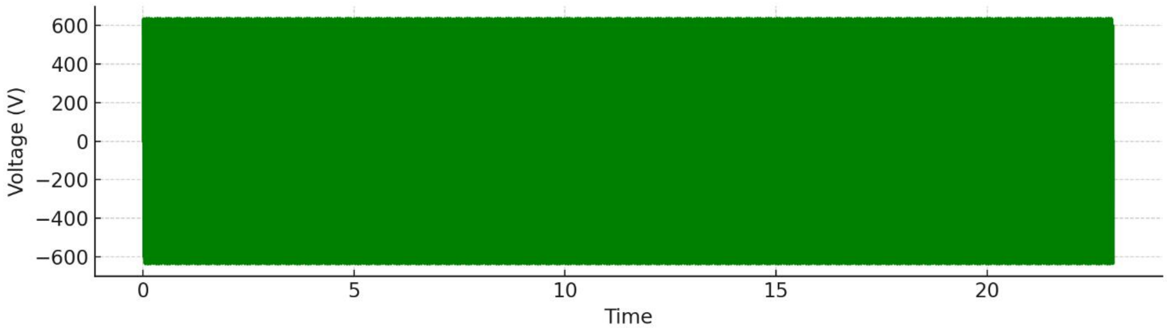

Figure 16: Vp-p of fuel cell

Peak-to-peak (p-p) mentions to the difference between the highest positive amplitude and the lowest negative amplitude in the waveform. For an alternating current (AC) wave without a direct current (DC) component, the amplitude pk-pk is twice the amplitude of the positive peak. In the case of an AC sine wave without a DC component, the peak-peak amplitude is approximately 2.828 times the mean square amplitude. The peak-to-peak current of the PV source is shown in Figure 17.

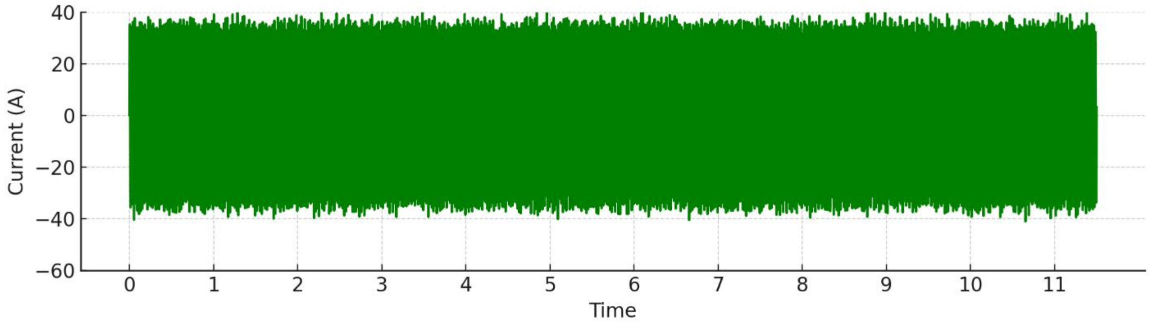

Figure 17: I_{p-p} of Fuel cell

The load is variable that the demand of load is changing hourly. The load which is attached with AC bus is variable that the demand of load is started from 15KW and it changes with every hour and approaches at the peak demand of load is around 58 KW that is why the smart switching is considered that will connect or disconnect the sources towards the load according to the demand of load. The load curve or the demand of load with time is shown in Figure 18.

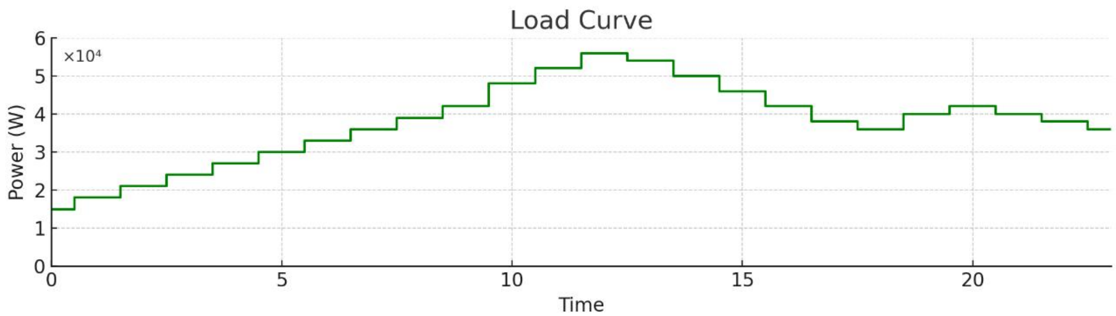

Figure 18: Load Curve of the connected load

The sources are connected with load via smart switching algorithm and three phase voltage controllers. The purpose of smart switching algorithm is connecting the sources with load according to its demand. When the demand is low from smart switching algorithm only one source is connected and the others sources will connect with the load when the demand of load is exceeds from the rating of that source. This algorithm connects from one source to three sources with load through algorithm. The real power of load with reference is shown in Figure 19.

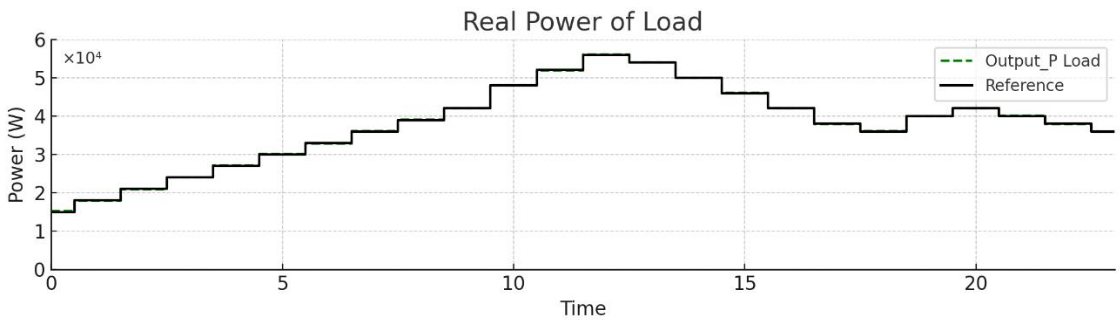

Figure 19: Output Real power of Load

The output reactive power of load is also changing hourly according the demand of load and real power of load the optimized output of the sources are satisfying the load through smart switching sources. The reactive power of load is shown in Figure 20.

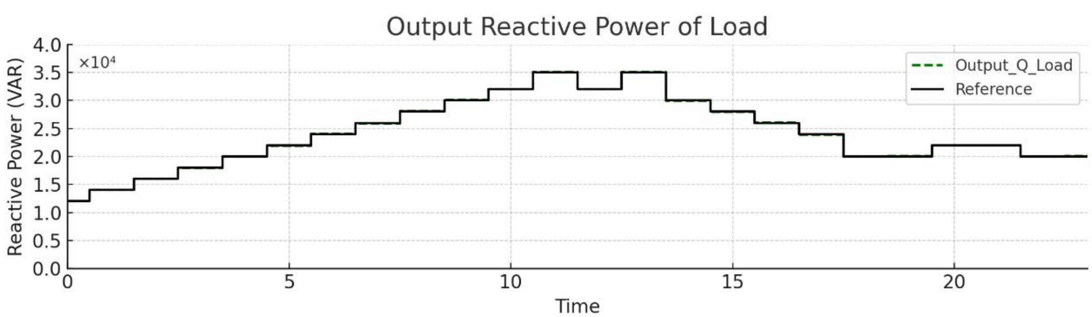

Figure 20: Output Reactive power of Load

The demand of load is changing with time that every hour the demand of load is changes. When the demand of load is changes the consumption of power from the sources to load changes it has effects on the current voltage and frequency. When the demand of load or consumption of power from the sources to load is changes the current changes according to the increasing or decreasing demand of load. The changing peak to peak sinusoidal current of load is shown in Figure 21.

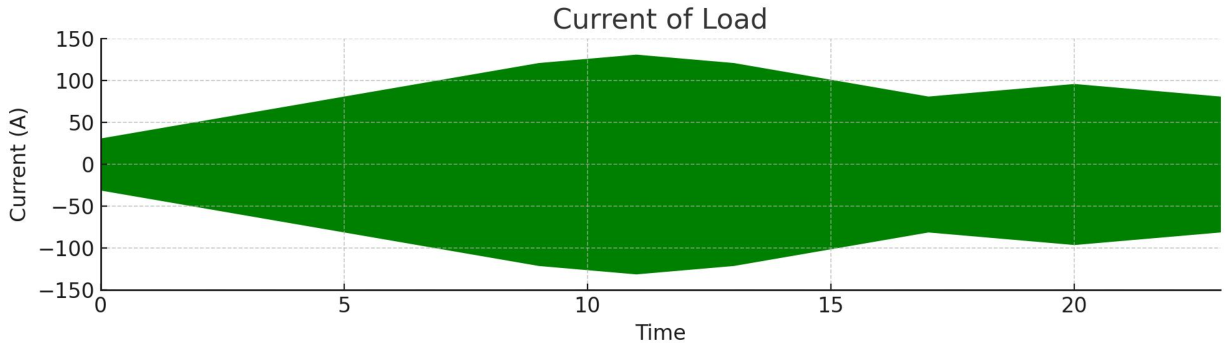

Figure 21: Ip-p of Load

The steady-state current flowing through a resistance of a known resistance within a given time. If the heat generated by the alternating current flowing through the same resistance in the same time is the same, the current is called RMS or actual value of the alternating current. AC and DC waveforms can represent voltage or current waveforms, but their shapes are different. AC waveform periodically oscillates between positive and negative voltage. This is why the RMS value of current and voltage is shown to compare with standard. The Irms of load is shown in Figure 22.

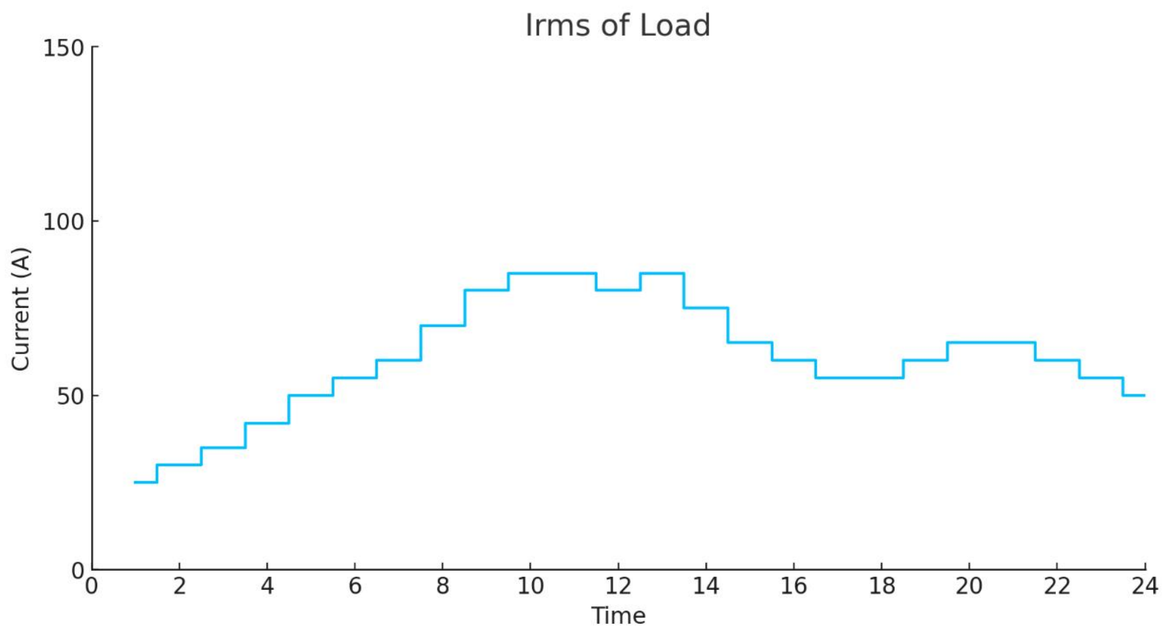

Figure 22: Irms of load

The frequency is the important parameter of the system that when the demand of load changes it has effects on the frequency as well. The transient in the frequency shows the changing of load that is why the frequency controller is used to control the frequency in case of changing load the frequency of system should not have transients in it. The steady state is reached after 0.096s and the variations at that time are within 0.1% of the desired frequency, which is within acceptable limits of the applied constraints. The frequency of system is shown in Figure 23.

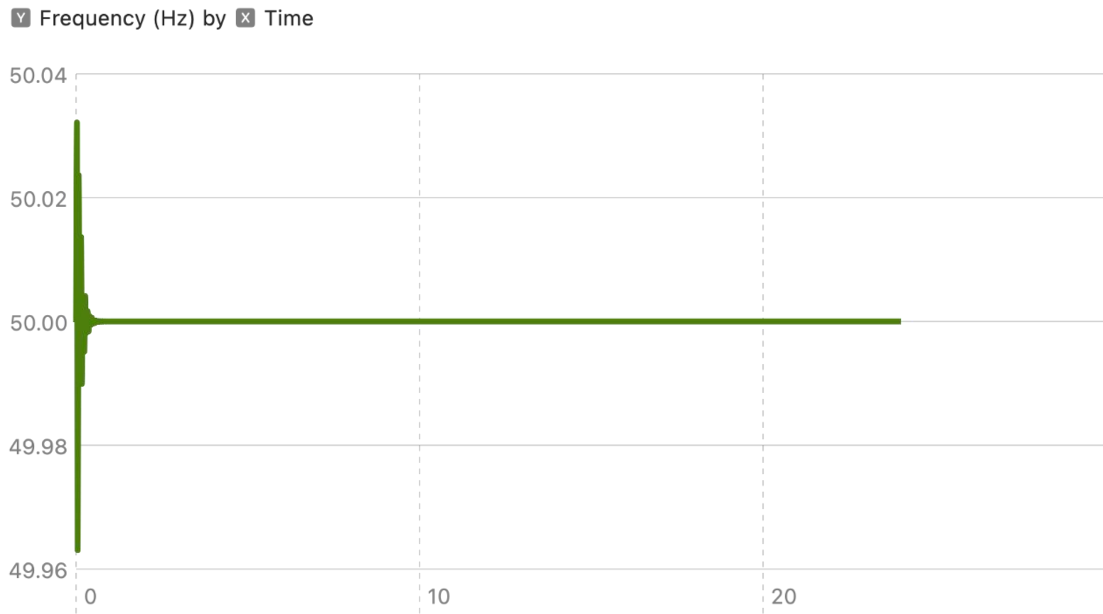

Figure 23 : Frequency of Load

Three phase voltage controller is utilized at the load end that when the demand of load changes the level of voltage should not exceeds or decrease from its level that is why the PID controller is used to minimize the error and keeps the voltage at its level to save the sensitive load. The RMS voltage of the load is shown in Figure 24.

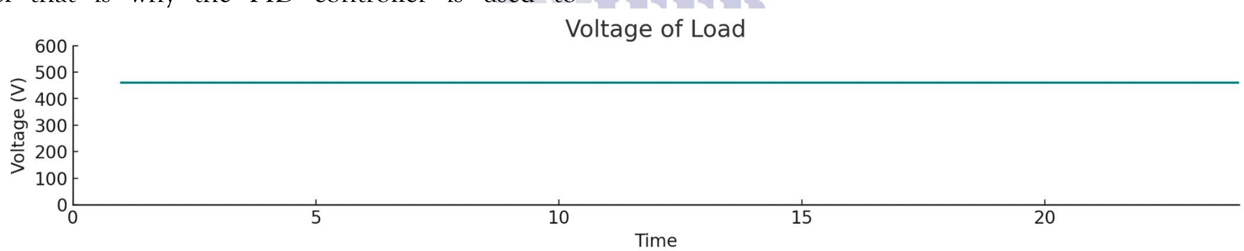

Figure 24: Voltage of Load

Proposed Power Management System Results

The proposed power management system for the hybrid nano-grid was discussed in previous chapters. This chapter contains the results of power management in the hybrid power nano-grid. The results include different currents, voltages and powers at various levels. According to $P_{PV} + P_{WT} + P_{FC} = P_{load}$ Which is the first deficient equation of power in which no surplus power is provided to storage devices?

In the proposed hybrid nano-grid topology, every source generates power of 20 kw. If one source of the system is turned off due to a fault, the system now has only two remaining sources generating power. Now the load demand is increased because one source of the system is not generating power, backup lines are utilised to prevent a blackout of the whole system, and the utility grid is brought online to maintain the power balance and fulfil the remaining demand of loads.

Figure 25- 26 shows that the primary source of system PV is turned off due to a fault or switching algorithm at 6 hours and turned on at 7 hours. During that time, the intelligent switching will have done its work to switch the sources according to the load demand.

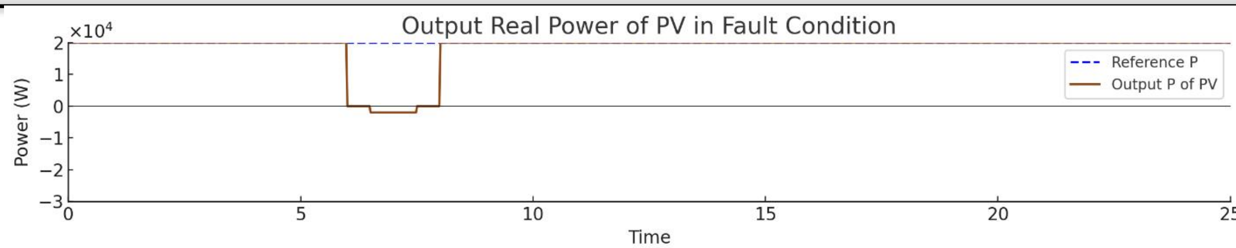

Figure 25: Real power output of PV in switching condition

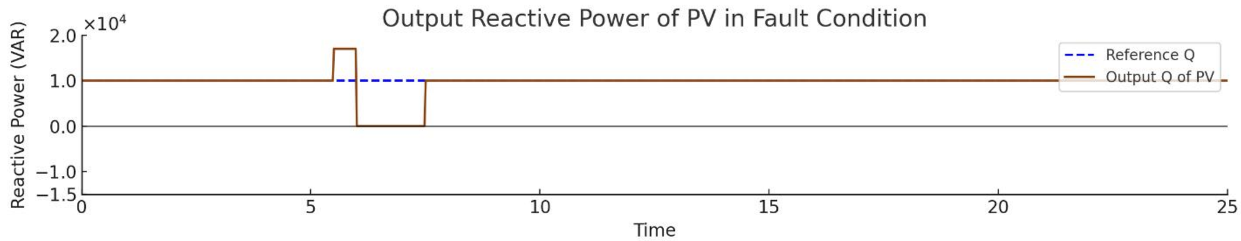

Figure 26: Reactive power output of PV in switching condition

The second source of the hybrid nano-grid is a wind turbine. The wind turbine is turned off at 12 seconds and turned on at 13 hours. The faults and speed of wind cause the wind turbine to turn off. During that time, due to a smart switching algorithm in the nano-grid, the backup line utilised that other source should supply the power to the load, and the utility grid is brought online to fulfil the remaining demand of the load in case of the absence of a source. The real and reactive power of wind turbine in switching or fault case is shown in Figure 27 and 28.

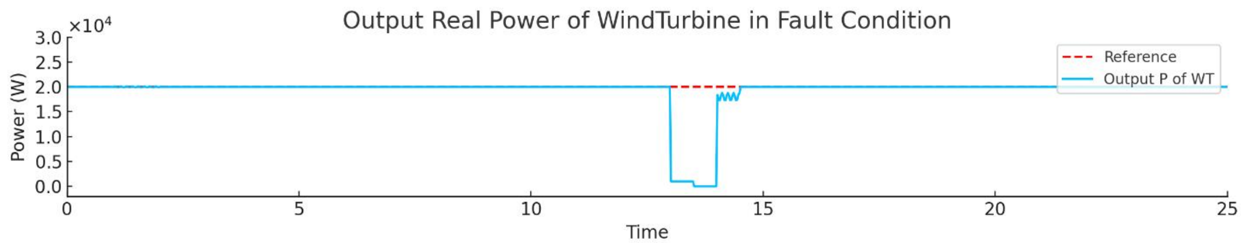

Figure 27: Real output power of wind turbine in switching condition

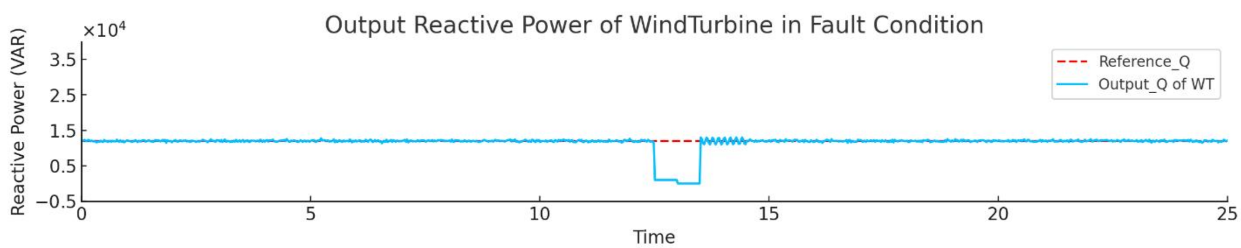

Figure 28: Reactive output power of wind turbine in fault condition

Fuel cell is the third source of nano-grid. Fuel cell is turned off at 19 of hours and turned on at 20 of hours. The source is connected with load through smart switching then the smart switching algorithm will switch the sources according to the demand of load and provide the uninterrupted power to load. The power quality parameters (load frequency, RMS load voltage and RMS load current) are within the standard limits which is shown in below figures. The real and reactive power of Fuel cell in condition of fault or switching is shown in the Figure 29 and 30.

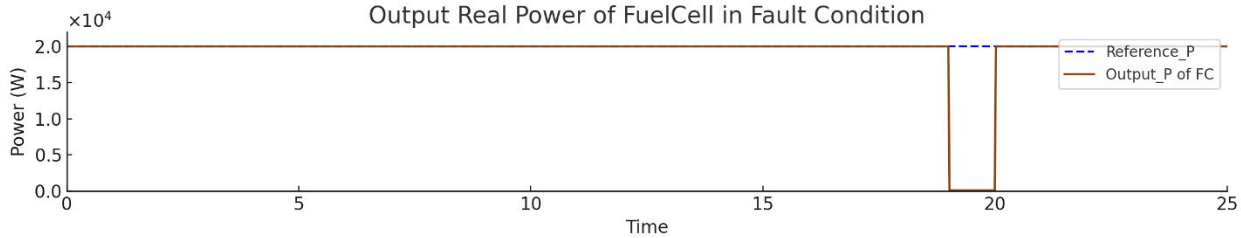

Figure 29: Real power of FC in fault condition

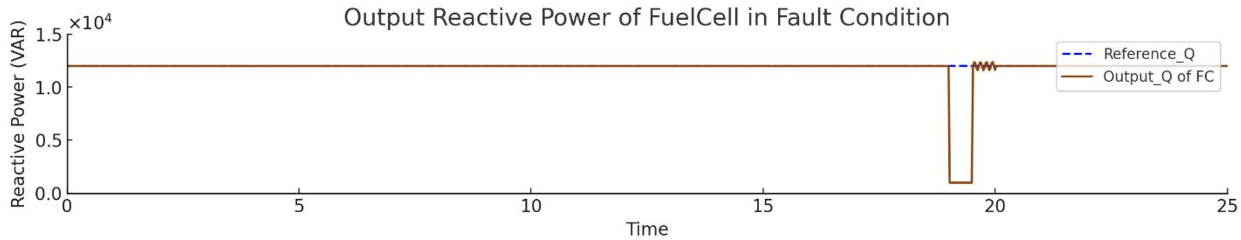

Figure 30: Reactive power of FC in fault condition

The smart switching algorithm is working smartly according to the demand of load and availability of sources that if source is unavailable then through smart switching the other sources are brough online to fulfil the demand of load. If any of source from the primary secondary and tertiary is unavailable and the demand of load is increased then utility grid is brought online according to the second mode of power management that system is in deficient mode. The remaining deficient power is used from grid to satisfy the demand of load. The real power of load in switching case is shown in Figure 31.

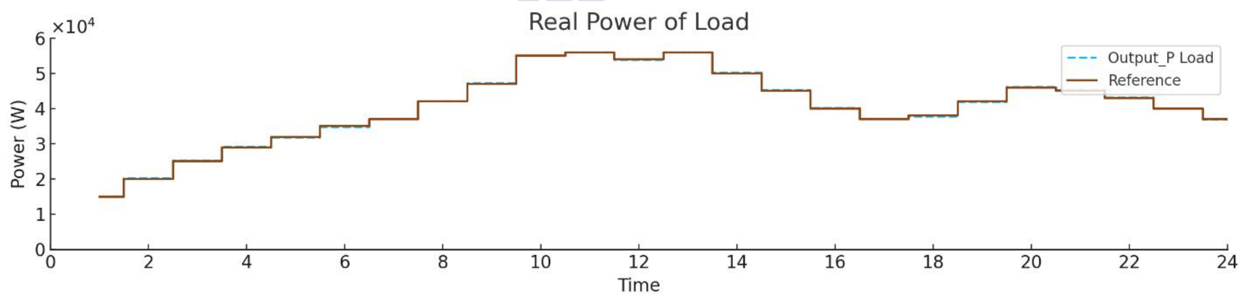

Figure 31: Real power of load in switching condition

In case of smart switching the demand of load is increased and the source is unavailable. In that case the deficient mode of power management the grid is brought online to satisfy the demand of load. The reactive power of load in switching condition is shown in Figure 32.

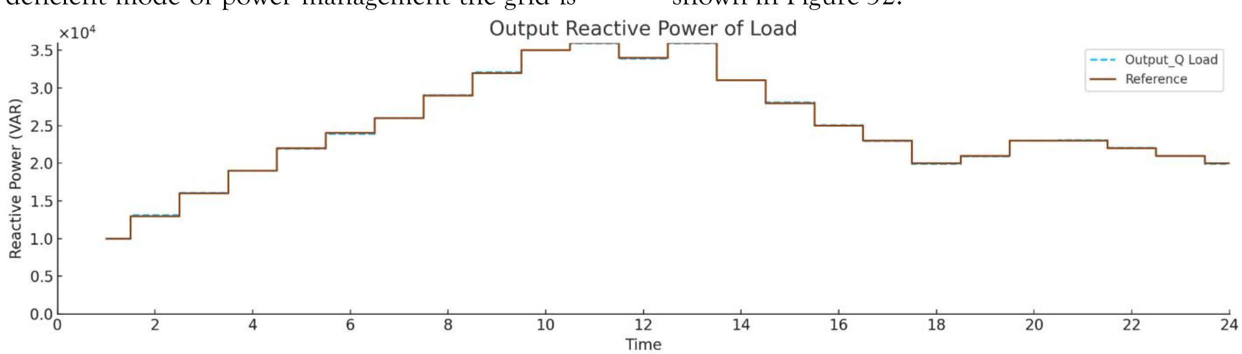

Figure 32: Reactive power of load in switching condition

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In case of switching the load is changing with respect to time and the demand of load is increasing every hour and after the peak demand it comes to its average demand. At every hour when the demand of load changed then with respect to load the current of that load is also changed. The RMS current of load in switching condition is shown in Figure 33.

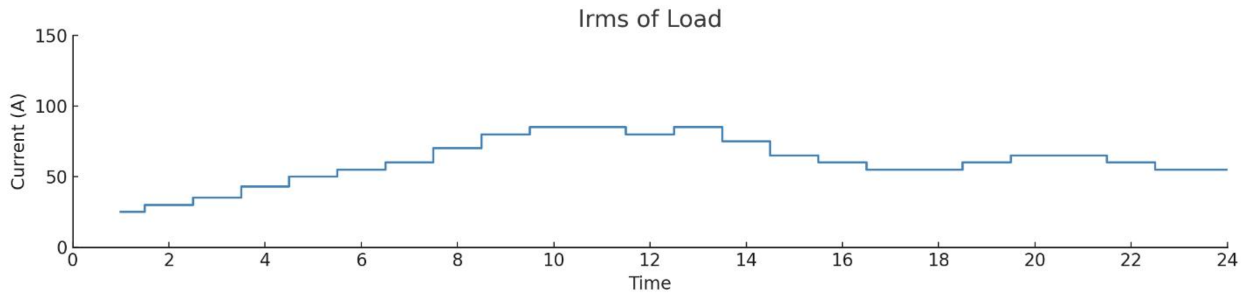

Figure 33: Irms of Load in switching condition

The power of sources provided to load is through three phase voltage controller and the purpose of controller is to lower the value of error and control the voltage from regulating and keeps the level of voltage at standard level to keeps the load safe. The RMS voltage of load in smart switching condition is shown in Figure 34.

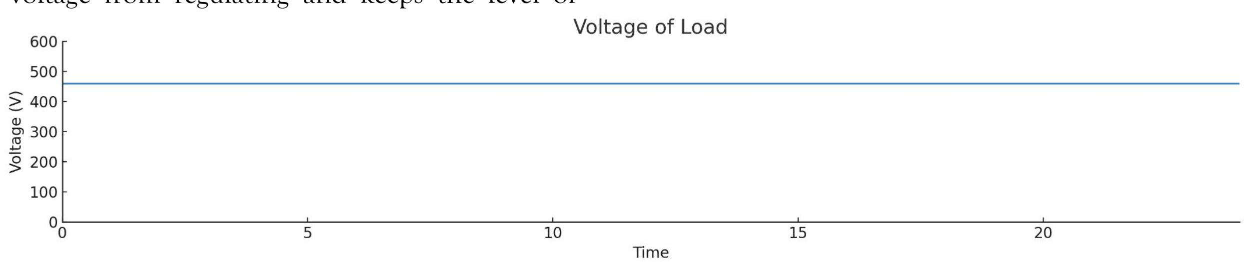

Figure 34:Vrms of Load in switching condition

When the demand of load changes then it has some effects on the parameters of power which is current, voltage and frequency. The frequency controller is utilized to control the frequency in changing demand of load and keeps the frequency at standard level. The steady state is reached after 0.096s and the variations at that time are within 0.1% of the desired frequency, which is within acceptable limits of the applied constraints. The frequency of system in switching condition is shown in Figure 35.

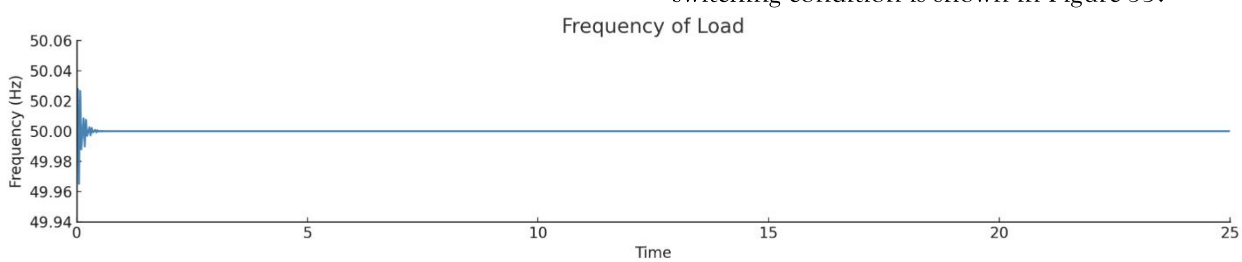

Figure 35: Frequency of Load in switching condition

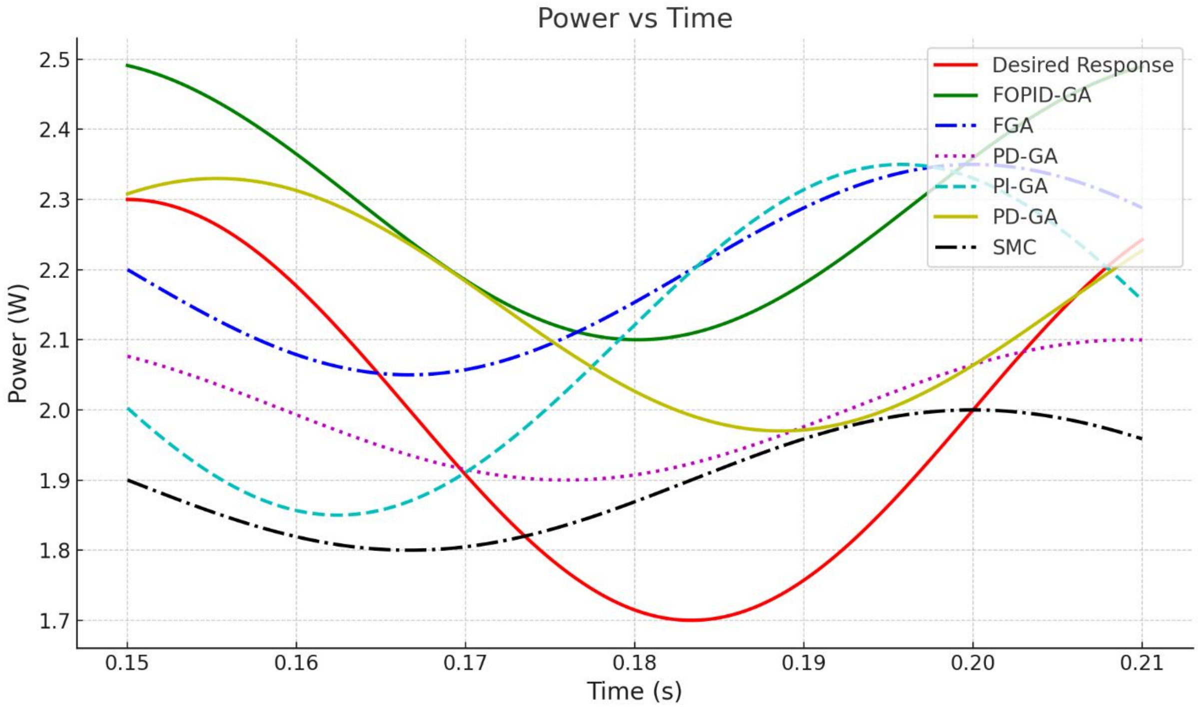

Figure 36: Zoom view of comparison of SMC with all optimized controllers with GA

It can be observed from the zoomed version that the response shown by the dotted line (SMC response) is extremely better than all other optimized controllers.

Furthermore, the SMC is optimized using PSO algorithm as well and its comparative analysis with all other optimized controllers is shown in Figure 37.

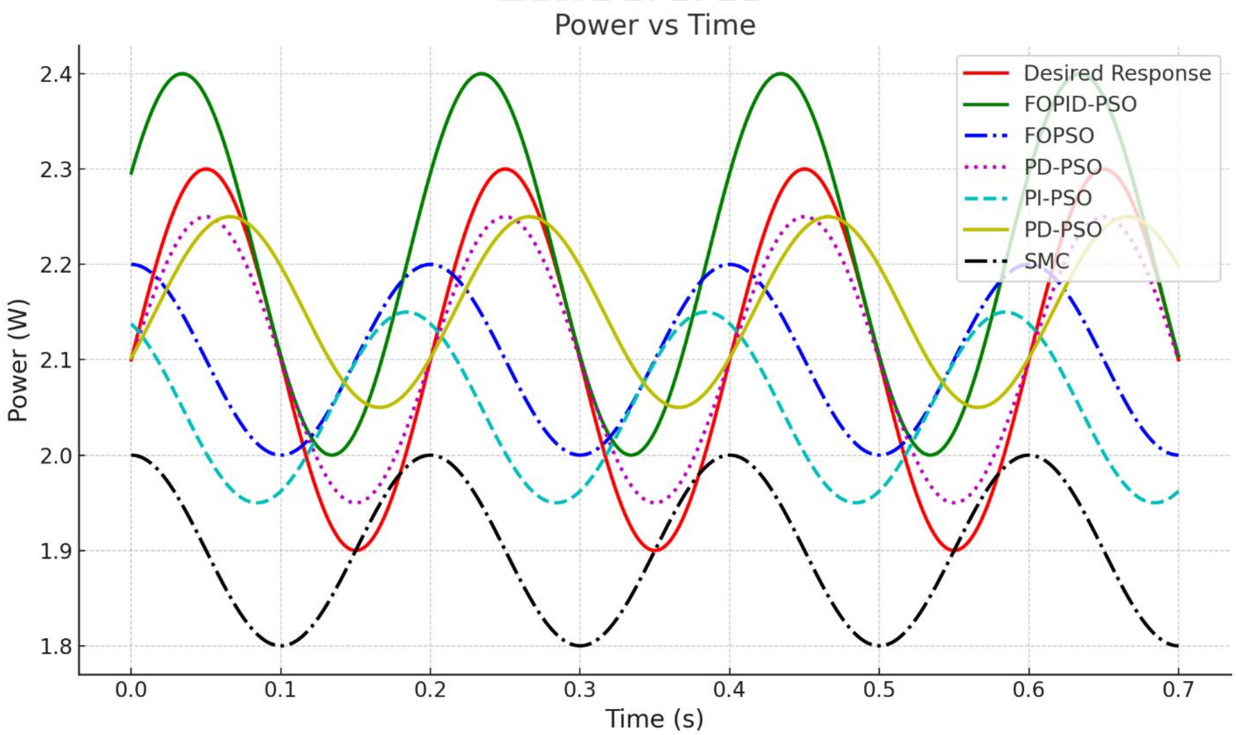

Figure 37: Comparison of SMC with all optimized controllers with PSO

The results yielded using PSO algorithm with SMC are exactly same as with GA. Both algorithms have yielded the same value of the gain for the SMC controller. Hence, the steady state is reached after 0.267s and the variations at that time are within 1% of the desired power, which is within acceptable limits of the applied constraints. The zoomed in version for all optimized controllers using PSO algorithm is shown in Figure 38.

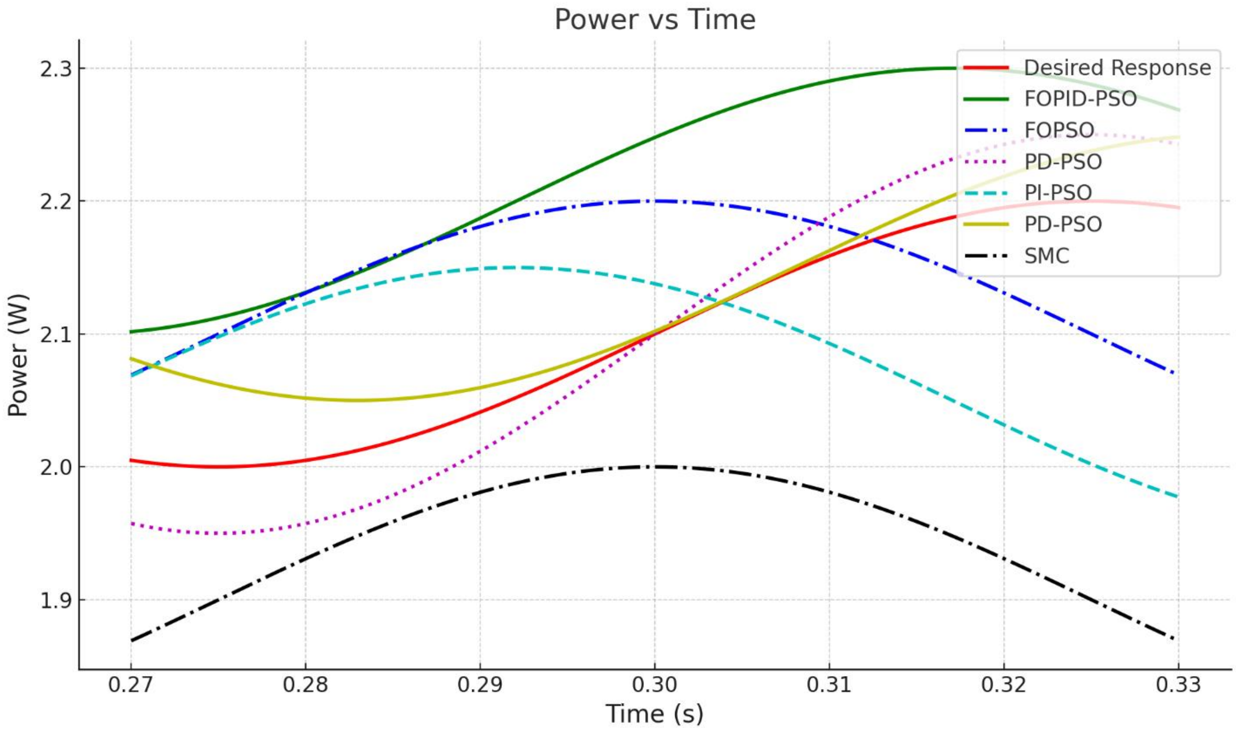

Figure 38: Zoom view of comparison of SMC with all optimized controllers with PSO

It can be noted that for the proposed system the behavior of PSO and GA algorithms with most of the controllers is almost the same. Although, the PSO algorithm has shown somewhat better results in comparison to the GA algorithm. The transients in the power using SMC with both algorithms are observed to be negligible. Furthermore, the numerical analysis for the performance of all optimized controllers is evaluated.

4. Discussion

This project focuses on the modeling and hybridization of a nano-grid, along with the power management of various energy sources, including photovoltaic (PV) arrays, wind turbines, batteries, fuel cells, and utility grids. The PV and wind turbines are highlighted as promising renewable energy sources for nano-grids, contributing significantly to the system's overall power generation. The project emphasizes ensuring power stability and quality by performing a power quality analysis within acceptable limits, confirming that all loads experience uninterrupted power. Simulation results for the modeled hybrid nano-grid and its energy management demonstrate effective power management. Optimizing controllers using Genetic Algorithms (GA) and Particle Swarm Optimization (PSO) for I, PI, PD, PID, FOPI, FOPID, and Sliding Mode Control (SMC) was a key part of the work. The performance of the SMC controller was particularly notable, surpassing all other controllers in terms of power stability, achieving 1% of desired power in under 0.267 seconds. The PID controller also showed excellent performance in frequency control, reaching 0.1% of the desired frequency in less than 0.096 seconds.

5. Conclusion

In conclusion, the proposed hybrid nano-grid effectively integrates multiple energy sources, including PV, wind turbines, batteries, fuel cells, and a utility grid, demonstrating a well-managed and stable power supply system. The optimization of controllers through GA and PSO significantly enhanced the performance of the nano-grid, with the SMC controller emerging as the most efficient for maintaining power stability. The results indicate that the proposed hybrid nano-grid can effectively handle power fluctuations, ensuring uninterrupted power supply to loads. The PID controller also performed well in maintaining frequency stability. Future work could extend this research by applying real-time PV case studies, scaling to a higher-order bus system, adding more renewable sources, or incorporating diesel engines. Further optimization through other intelligent algorithms and controllers, as well as increased iterations for FOPI/FOPID controllers, could improve performance. Hardware testing could also be considered for future validation of the system.

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