



ENERGY MANAGEMENT STRATEGY FOR A HYBRID MICROGRID SYSTEM

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ABSTRACT

Microgrids play a vital role in satisfying the rising need for dependable and sustainable energy sources. They can operate either independently (island mode) or in conjunction with the main power system (grid-connected mode). Hybrid microgrids, which consist of renewable and non-renewable energy resources become popular nowadays because it helps to reduce pollution and greenhouse gas emissions. However, an important issue in hybrid microgrid systems occurs with the increase in distributed generation (DG). The issues are maintaining the voltage level within allowable limits and controlling the power loss of the system. Hence, a method is proposed in this paper to solve these problems, which is implementing a Harris Hawk Optimization (ERHHO)-based PI controller tuning in the system. This type of PI controller can maintain the voltage profile and regulate the reactive power of the microgrid system. A hybrid microgrid system with a three-phase inverter was set up and connected with a three-phase load system. Its single-phase power output was calculated and measured for power calculation and control verification. All the analysis and comparison results before and after implementing the controller will be run using a program called Matlab/Simulink. Overall, this research evaluates the effectiveness of the suggested ERHHO tuning using extensive simulations.

Keywords: battery energy storage, fuel cell, microgrid, photovoltaic, small scale.

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INTRODUCTION

Due to their environmental benefits, renewable energy sources have been widely discussed in every country during globalization. As technology advanced, many countries began using hybrid microgrids for power delivery. Combining renewable and non-renewable energy at one connection point generates electricity in hybrid power systems. It was created to improve microgrid renewable energy use to reduce air pollution and protect the environment. Due to increased energy demand and weather, microgrid efficiency was unpredictable and lower than predicted. Cloudy days reduce photovoltaic (PV) array electricity generation, especially when demand is strong. Solar panels require enough irradiance and temperature to produce their maximum output. Research aims to maximise load sharing in real-time power and distribution networks. It studies how real-time load sharing affects distribution and power networks and finds the best method. Various fields that require precise job completion have driven real-time computing. Speed and fault tolerance make distributed systems ideal for real-time applications. Differentiating periodic from aperiodic tasks while scheduling real-time jobs in these systems to fulfil deadlines is an important study.

Microgrid efficiency can be optimized by increasing Distributed Generators (DG) sources to three or four and installing energy storage in the power distribution network. This paper discusses a hybrid microgrid using PV, a wind turbine, and a fuel cell. In addition, this microgrid system will include a battery storage system to store excess energy from those energy sources. Battery storage will be

employed when the load demands more electricity. However, integrating into existing distribution systems was difficult, especially when switching from passive to active architecture. Power from the central power station to passive loads was unidirectional. DG-equipped active distribution systems featured bidirectional power flows and voltage. This allowed power to flow to and from the microgrid at different times. Thus, the power distribution network will be unstable and lose more power.

Microgrid System

This part was mainly about an overview of the microgrid system and each type of DG investigated in this paper. The microgrid system designed included DG such as PV, wind turbines, fuel cells, and BESS. Each system operation method is discussed in detail in this part. Besides that, the operation of the ERHHO-based PI controller will be explained in detail in this part.

Components of Microgrid

A microgrid would integrate Distributed Energy Resources, Energy Storage Systems (ESS), and various energy needs into a control-signaled main grid. This microgrid's distributed energy resources could be microturbines, fuel cells, solar panels, wind turbines, or any other power source. A microgrid is a distributed system of power users and resources with one or more network coupling points [1]. At the Point of Common Coupling, it connects to a main power system. This is usually on the distribution power system's low-voltage side. Through monitoring and control technology, a microgrid makes



energy more affordable, sustainable, and ecologically benign. Figure-1 shows a typical microgrid layout.

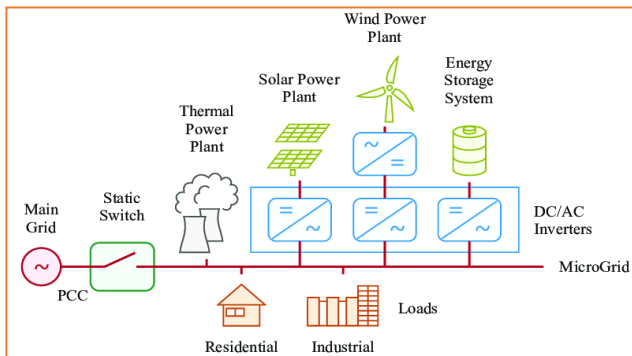


Figure-1. Schematic representation of a typical microgrid.

Working Mode of Microgrid

Microgrids could operate in island or grid-connected modes. PCC-free microgrids are called standalone. Microgrid Island Mode allows a microgrid to function independently from the electrical grid [2]. This mode allowed the microgrid to generate and store power outside the grid. The islanding capabilities minimised power outages and improved power quality. In case of main grid-microgrid connection errors, this mode was employed as a backup power supply [3]. Islanding mode was further split into planned and unplanned. The microgrid separated from the main grid under controlled conditions, such as planned maintenance, to improve electricity quality [4]. Unplanned islanding happened when the microgrid detached from the main grid owing to unanticipated circumstances like main grid system breakdowns.

Grid-Connecting Mode allowed a microgrid to exchange power with the main grid. The microgrid's generation sources, loads, and energy storage devices communicated with the main grid to receive or deliver electricity [5]. To transfer electricity without difficulties, the main grid and microgrid frequencies must be synchronized. Through the PCC Point of Common Coupling, the main grid met peak demand when Distributed Energy Resources failed. Thus, if generation resources failed, electricity was supplied continuously. In summary, the utility grid provided backup power during high voltage demand. Thus, load shaving was negligible; if there was extra power, the microgrid could send it to the grid. The island and grid-connecting modes of a microgrid were shown in Figure-2 [6].

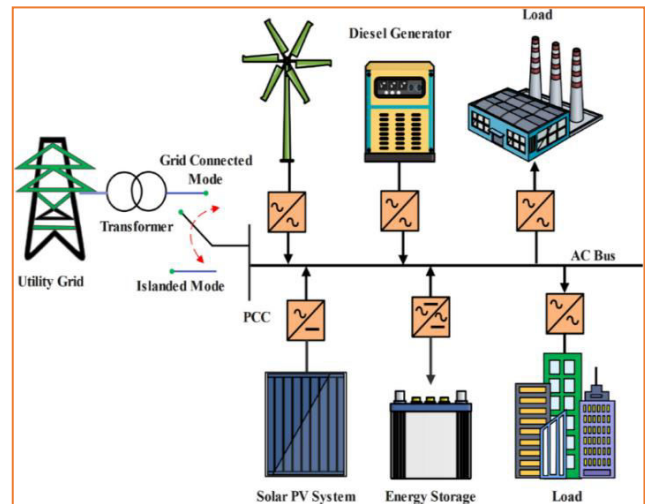


Figure-2. Visual connection of the microgrid in Islanded Mode and Grid Connecting Mode.

Hybrid Microgrid

Globalisation has led microgrids to use hybrid energy systems. Figure-3 shows energy systems including solar, wind, fuel, and battery storage. This improved microgrid stability, efficiency, and reliability [7]. First, a renewable energy system with a backup generator reduced microgrid dependence on one source. When renewable energy sources were few or in great demand, gasoline powered the microgrid. If the main grid failed, a hybrid microgrid might operate in island mode to maintain power in certain areas.

However, a hybrid microgrid optimised resource use. Power generation was balanced by availability, cost, and renewable utilisation. Advanced control systems balanced power loads and optimised stored energy use. This technology reduced fossil fuel use, lowering operational costs and environmental impact. The microgrid was powered by solar energy during the day and fossil fuels as a backup. Thus, microgrid efficiency rose indirectly [8].

Hybrid energy microgrids also ensured environmental sustainability. The 2015 Paris Agreement sealed international efforts to limit global warming to well below 2°C above preindustrial levels. Minimising fossil fuel use and using fuel generators as backups can help. Using hybrid microgrids in daily life protects the environment. However, more converters and power electronics diffuse reactive power and increase power transfer losses [9].

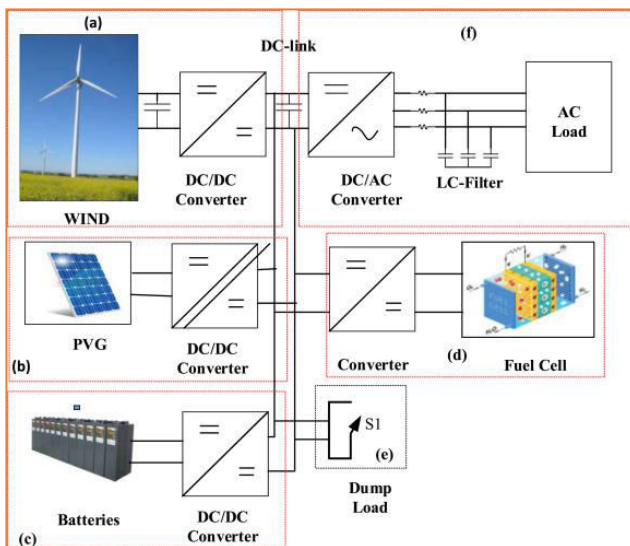


Figure-3. Combined system of DG used in the research.

Photovoltaic System

Figure-4 shows PV arrays, charge controllers, power conversion systems, grids, ESS, and loads in a PV-based microgrid. The solar array harvested solar energy. A solar charge controller controlled the voltage and current of the incoming electricity from these panels. This was crucial since it converted electricity without damaging the microgrid batteries. The battery stored generated energy for backup. This system generated only DC energy. This energy supplied DC loads and sent any remaining energy to the inverter. The inverter converted DC to AC, making it suitable for daily use. This helped villages become energy independent and reduce grid dependence. To maximise grid-connected efficiency, several systems fed extra energy into the main grid [10].

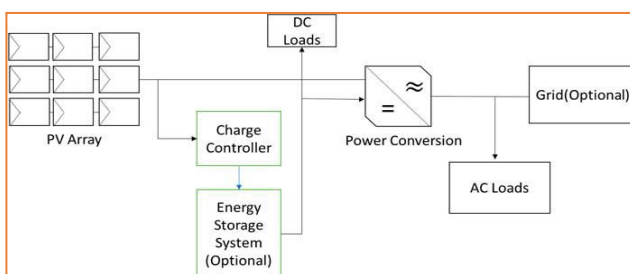


Figure-4. Energy conservation from PV to grid.

Wind Turbine

Wind turbine rotor blades, like helicopter rotor blades, transform wind energy into electricity using aerodynamic force [11]. Horizontal-axis and vertical-axis wind turbines were classified. Three-bladed horizontal wind turbines operated "upwind," pivoting at the tower top to face the wind. Vertical wind turbines worked without pointing into the wind since they were omnidirectional [12]. Since their blades were always facing the wind, horizontal-axis turbines were more popular because they converted energy more efficiently. They extracted greater wind

kinetic energy than vertical-axis turbines. Additionally, horizontal wind turbines have been widely researched and constructed. This made their design more reliable and cost-effective.

Figure-5 shows that a wind turbine's critical components worked together to transform wind energy into electricity. The frontal blades were aerodynamically designed to capture wind energy. These blades were coupled to the rotor, which converted wind energy into rotation [13]. The low-speed shaft fed this rotational energy to the gearbox, which boosted it to power generation speed. The high-speed shaft connected the gearbox to the generator, which turned mechanical energy into electrical energy via electromagnetic induction.

All these components were protected from environmental factors by the nacelle. A yaw drive and motor kept the nacelle moving and the blades facing the wind to maximize energy capture. In addition, a brake mechanism stopped the rotor in emergencies or repairs. The tower held the nacelle and rotor at wind-optimal height and housed power transmission ladders and wiring. Anemometers and wind vanes measured wind speed and direction, providing vital data to the turbine's controller [13]. The pitch system controlled blade angle, rotor speed, and wind protection to optimize turbine operation.

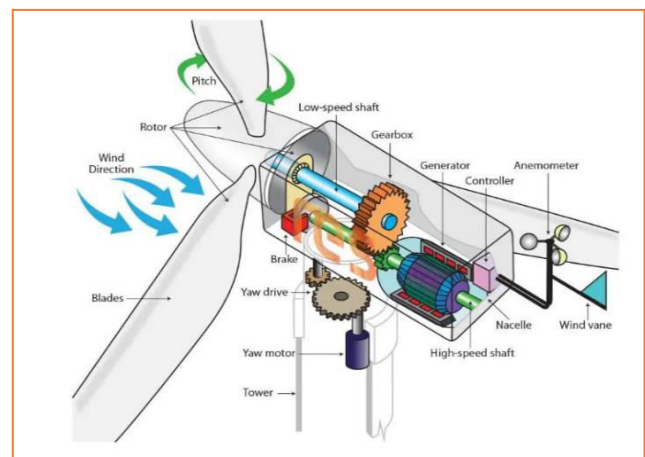


Figure-5. Components of a wind turbine.

Fuel Cell

Fuel cells electrochemically convert hydrogen-rich fuels into electricity and high-quality heat. Hydrogen-rich fuels like clean natural gas electrochemically react with oxygen in fuel cell stacks. Electricity, heat, and water are created. Figure-6 depicted fuel-based microgrid components [14].

The fuel cell stack's electrochemical processes required an air blower; thus, it was incorporated first. It supplied fuel processors with electricity. It turns fuel into hydrogen-rich petrol. Hydrogen gas was then supplied into the fuel cell anode. Fuel cell stacks have anodes, electrolytes, and cathodes. At the anode, molecular hydrogen was split into protons and electrons. A direct current was generated by externally guiding electrons via



an electrical circuit. Direct current was converted to alternating current via a DC-AC converter and fed to the grid. The electrolyte only permitted protons to travel to the cathode; thus, electrons took the external path, generating power. Protons and electrons recombined with air oxygen to produce water and release heat at the cathode.

The fuel cell's residual air stream was burned by the burner to produce high-energy steam to capture heat energy. Heat/water management also managed fuel cell heat. It used waste heat for heat recovery and hot water generation. Heat recovery returned heat to the fuel processor, whereas hot water production used it for residential needs. This reduced fuel-based microgrid energy waste. Water from the fuel cell was recycled in the water pump and recycling system to cool the system. Unneeded heat was sent to the thermal circuit or saved in a hot water tank.

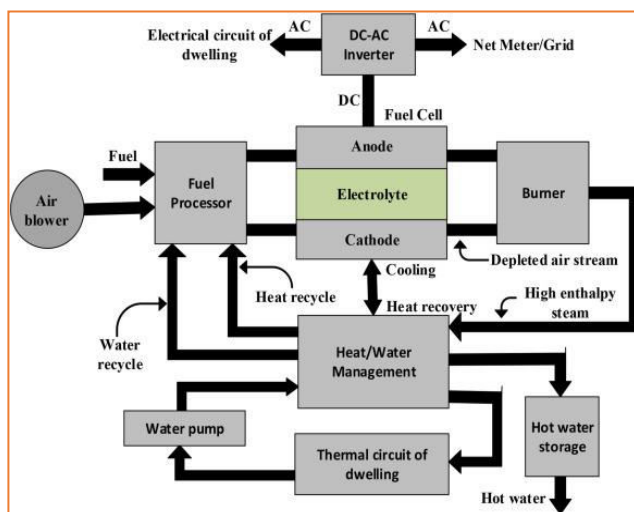


Figure-6. Components of a fuel-based microgrid.

Battery Energy Storage System (BESS)

A hybrid microgrid generates power from renewable and non-renewable sources. Due to more DGs in the electricity distribution network, the microgrid system was operational. Thus, power loss and voltage levels must be managed to reduce power loss. Managing reactive power for each dispersed generation improved system dependability and reduced power loss. Figure-7 shows all hybrid microgrid components with the control system [15].

It started with PV power plants, wind turbines, and fuel generators. Previous discussions covered their workings. All electricity then went to the microgrid's brain, a control system. It monitored power supply, stabilised it, and reconnected it based on renewable resources and microgrid demand. The control system dominated this paper.

ESS, RES, and EMS comprised the BESS; ESS stored extra RES energy during high output and low demand. This ESS has supercapacitors, hydrogen storage, and batteries. Battery storage was reliable for short- to medium-term storage, while hydrogen storage used fuel

cells for long-term storage. Supercapacitors managed abrupt power demand variations by rapidly discharging and recharging. A cooling system was sometimes employed to manage temperature and ensure safe operation under fluctuating load and storage conditions.

In addition, the power conversion system connected the ESS and renewable energy source to the grid. This system converted RES-generated DC electricity stored in the ESS to grid- and household-compatible AC power. The microgrid received power from the grid when needed and supplied power to it during surpluses due to bidirectional energy flow.

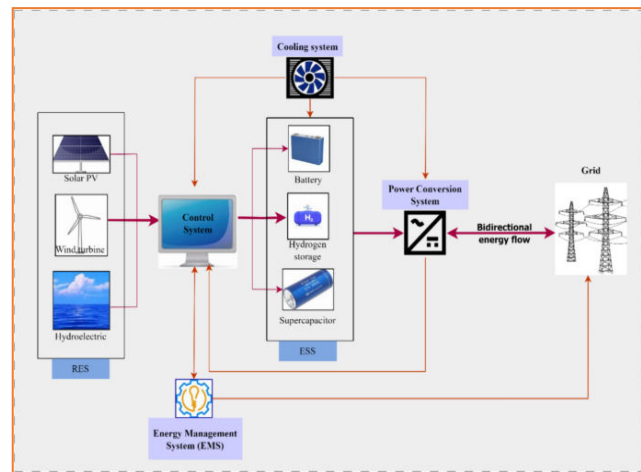


Figure-7. Hybrid microgrid system with the control system.

Usage of Reactive Power in Microgrid System

In DG-based microgrids, loads and generators were able to provide a supply of power all day. The main elements of microgrids, such as PV generators, wind turbines, fuel cells, and BESS that are connected to the conventional grid with power converters. Conventional converters were used to ensure optimal operation and flexible control. However, the power-converting interface between a DG system had brought about several major challenges to power quality, such as reactive power compensation and the development of harmonics. On the other hand, reactive power involves the control of reactive energy to improve the performance of AC. Reactive power can improve power factor and balance real power. This could minimize voltage fluctuations at the terminals of one transmission line. Hence, this indicated that controlled reactive power will increase efficiency and reduce could minimize the transmission process.

Active Power

In general, active power was the amount of power consumed or utilized in an alternating current circuit. It was also known as actual power or true power. Active power was the product of voltage and current in a circuit multiplied by the power factor, which represents how efficiently the power was used. It was commonly indicated as P and



measured in watts (W). Active power, or true power were actual power that does work in a circuit.

Reactive Power

Reactive power is a type of electrical power that oscillates between the load and the supply without performing any meaningful function. It occurs when an alternating current circuit's voltage and current are out of phase [16]. Unlike real power, reactive power flows back and forth. As a result, this type of power moved in a way around the circuit or reacted back to itself. It was useless power stored in the circuit. It was measured in volt-ampere-reactive (VAR). Reactive power was generated when inductive or capacitive elements were present in an electrical circuit. These elements generated a phase discrepancy between voltage and current waveforms in alternating current circuits.

Complex Power

The total reactive and actual power was known as complex power. The vector sum of reactive and real power is known as apparent power. It stood for both the reactive power that stayed in the AC circuit and the actual power that had been sent out to power up objects. It was measured in volt-amperes (VA) or kilovolt-amps (kVA). The apparent power was found by multiplying the RMS values of voltage and current, regardless of any phase relationship. The formula for apparent power was given by equation (1):

$$S = V \times I \quad (1)$$

where S was the apparent power, V was the RMS voltage, and I was the RMS current [17].

Power Factor

Furthermore, power factor was the ratio of an electrical load's true power to apparent power in an AC circuit. It was expressed in percentage form. The higher the power factor, the higher the efficiency of the power used in the load. Power factors were in the range from 0 to 1 only. The reactive power was inversely proportional to the power factor. This means that power factors would decrease when reactive power increased [18]. This paper focused on discussing methods to control reactive power and increase the power factor on the microgrid.

Effect of Reactive Power in Microgrid System

Reactive power in a microgrid is mainly produced by inverters and converters, which are responsible for converting DC power sources into AC before being supplied to AC loads. Besides, synchronous generators from micro-turbines also produce reactive power. Reactive power is not used in power transfer, but it contributes to the total current flowing through the transmission line. Since power loss in the power system is proportional to the square of the current, as in equation (2).

$$P = I^2 R \quad (2)$$

Hence, excess reactive power would increase the total current and lead to high losses in the transmission line. This would indirectly decrease the efficiency of power transmission decrease indirectly.

On the other hand, reactive power is critical for keeping voltages within tolerable limits. Without enough reactive power, voltage could become unstable, resulting in sags, oscillations, or even voltage collapse. This instability could disturb the operation of sensitive equipment and cause power quality issues. Aside from this, reactive power affects the available transmission capacity of power systems. Without adequate reactive power assistance, the grid's capability to transfer active power may be constrained, resulting in congestion and a decreased ability to fulfil rising power needs. In short, we could work toward a more balanced and sustainable electrical infrastructure. This may ensure a steady power supply and reduced waste by implementing the correct measures to address reactive power in a microgrid system.

Method to Control Reactive Power

Figure-8 shows the K chart of AC and DC microgrid control approaches. All approaches in this chart can stabilize the system by maintaining voltage and reactive power. Methods only differed by system operating mode and load type. Since this thesis concentrated on AC loads and grid-connected mode, only the ERHHO-based Proportional-Integral (PI) controller was examined. The ERHHO-based PI controller integrated PI with ERHHO. System dynamics and stability depended on the PI controllers. With the ERHHO algorithm, voltage and reactive power can be better managed [19].

The optimization method ERHHO used Harris hawks' social behaviour. The fundamental Harris Hawk Optimization (HHO)'s exploration and exploitation capabilities were improved to find better solutions in tough optimization circumstances. The PI controller controlled synchronous generators, voltage regulators, and reactive power compensators to generate reactive power. This controller ensured that voltage deviations from the setpoint were quickly adjusted. ERHHO helped set the PI controller to limit voltage changes and maintain stability.

To determine reactive power compensation, ERHHO optimized the PI controller parameters in real time for fluctuating load and renewable generation [20]. The controller controlled reactive power injection or absorption by capacitor banks and voltage regulation equipment to prevent voltage sags or overvoltage. ERHHO made sure the PI controller handled such adjustments to maintain voltage stability and reactive power flow.

PI Controller

A PI controller combines proportional and integral control. It is usually used to regulate processes and maintain production. A proportional controller controls a system step-by-step. First, it calculated the error between the desired output and the present process variable. The controller's proportional (P) element amplifies this error by



proportional gain (K_p). It takes quick action proportional to the error.

The integral (I) estimated cumulative prior errors by integrating gain (K_i). P and I were combined to produce the control output, which was applied to the system. This output reduced mistakes over time while retaining the setpoint, changing the system's output [21]. Equation (3) was its output equation. It was used to adjust the voltage and reactive power of each DG in hybrid microgrids. However, renewable energy sources are volatile and nonlinear, making PI controller parameter tuning for reactive power difficult. The parameters need to be tuned using the ERHHO method.

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \quad (3)$$

Harris Hawks Algorithm (HHO)

Harris's hawks were known for their cooperative hunting behaviour in flocks. Harris's hawks adapted their feeding and besieging methods to match the behaviour of their prey. There were several steps involved in HHO to hunt prey successfully.

Exploration Mode

Individual hawks from HHO served as search agents. Hawks can struggle to find prey and spend hours searching for it. Hawks were chosen as potential solutions, with probable prey as the best option. Hawks used two tactics when resting to look for prey. Hawks can rest near other members (equivalent in (1) for $p < 0.5$) or at random locations (equivalent in (1) for $p \geq 0.5$). The best result in each cycle was regarded as an objective bunny or prey. These steps were explained in equations (4) and equation (5) as follows:

$$H(k+1) = H_{rand}(k) - c_1 |H_{rand}(k) - 2c_2 H(k)| \quad p \geq 0.5 \quad (4)$$

$$H(k+1) = H_{rabbit}(k) - H_m(k) - c_3 (lb + c_4 (ub - lb)) \quad p < 0.5 \quad (5)$$

In this iteration, Rabbit(k) represented the prey's position, H(k) represented the hawk's position, c_1 , c_2 , c_3 , and c_4 were random parameters in the interval (0, 1), ub and lb are the search limits, rand(k) was a randomly picked hawk's position, and $H_m(k)$ represented the average position of all hawks in the kth iteration. H(k+1) represents the hawk's location vector in the next phase.

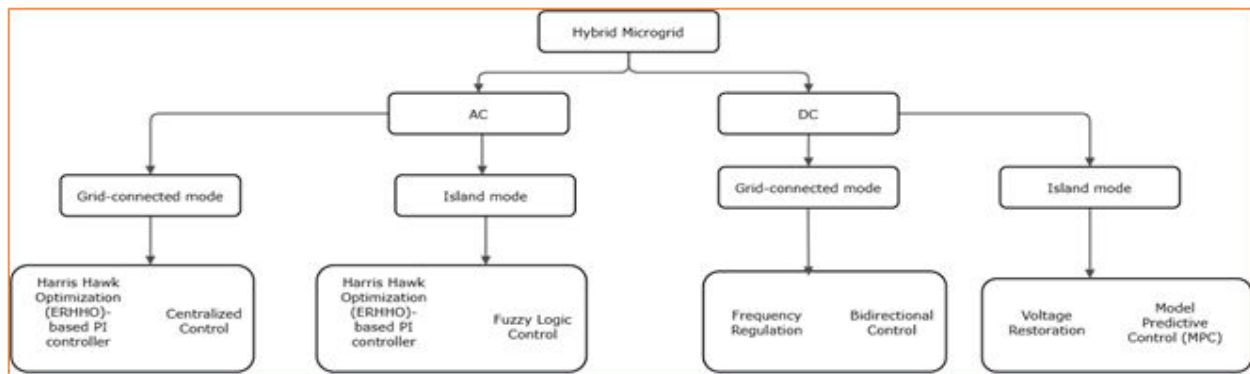


Figure-8. K chart of the designed system.

The hawk's average position, $H_m(k)$, was computed in equation (6) as follows:

$$H_m(k) = \frac{1}{N} \sum_{i=1}^N H_i(k) \quad (6)$$

where N was the total number of hawks and $H_i(k)$ was the position of each hawk in the i-th iteration.

Crossover from Exploration to Exploitation Stage

During the hunt, the prey's escape energy dropped as seen in equation (7).

$$E = 2E_0 (1 - k/l) \quad (7)$$

In this equation, E represents the fleeing energy of the prey, E_0 represents the initial energy, and l represents the number of rounds. E_0 varied randomly in the limits (-1, 1) at each k, as specified in equation (8).

$$E_0 = rand(-1, 1) \quad (8)$$

$|E| \geq 1$ represented the exploration period, while $|E| < 1$ indicated the exploitation period.

Exploitation Phase

During the exploitation phase, hawks launched unexpected assaults on their victims. Here, the parameter reflected the prey's possibility of evading the hawk's attack. For $e < 0.5$, the prey successfully escapes, but for $e > 0.5$, the prey is captured. Depending on the prey's escape pattern and energy, hawks adopted the besiege method. The besiege and hunt strategies were classified into four states based on the prey's energy level and ability to escape from hawks [22].



Soft Siege Mode

For $e \geq 0.5$ and $|E| \geq 0.5$, the prey had enough energy to move randomly, but could escape, as shown in equations (9) and (10):

$$H(k+1) = \blacktriangle H(k) - E|R_j H_{rabbit}(k) - H(k)| \quad (9)$$

$$\blacktriangle H(k) = H_{rabbit}(k) - H(k) \quad (10)$$

where $R_j = 2(1 - cs)$, which matched the above movement of prey, which changed with k , $cs = \text{rand}(0,1)$.

Hard Besiege Mode

For $e \geq 0.5$ and $E < 0.5$, the victim became fatigued and unable to escape, leading to a close encounter with the hawks. The hawk's position was provided in equation (11) [22].

$$H(k+1) = H_{rabbit}(k) - E|\blacktriangle H(k)| \quad (11)$$

Soft Besiege with Rapid Dives

For example, at $E = 0.5$ and $E \geq 0.5$, the prey had enough energy to squirt effectively. During this time, a Levy flying (LF) pattern was used to mimic prey's erratic movements and hawks' quick leaps. The hawk's locations were as follows in equations (12) and (13):

$$H(k+1) = S_b \text{ if } J(S_b) < J(H(k)) \quad (12)$$

$$H(k+1) = S_{LF} \text{ if } J(S_{LF}) < J(H(k)) \quad (13)$$

where $J = \text{Objective Function}$

Hawks began with a soft besiege and if the outcome was unsatisfactory, they proceeded to construct a pattern dive as shown in equation (14) and equation (15)

$$S_b = H_{rabbit}(k) - E|R_j H_{rabbit}(k) - H_m(k)| \quad (14)$$

$$S_{LF} = S_b + V \times \text{LF}(d) \quad (15)$$

In this equation, d indicates the variable's dimension, V is a random vector with a dimension of $1 \times d$ and LF represents the LF function as shown in equation (16).

$$\text{LF}(d) = 0.01 \times \frac{u \times \sigma}{|v|^{\beta}}, \quad \sigma = \left[\frac{r(1+\beta) \times \sin\left(\frac{\pi\beta}{2}\right)}{r\left(\frac{1+\beta}{2}\right) \times \beta \times 2^{\left(\frac{\beta-1}{2}\right)}} \right]^{\frac{1}{\beta}} \quad (16)$$

where u and v are in $(0,1)$ and $\beta = 1.5$.

Hard Besiege Mode with Rapid Dives

For $r < 0.5$ and $E < 0.5$, the prey's escape energy decreased significantly. Hawks used a forceful besiege to close the distance between themselves and their prey. Hawks used both the LF model and hard besiege to

successfully capture their prey. Equation (17) and equation (18) model the behaviour of hawks:

$$H(k+1) = S_h \text{ if } J(S_h) < J(H(k)) \quad (17)$$

$$H(k+1) = S_{LF} \text{ if } J(S_{LF}) < J(H(k)) \quad (18)$$

where S_h and S_{LF} are shown in equations (19) and equation (20).

$$S_h = H_{rabbit}(k) - E|R_j H_{rabbit}(k) - H_m(k)| \quad (19)$$

$$S_{LF} = S_h + V \times \text{LF}(d) \quad (20)$$

The switch from exploration to exploitation was determined by the prey's escape energy value. Excessive examination of a search region may introduce unpredictability and lead to a local minimum. Thus, it was critical to find a balance between exploration and exploitation. At this phase, E and E_0 are determined using equation (21) and equation (22), not equation (7) and equation (8) as in HHO.

$$E = 2E_0 \left(1 - \frac{k^{0.5}}{l^{0.5}}\right) \quad (21)$$

$$E_0 = 2 \cos(\text{rand}()) - 1 \quad (22)$$

It was evident from equation (21) that a lesser number of iterations was allocated for the exploration phase than the exploitation phase, which was achieved by a cosine function used in equation (22). The cyclic cosine function relocated the solution, which ensured suitable exploration of the search area, and the method could be searched in another place and between their equivalent locations.

The remaining hawks in the HHO moved around to find the optimal place. Initially, the optimal site for hawks was unknown. Using big initial steps might cause hawks to deviate from their optimal value. Thus, SFs were used to regulate the movement of hawks in the early stages. In all iterations, the location of hawks ($H_m(k)$) was adjusted as shown in equation (23):

$$H_m(k) = \frac{H(k)}{\text{SF}} \quad (23)$$

where SF is given by equation (24).

$$\text{SF} = 2 - k/l \quad (24)$$

Inserted SFs allowed hawks to progressively shift throughout the first phase of search, restoring HHO's searching ability. During advanced phases, hawks moved at a typical rate and achieved superior results. The complexity of its implementation was the same as the number of nested loops in the original HHO and ERHHO were the same.



Enhanced Randomized Harris Hawk Optimization

A PI controller combines proportional and integral control [21]. Applications that retain a setpoint use it. Control systems are step-regulated using proportional controllers. The error, the difference between the desired setpoint and the present process variable, was calculated first. The proportional part of the controller had an instant action directly proportionate to the error by multiplying the error by K_p .

Gain (K_i) was integrated to calculate the cumulative sum of prior errors in Integral (I). Summing K_p and K_i gave the system the control output. This output minimized system output error over time relative to the set point [21]. Its output equation was (3). The hybrid microgrid system uses it to regulate the voltage profile and reactive power of each DG. Renewable energy sources are dynamic and nonlinear, making PI controller parameter calibration for reactive power management difficult. The ERHHO method must be used to optimize parameters.

ERHHO improves on HHO by improving performance, scalability, and addressing more complicated and multi-dimensional optimization problems. The ERHHO algorithm was used to find the optimal proportional-integral controller gains, such as the proportional gain and integral time constant. Optimization sought to improve system dynamics. These methods searched the parameter space for controller settings that minimized overshoot or settling time [23].

Its functioning premise involves initialization, fitness evaluation, and exploration. First, it defined the microgrid performance goal function. Second, the ERHHO algorithm initialized the solution population. After that, PI controller gains were spread across the microgrid model and simulated under various operating conditions to test each solution.

ERHHO iterated across the solution space and updated candidate solutions based on fitness scores. Exploration and exploitation were used to find an optimal or near-optimal solution. The algorithm repeated solution fitness checks and made adjustments. After that, optimization ran for a predetermined number of iterations or until a termination condition was met. After optimization, the ERHHO algorithm selects the best K_p and K_i values for the microgrid system [23].

ERHHO PI Controller (Outer Reactive Power Control Loop)

The reactive power measured in equation (25) is calculated by transforming three-phase current and voltage into V_d , V_q , and I_d , I_q . An equation-based one-step transformation can do this in equation (26). Time-varying sinusoidal impulses in the ABC frame make system control challenging. Thus, the three phases of voltage and current (ABC frame) must be converted to the dq frame to convert AC signals into DC signals with constant values and make PI controller tuning easy [26].

ERHHO will calculate the best integral gain (K_i) and proportional gain (K_p) for the PI controller based on the

I_q reference value in equation (27). The inverter should inject this current to meet reactive power needs.

$$Q_{meas} = \frac{3}{2} (V_d I_q - V_q I_d) \quad (25)$$

$$\begin{pmatrix} V_d \\ V_q \end{pmatrix} = \frac{2}{3} \begin{pmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin \theta & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{pmatrix} \begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} \quad (26)$$

$$I_{q_ref} = K_p Q_{error} + K_i \int Q_{error} dt \quad (27)$$

Second PI Controller (Inner Current Control Loop)

This PI controller will link to the inverter PWM. It checks the injected q-axis current (I_{qmeas}) against the outer loop-supplied target current (I_{qref}). Calculate the error between I_{qref} and I_{qmeas} in equation (29). The loop will then generate a voltage reference (V_{qref}) using the error. An inverse Park transformation, like equation (28), converts this voltage from dq to three-phase abc coordinates. Due to its mathematical nature, the DQ frame does not directly represent real voltage or current waveforms [24]. Without ABC transformation, PWM cannot produce correct switching signals. The current output is V_{abc} . The output signals go to the PWM generator, which generates inverter switch gate signals. This ensures the inverter injects the right current with the right voltages. ERHHO algorithm gives both controllers the same integral gain (K_i) and proportional gain (K_p). To summarise, the outer PI controller manages reactive power tracking, while the inner PI controller regulates current accurately.

$$\begin{pmatrix} V_a \\ V_b \\ V_c \end{pmatrix} = \begin{pmatrix} \cos \theta & -\sin \theta \\ \cos(\theta - \frac{2\pi}{3}) & -\sin(\theta - \frac{2\pi}{3}) \\ \cos(\theta + \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \end{pmatrix} \begin{pmatrix} V_d \\ V_q \end{pmatrix} \quad (28)$$

$$I_{q_error} = I_{q_ref} - I_{q_meas} \quad (29)$$

Voltage Conversion

In a three-phase power system, sinusoidal waveforms are usually described in terms of their peak values or root mean square (RMS) values. When the line-to-line voltages are being considered, it is sometimes necessary to switch between V_{peak} for a sinusoidal voltage. The line-to-line RMS voltage can thus be obtained from the line-to-line peak voltage by the equation (30):

$$V_{rms} (L-L) = \frac{V_{peak} (L-L)}{\sqrt{2}} \quad (30)$$

An accurate conversion between peak and RMS values is important in the design and analysis of inverters and controllers in microgrids. This can ensure the voltage levels meet the load requirements and system standards.



METHODOLOGY

This part discusses the build-up and circuit design of every subsystem required in the microgrid system. Furthermore, it also explains each of the controllers' roles in the system. Lastly, it reviews all three scenarios designed to evaluate the performance of the controllers in the system.

Photovoltaic Design

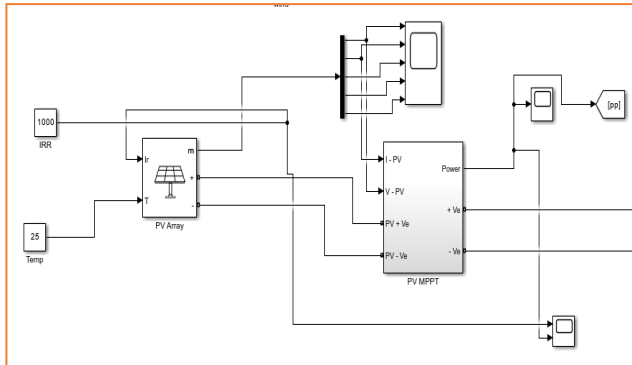


Figure-9. Circuit diagram of a photovoltaic panel with MPPT.

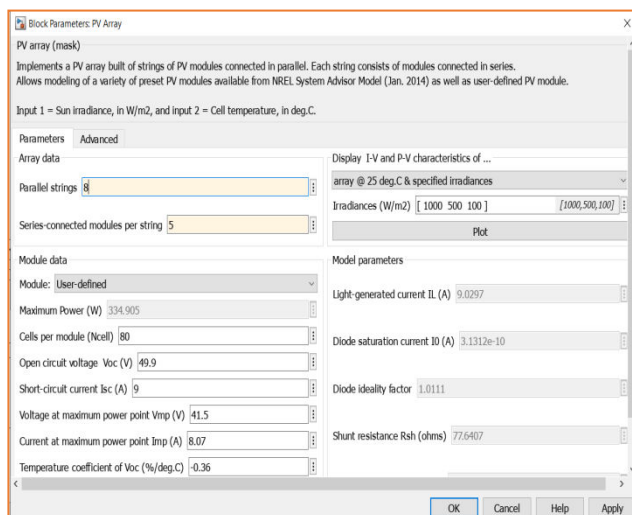


Figure-10. Photovoltaic parameters used.

Table-1. Photovoltaic parameters used.

PV Array Model = 12.5kW	
Parallel Strings	8
Series-connected modules per string	5
Module Data	
Maximum Power (W)	334.905
Cells per module (Ncell)	80
Open-circuit voltage, Voc (V)	49.9
Short-circuit current, Isc (A)	9

Voltage at Max. Power point, Vmp (V)	41.5
Current at Max. Power point, Imp (A)	8.07
Temperature coefficient of Voc (% °C)	-0.36

Figures 9 and 10 show the connection of the photovoltaic system and the parameters used in the block diagram. This system will provide about 12.5kW power to the load. The MPPT system is used to extract maximum power from the solar system. From the circuit, 1000Wm² and the standard temperature for solar (25°C) are used. From Table-1, there are 8 parallel solar strings, and each string has 5 modules connected in series.

Fuel Cell Design

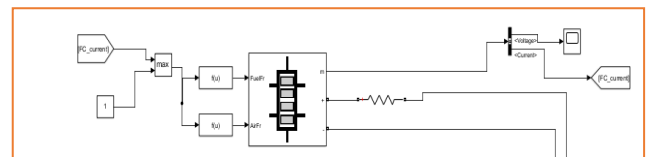


Figure-11. Circuit diagram of the fuel cell in the system.

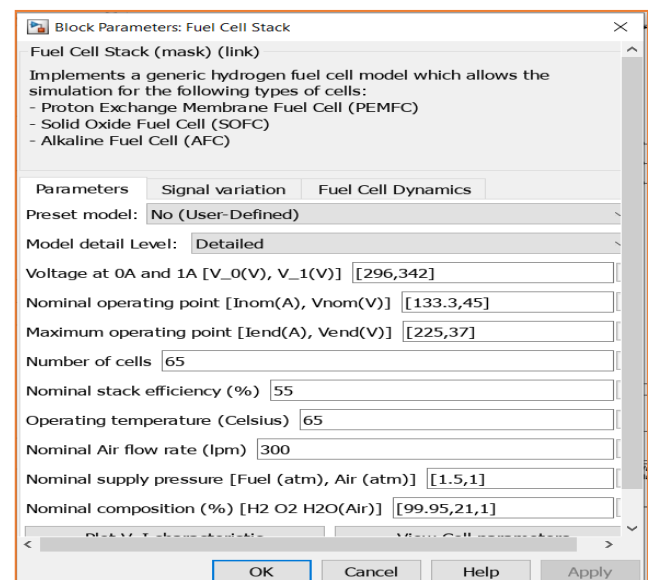


Figure-12. Fuel cell parameters used in the block diagram.

Table-2. Fuel cell parameters.

Fuel Cell Stack Model = PEMFC - 6 kW 45VDC	
Voltage at 0A and 1A [V0, V1 (V)]	[296,342]
Nominal Operating Point [Inom (A), Vnom (V)]	[133.3,45]
Maximum Operating Point [Iend (A), Vend (V)]	[227,37]
Number of cells	65
Nominal Stack Efficiency (%)	55%
Operating Temperature (°C)	65



Nominal air flow rate (Ipm)	300
Nominal supply pressure [Fuel (bar), Air (bar)]	[1.5,1]
Nominal composition (%) [H2 O2 H2O (Air)]	[99.95,21,1]

Figure-11 shows the circuit design of the fuel cell subsystem in the microgrid system, while Figure-13 shows the fuel cell parameters used in the block diagram. Besides, Table-2 shows the parameters of the fuel cell used. In short, the fuel cell system will provide 6kW in the system.

Wind Turbine Design

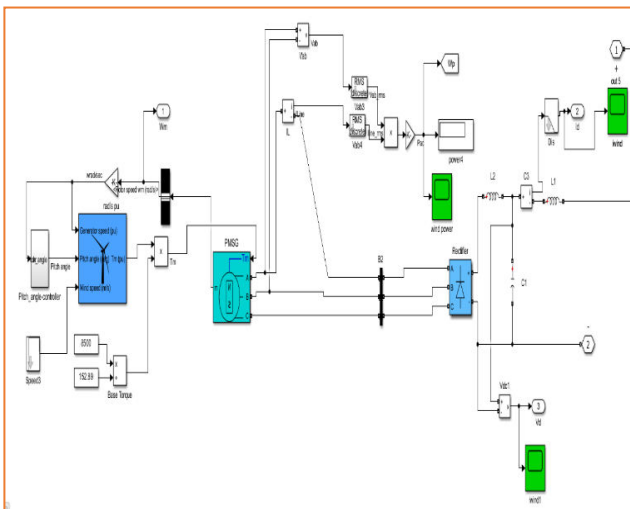


Figure-13. Wind turbine circuit in Simulink.

Table-3. Wind turbine parameters.

Nominal mechanical output power (W)	9.5k
Base power of the electrical generator (VA)	9.5k/0.9
Base wind speed(m/s)	8
Maximum power at base wind speed (p.u. of nominal mechanical power)	0.73
Base rotational speed (p.u. of base generator speed)	1.2

Block Parameters: Wind Turbine

Wind Turbine (mask) (link)

This block implements a variable pitch wind turbine model. The performance coefficient C_p of the turbine is the mechanical output power of the turbine divided by wind power and a function of wind speed, rotational speed, and pitch angle (β). C_p reaches its maximum value at zero β . Select the wind-turbine power characteristics display to plot the turbine characteristics at the specified pitch angle.

The first input is the generator speed in per unit of the generator base speed. For a synchronous or asynchronous generator, the base speed is the synchronous speed. For a permanent-magnet generator, the base speed is defined as the speed producing nominal voltage at no load. The second input is the blade pitch angle (β) in degrees. The third input is the wind speed in m/s.

The output is the torque applied to the generator shaft in per unit of the generator ratings.

The turbine inertia must be added to the generator inertia.

Parameters

Nominal mechanical output power (W): 9500

Base power of the electrical generator (VA): 9500/0.9 10556

Base wind speed (m/s): 8

Maximum power at base wind speed (p.u. of nominal mechanical power): 0.73

Base rotational speed (p.u. of base generator speed): 1.2

Pitch angle β to display wind-turbine power characteristics ($\beta \geq 0$) (deg): 0

Display wind turbine power characteristics

OK Cancel Help Apply

Figure-14. Wind turbine parameters used.

Figure-13 shows the circuit design of the wind turbine subsystem in the microgrid system, while Figure-14 shows the wind turbine parameters used in the block diagram. Other than this, Table-3 shows the parameters of the wind turbine system used. In short, the wind turbine system will provide 9.5kW in the system.

Battery Energy Storage System (BESS)

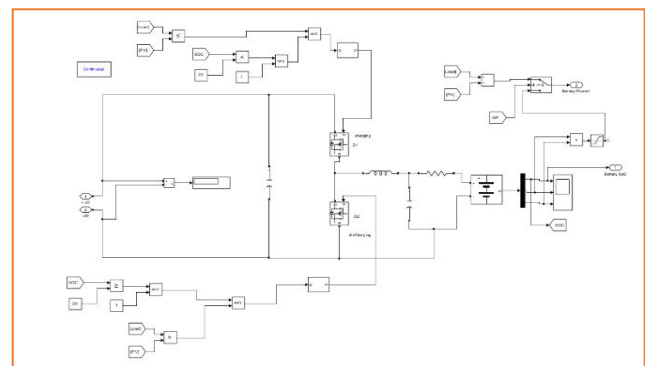


Figure-15. Battery Energy Storage System (BESS) in Simulink.

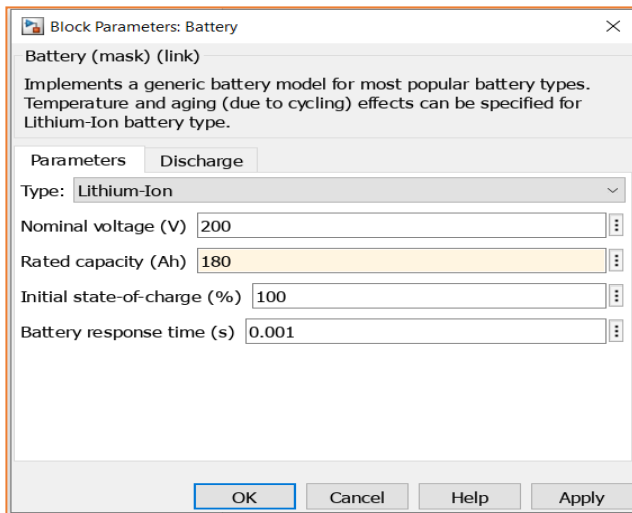


Figure-16. BESS parameter.

Table-4. BESS parameter used.

Type	Lithium-Ion
Nominal Voltage (V)	38k/0.9
Rated Capacity (Ah)	165
Initial state-of-charge	0.73
Battery response time (s)	1.2
Discharge	
Maximum capacity (Ah)	100
Cut-off Voltage (V)	150
Fully charged voltage (V)	232.7974
Nominal discharge current (A)	163
Internal resistance (Ω)	0.02
Capacity (Ah) at nominal voltage	170
Exponential zone [Voltage (V), Capacity (Ah)]	[16.0772, 4.913043]

Figure-15 shows the circuit design of the wind turbine subsystem in the microgrid system. Furthermore, Figure-16 illustrates the data sheet of the battery used. Other than this, Table-4 shows the detailed parameters of the BESS system used. In short, the BESS system can store up to 36kW

Main Grid Design

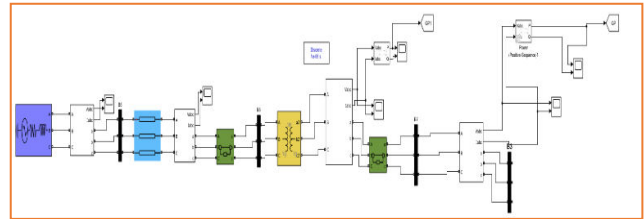


Figure-17. Main grid circuit design in Simulink.

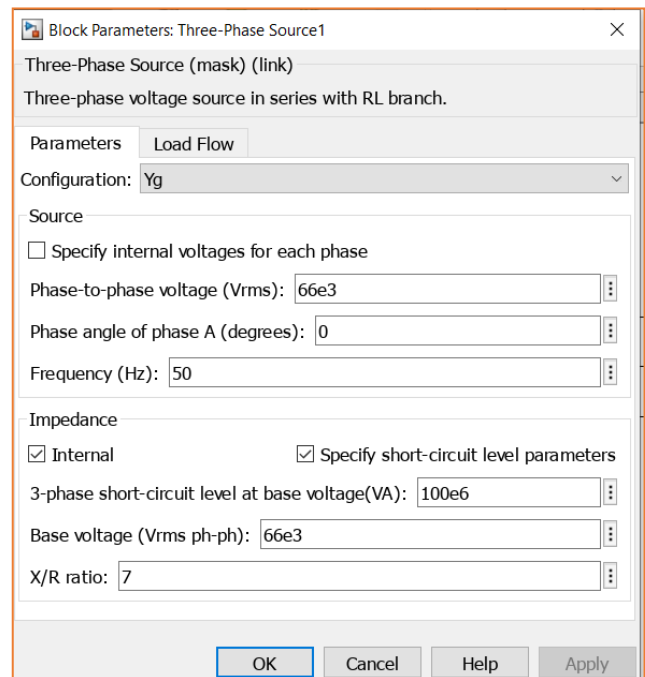


Figure-18. Main grid circuit parameters in Simulink.

Table-5. Main grid circuit parameters used.

Phase to phase voltage (V_{rms})	66k
Frequency, Hz	50
3-phase short-circuit level at base voltage (VA)	100e6
Transmission line length (km)	10

Figure-17 shows the circuit design of the main grid system in the microgrid system. Furthermore, Figure-18 illustrates the value of the grid supplied. Other than this, Table-5 shows the detailed parameters of the grid system used. The transmission line from the main grid to the microgrid system is set at 10 km. In short, the main grid system will have a transmission level of 66 kV. It is a medium-voltage system that normally supplies local distribution and industries.



ERHHO Controller (Outer PI Controller)

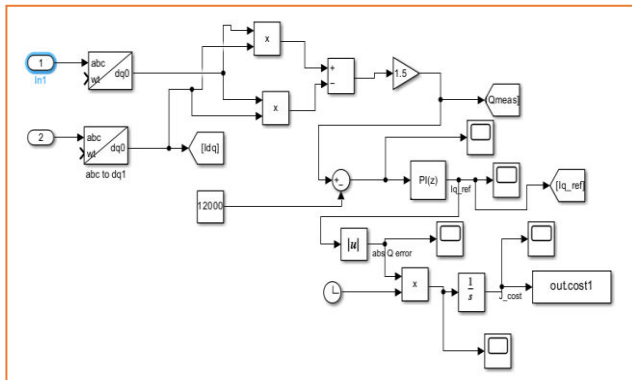


Figure-19. Circuit design for ERHHO controller in MATLAB Simulink.

Table-6. Number of times the simulation runs.

Number of hawks (population)	5
maximum iteration	2
Lower bounds [K_p , K_i]	[0.01,0.01]
Upper bounds [K_p , K_i]	[10,10]

Table-7. Initial Hawks parameter used for ERHHO in the first simulation.

Initial Hawk Parameters	
Initial K_p	6.5582
Initial K_i	0.3280

Table-8. Best K_p and K_i values after ERHHO ran all the simulations with the set number of simulations.

Final Tuned PI Gains	
Best K_p	8.0048
Best K_i	4.2234

Figure-19 shows the circuit design of the ERHHO controller in Simulink. This controller needs some script or coding in MATLAB for simulation. This controller will run the simulation automatically with the number set in the script “run_erhho”. After running, it will show the best K_p and K_i values obtained in those simulations. The component “In 1” will be connected to V_{abc} , while component “In 2” will be connected to I_{abc} . Then, these two values will be transformed to dq form to get the value of the reactive power measure, Q_{meas} . Next, the ERHHO PI tuning controller will use the best K_p and K_i values to obtain the reference I_q value, I_{qref} . Other than this, the “J_cost” is used to evaluate the performance of the ERHHO controller. Then, the “eval_cost” script calculates the fitness value for a given set of PI controller parameters. It tells the ERHHO algorithm how good or bad a candidate solution is. All the

scripts used in this controller will be attached in the appendix of this report. Other than this, Table-6 shows part of the ERHHO controller script. The number of simulations the controller takes to get the best K_p and K_i values can be set in that part. The script shows that it will run 10 simulations: 5 hawks with 2 iterations. In addition, Table-7 shows a sample when the ERHHO starts the first simulation with a random value of K_p and K_i . After 10 times of simulation, it will show the best values of K_p and K_i , as shown in Table-8. Then, these values have to be entered manually for both PI controllers, which are the ERHHO controller and PI controller 2.

PI Controller 2 (Inner PI Controller)

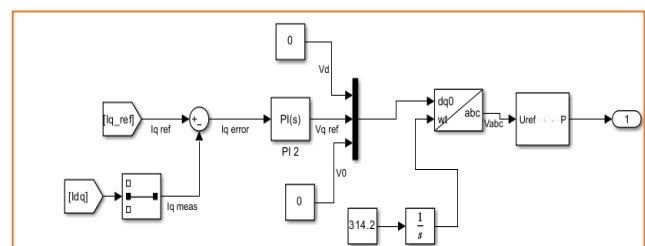


Figure-20. Circuit Design of PI controller 2, which will connect to the PWM of the inverter.

Figure-20 shows the circuit connection of PI controller 2, which will connect to the PWM of the inverter. The inverter is duties to convert the DC voltage from DGs to AC form and supply to the load. The I_{qref} value got from the ERHHO controller is used to calculate the I_{qerror} . Then, it will be transformed to $V_{(qref)}$ after Controller 2 and transformed to V_{abc} to regulate the reactive power and voltage of the load. This controller will also use the best K_p and K_i values as its proportional gain and integral gain values.

System without Controller

Scenario 1: Island mode

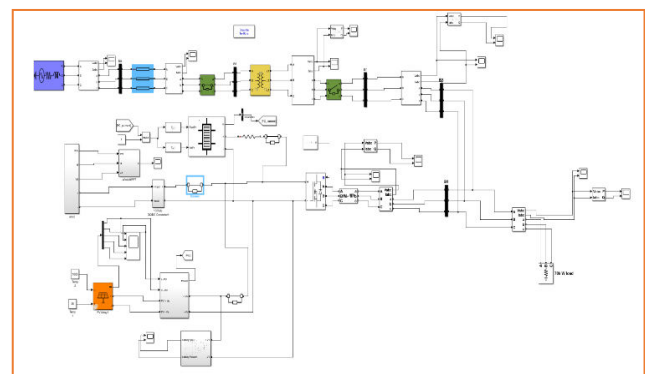


Figure-21. Circuit design for microgrid in Island Mode.



Scenario 2: Grid-connected mode

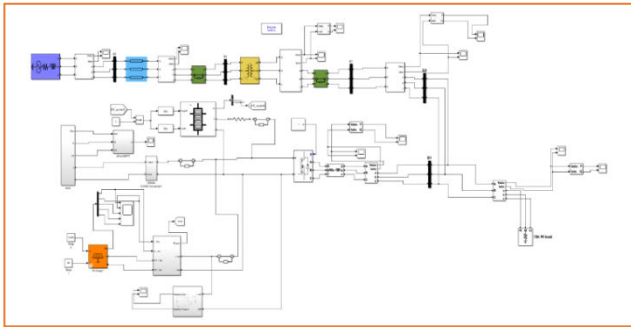


Figure-22. Circuit design for Microgrid in Grid-connected mode.

Figures-21 and 22 illustrate the circuit design of the whole hybrid microgrid system without a controller. In Figure-21, the breaker of the main grid is opened to demonstrate the situation of island mode. Besides, the breaker of the main grid is in a closed state to illustrate the grid-connected mode of the system, as shown as Figure-23. As shown in the figure, the load is set to 70 kW per phase to demonstrate the power supply for a small village.

System with Controller

Scenario 1: Island mode

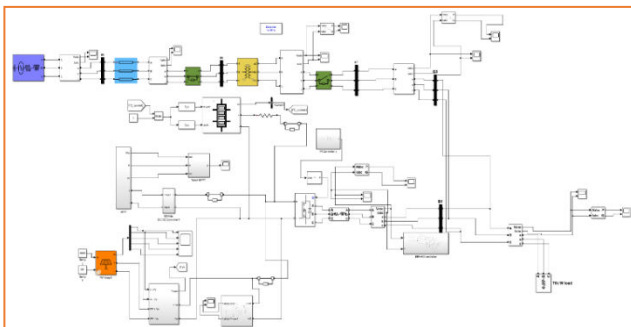


Figure-23. Circuit design after implementation of controllers in Island Mode.

Scenario 2: Grid-connected mode

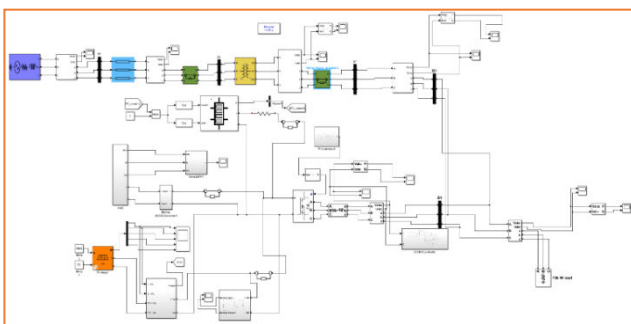


Figure-24. Circuit design after implementation of controllers in Grid-Connected Mode.

Scenario 3: Disconnection of the wind turbine system in island mode

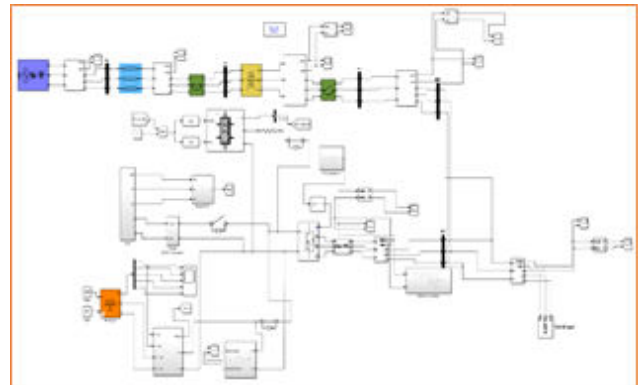


Figure-25. Circuit design without wind turbine system after implementation of controllers in Island Mode

After implementation of controllers, there are three scenarios designed in this condition. They include implementation of controllers in island mode, grid-connected mode, and disconnection of the wind turbine system in island mode. The circuit for each scenario is shown in figure 23, 24, and 25, respectively. These scenarios are designed to evaluate the effectiveness of controllers in different situations. These scenarios can be designed by switching the circuit breakers on and off according to requirements in MATLAB Simulink.

Simulation Process

Simulate the MATLAB Simulink model to get the desired results. All subsystems will be implemented and tested in MATLAB Simulink. The subsystems can achieve their goals after the exercise. Photovoltaic, fuel cell, wind turbine, main grid, and battery subsystems will be developed and selected using the model library. A small village's load demand is 70kW per phase; these subsystems will interface with the BESS, which will store photovoltaic energy in this system. Every subsystem and the main grid has breakers. These illustrate three real-life situations. One scenario shows system performance when the grid is under maintenance and does not supply electricity to the load, while the other shows performance when connected to the main grid. The final scenario is to observe controller performance while one DG has connectivity issues in island mode. To display the system output graph under these three conditions, two scopes will be deployed at the load. Voltage profile and system performance will be analyzed using the scope graph. Two scopes will illustrate four waveforms. The first scope will show voltage and current, while the other will show load active and reactive power. Verify MATLAB Simulink installation to build up the simulated circuit design. After setting up the model, circuit and subsystem designs are created. After checking subsystem and controller parameters, the simulation begins. All load waveforms were captured and will be analyzed. This study aims to use Enhanced Randomized Harris Hawk



Optimization to tune the system's PI controller. Therefore, the simulation will record and analyse the comparison before and after controller implementation.

RESULTS AND DISCUSSIONS

Simulation before Proposed Method

Scenario 1: Island Mode

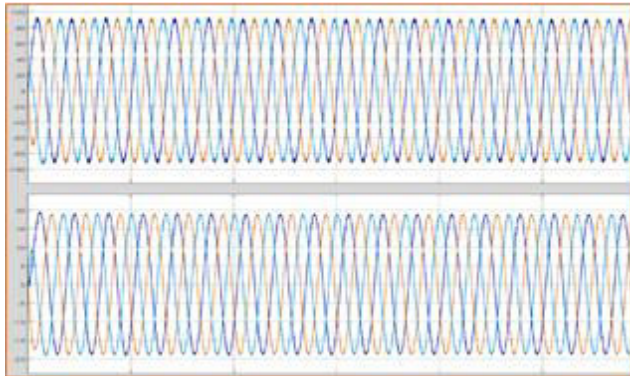


Figure-26. Voltage and current waveforms of the load.

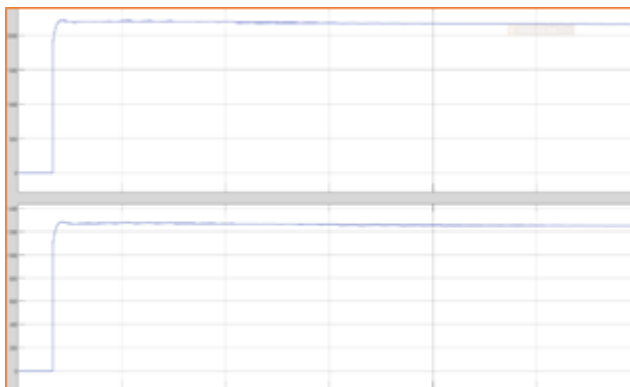


Figure-27. Real power and reactive power waveform of the load.

Figure-26 depicts the microgrid's island mode load voltage and current waveforms. In island mode, the electrical system operates without the utility grid. The figure shows three-phase, 90.00 V peak waveforms, which are unsuitable for village use. Table-9 shows its present as 19 I_{peak} . Phase imbalance is seen in these waveforms. Figure-27 illustrates island mode actual and reactive power. Real and reactive power started at zero and rose to 2200 W mean and 1250 VAR mean, respectively, as shown in the figure. Waveforms overshoot somewhat. Power is charging

the battery before supplying the load; hence, the power and reactive power waveforms are zero.

Despite increasing RE supply, all four waveforms remain unchanged. Because the same DC bus connects renewable energy sources, voltage-induced flow back occurs. Increased power or voltage from one renewable energy source can cause converter voltage imbalance. Power can be transferred due to this imbalance. If PV output voltage is higher than wind turbine output voltage, current can flow across the DC bus from PV to the wind source. Instead of powering the load, energy is redistributed internally. Since RE systems are not electrically isolated and not connected to separate buses, shared voltage lines cause one RE unit to partially absorb or negate another's output. Thus, an ERHPO-PI tuning controller is needed to maintain the voltage profile and power transformation.

Scenario 2: Grid-Connected Mode

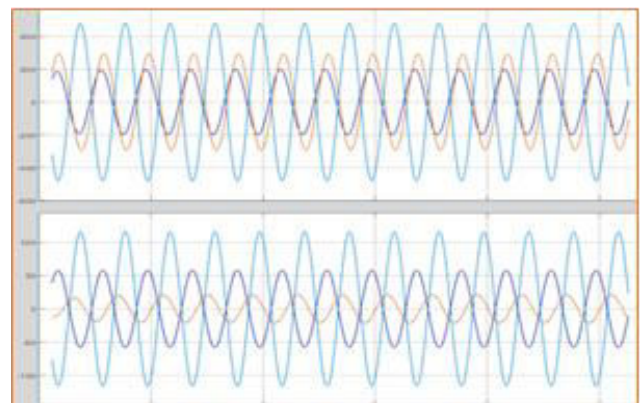


Figure-28. Voltage and current waveform of the load.

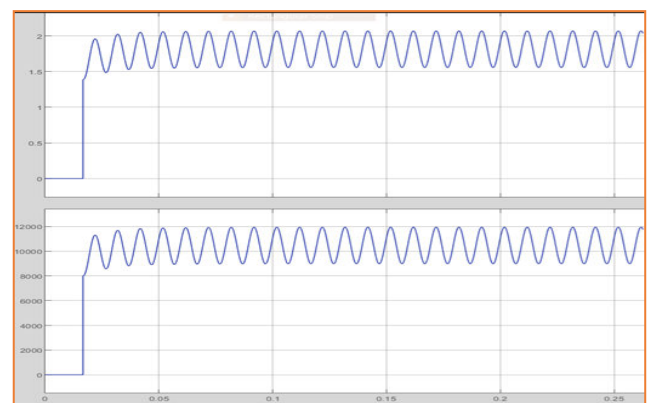


Figure-29. Real power and reactive power waveforms of the load.

Table-9. Data tabulated before the controller.

	Voltage (V) (peak)	Current (A) (peak)	Active Power (W) (mean)	Reactive Power (VAR) (mean)
Island mode	90.00	19.00	2200	1250
Grid-connected mode	565.58	120.00	1.7k	11k



Figure-28 illustrates hybrid microgrid load voltage and current in grid-connected mode. The figure indicates that the three-phase voltage and current waveforms are not balanced. This indicates inadequate system control due to uncontrolled reactive power flow. Even with a constant main grid voltage, the waveforms demonstrate poor power quality due to uncontrolled reactive power.

Figure-29 shows the grid-connected load's real and reactive power waveforms. In grid-connected mode, the main grid powers the microgrid. The figure demonstrates that real power ranges from 0 to 1.5 W, while reactive power is around 11 kVAR (see Table-9). Figure-32 shows substantial oscillation in reactive and active power. Power is charging the battery before supplying the load; hence, the power and reactive power waveforms are zero. Internal power circulation or voltage-induced flowback occurs on the DC bus between renewable energy sources. Despite using four DGs, the true power waveform is just 1.5W. Also, the microgrid's contact with the main utility grid causes irregular reactive power growth. Reactive power injection is needed for microgrid voltage control and power factor enhancement. The inverter should actively manage reactive power to stabilise voltage and reduce reactive power flow in a properly managed system. The inverter fails without a controller. System losses and power quality might result from unregulated reactive power exchange. This shows the need for a reactive power control loop, supporting this project's goal.

Simulation after Implementation of Controllers

Scenario 1: Island Mode

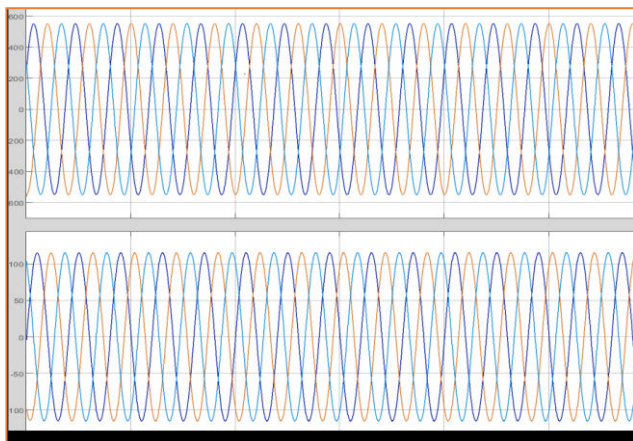


Figure-30. Voltage and current waveform of the load.

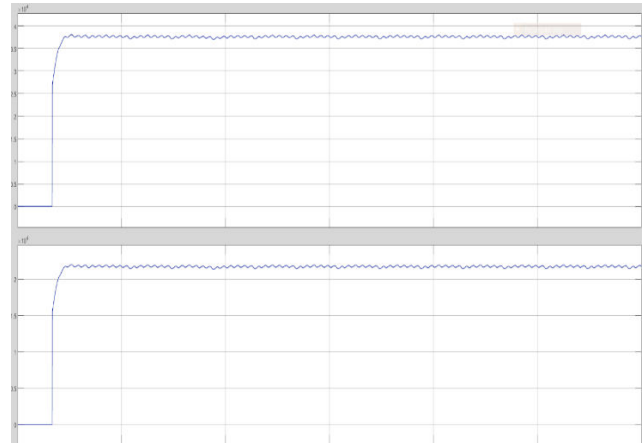


Figure-31. Real power and reactive power waveforms of the load.

After implementing the ERHHO PI controller, the voltage and current of the load have perfect waveforms, as shown in Figure-30. They are recorded as 565.58V peak and 120 A peak, respectively, as shown in Table-10. From Table-10, the voltage waveform is recorded as 565.58 V peak, which is equivalent to 400V rms (line-to-line) by using equation (31).

$$V_{rms} (L - L) = \frac{V_{peak} (L-L)}{\sqrt{2}} \quad (31)$$

Three-phase voltage and current are sinusoidal and balanced. This indicates that the ERHHO controller's optimised PI gains can regulate voltage and power quality in the inverter. The lack of overshoot or oscillation in both waveforms shows that the ERHHO algorithm reduced transient responses and steady-state inaccuracy by improving controller settings (K_p , K_i). A balanced load is also indicated by the symmetrical current distribution among phases.

Figure-31 depicts active power on top and reactive power of the load in island mode below. Table 10 shows active power at 37.5 kW peak and reactive power at 22.5 kVAR. The simulation begins with both waveforms rising quickly and smoothly until stabilising into steady-state operation. Low ripple and no overrun on both signals. Reactive and active power now reach normal levels. This indicates strong controller dynamics. The controller reduces DC bus imbalance and circulation between RE sources by boosting inverter response.

In island mode, the inverter must govern power distribution to the load without grid backup; therefore, performance is crucial. Figures 31 and 32 show that the ERHHO-tuned PI controller maintains power stability and prevents unmanageable reactive power flow in island mode microgrids.



Scenario 2: Grid-Connected Mode

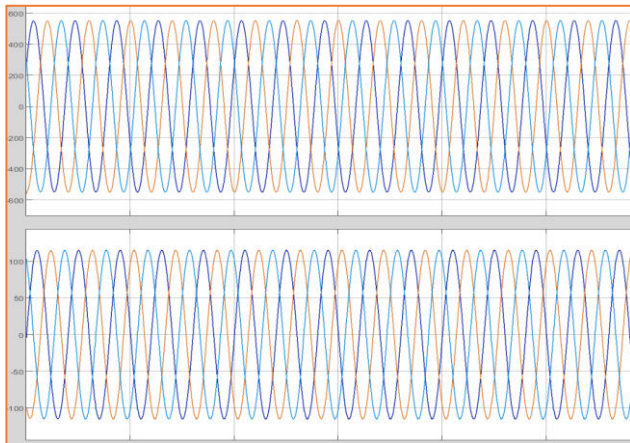


Figure-32. Voltage and current waveforms of the load.
waveform of the load.

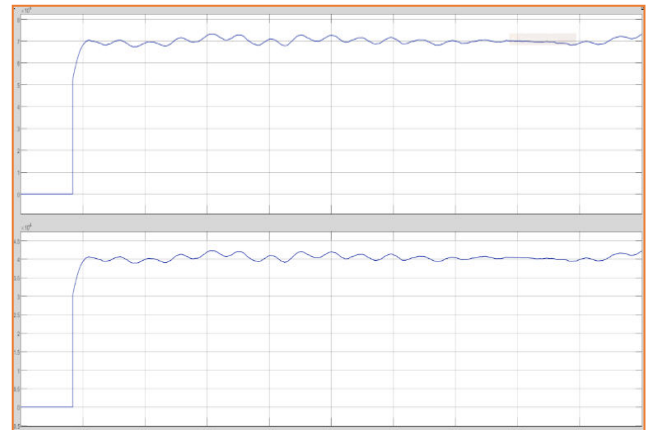


Figure-33. Real power and reactive power.

Table-10. Data tabulated before the controller.

	Voltage (V) (peak)	Current (I) (peak)	Active Power (P) (mean)	Reactive Power (Q) (mean)
Island mode (Scenario 1)	565.58	120.00	37.5k	22.5k
Grid-connected mode (Scenario 2)	565.58	120.00	70k	40k

Figure-32 depicts the voltage waveform at the top and the load waveform transfer in grid-connected mode after ERHHO PI controller implementation. Table-10 shows a voltage waveform of 565.58 V peak, or 400V rms. Line-to-line current is 120V peak. These are the standard Malaysian three-phase voltage levels. Both graphs have sinusoidal amplitude. This means the system regulates voltage and synchronises with the power grid. The smoothness of voltage and current signals without distortions or overshoot shows that the system is stable once the controller is employed.

After deploying the ERHHO PI controller in grid-linked mode, Figure-33 shows the microgrid system's active and reactive power waveforms. Table-10 shows load active power at 70kW and reactive power at 40 kVAR. Despite small oscillations after the step response, the power waveform exhibits strong damping and a steady-state waveform with some overshoot. Figure-33 starts with zero real and reactive power because the power must charge the battery. As in island mode, the controller improves inverter response to reduce DC bus imbalance and RE source circulation. Thus, all RE give the correct voltage, current, real, and reactive power.

Other than this, both waveforms include tiny ripples. This shows that ERHHO tuning PI controllers can regulate dynamic grids well. Additionally, the system can supply 70kW per phase, enough for a small community. The controller fails to control reactive power as the ERHHO controller sets it, but it helps the system regulate reactive power to a normal and acceptable amount. In scenario 1

(island mode), reactive power dropped from 780 kVAR to 22.5 kVAR. ERHHO may not replicate enough scenarios to acquire excellent K_p and K_i values. Only 10 ERHHO runs are done in this thesis to find the optimal K_p and K_i values. In summary, the ERHHO PI tuning controller can regulate the voltage profile and improve reactive power regulation in hybrid microgrids.

Scenario 3: Wind Turbine Disconnected Island Mode

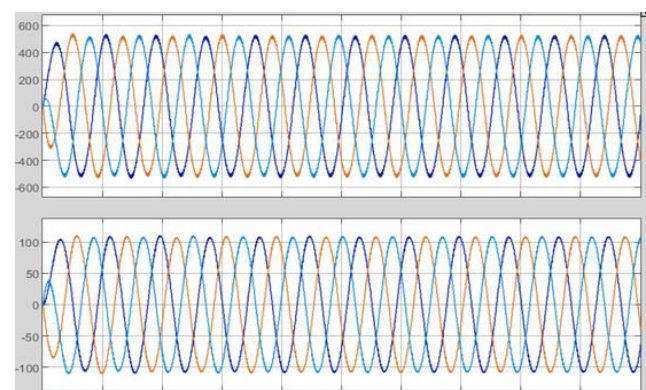


Figure-34. Voltage and current waveforms when the wind turbine is disconnected in Island Mode.

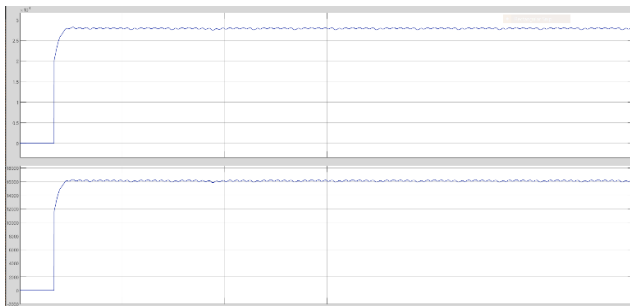


Figure-35. Active power and reactive power waveforms when the wind turbine is disconnected in Island Mode.

Table-11. Data tabulated after the controller in island mode when the wind turbine is disconnected.

	Voltage (V) (peak)	Current (I) (peak)	Active Power (P) (mean)	Reactive Power(Q) (mean)
Island mode (Scenario 3)	565.58	110.00	28.0k	16.1k
Island mode (Scenario 1)	565.58	120.00	37.5k	22.5k

Figure-34 shows the island mode voltage and current waveform following wind decoupling. The voltage waveform is balanced and sinusoidal over all three phases. This shows that the inverter and ERHHO PI controller can stabilize voltage for the remaining energy sources. Table-11 shows that the voltage and current waveforms initially had lower peak values but ultimately grew to 565.58V and 110A. These two waveforms employ the ERHHO algorithm to optimize the inverter's PI controller to detect voltage and current drops caused by lower reactive power supply. I_q regulation in the inverter adjusts reactive power output. The output voltage and current were balanced after this modification rose gradually. As shown in Table-11, the rebalanced current (110A) has fallen from the original 120A energy resources. These results show that the PI controller can help the inverter restore voltage to nominal levels and boost current injection when energy resources decrease. Real and reactive power waveforms are shown in Figure-35. These two waveforms are stable and oscillation-free despite the wind turbine being disconnected. Real power stays at 28 kW, whereas reactive power stays around 16.1 k VAR.

Table-11 shows lower real and reactive power after energy resource reduction. The 20kW-80kW per phase power is enough for a small settlement. These declines are predicted as the wind turbine generates a lot of active and reactive power. After disconnection, only solar and fuel sources supplied the load. Power decreases indicate generation capacity loss. Otherwise, active and reactive power waveforms are stable with no noticeable oscillations. This indicates that the ERHHO-optimized PI controller adjusted the inverter's reactive power output to match the new system configuration. Hardware limitations prevented the controller from restoring power levels. Success in maintaining voltage and power quality changed.

CONCLUSIONS

This paper concludes that hybrid microgrids can increase power distribution network reliability, efficiency, and sustainability. Combining renewable and non-renewable energy sources with power electronics helps the controllers increase energy consumption and environmental sustainability. The work uses the ERHHO-based PI controller to regulate reactive power, power transmission quality, and voltage profiles in hybrid microgrids. The theory of the proposed technique and each distributed generation subsystem for a small village are simulated and explained in this study. The simulation without controls showed unregulated voltage and reactive power. Voltage-induced flowback among RE sources before the controller also alters active power transmission. After installing the ERHHO controller, voltage and reactive power were stabilised. Implementing the controller improves regulation, even when output reactive power is not totally controlled.

The suggested reactive power controller is incomplete. Reactive power regulation is improving but not entirely regulated. This is because there are not enough case simulations to determine the best K_p and K_i values. To find the best K_p and K_i parameters, the ERHHO controller is simulated 10 times. The simulation periods may not be enough because hybrid microgrid systems are complicated, especially with several DG and main grids. At least 600 simulations are needed to find the best K_p and K_i values for both PI controllers. This ensures that output reactive power may be fully controlled and matches the ERHHO controller reactive power. In a perfectly working 3-phase microgrid, the total active power equals the sum of all three phases. Therefore, future simulations and hardware implementations must incorporate a thorough three-phase power analysis to accurately depict real performance.



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