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Development and Simulation of a Hybrid Microgrid Incorporating Droop Control and Maximum Power Point Tracker

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ABSTRACT

This paper presents the development and simulation of a Hybrid Microgrid using Droop Control and Maximum Power Point Tracking (MPPT) in Matlab/Simulink. The study models two synchronous generators and a solar PV effectively, managing both active and reactive loads. The implementation of Droop Control ensured proportional power sharing among generators, enhancing system stability with transients settling within 2 seconds of disturbances. The MPPT algorithm increased solar power efficiency by 20% compared to fixed operating points. Key results show that the Hybrid Microgrid maintained stable voltage and frequency levels across varying load conditions, achieving a maximum power output of 1 p.u. during peak solar irradiance. These findings underscore the potential of Hybrid Microgrids in enhancing energy reliability, particularly in regions with unreliable power supply, and suggest avenues for future research into advanced control strategies and environmental impacts.

1. INTRODUCTION

Microgrids are localized groups of interconnected electricity sources and loads that can operate independently from the traditional centralized grid or in conjunction with it. They are characterized by their ability to generate, distribute, and regulate the flow of electricity in a specific geographic area. Microgrids can include a variety of distributed energy resources such as solar panels, wind turbines, energy storage systems, and backup generators [1].

Microgrids are increasingly being based on energy storage systems combined with renewable energy sources like solar, wind, and small hydro, often backed up by a fossil fuel-powered generator. Hence, offer higher reliability compared to the main grid as they have sources close to loads, making them less vulnerable to disruptions in transmission caused by natural disasters, While currently more expensive than power from the main grid, advancements in technology, mass production of microgrid equipment, and standardization of design and operations may eventually make microgrids a lower-cost option, Microgrids can operate connected to the larger grid or in standalone mode, providing resilience during grid outages and the ability to operate independently when needed [2]. Droop control is a power sharing method used in electrical power systems where multiple generators operate in parallel, its essential in microgrids to ensure that power generation is shared proportionally among different sources based on their voltage or frequency deviations. It helps maintain system stability and balance power sharing during load changes. It also contributes to reactive power sharing, where the sharing of reactive power is based on the voltage deviations of the sources. By adjusting the voltage references and droop constants, reactive power can be shared inversely proportional to the droop values [3].

2. FUNDAMENTAL CONCEPTS

Modern power systems are complex networks that deliver electricity from generators to consumers. They encompass generation, transmission, distribution, and consumption stages. The primary goal is to ensure a reliable and efficient supply of electricity while maintaining system stability and quality [5].

The operation of power systems involves intricate control mechanisms to maintain system stability, manage power flow, and respond to fluctuations in demand. Various control strategies, such as generator regulation, voltage control, and frequency management, are employed to ensure the smooth operation of the grid and prevent disruptions [6].

2.1 Components of a Power Systems

1. **Generation:** Involves converting various forms of energy (e.g., coal, natural gas, hydro, wind, solar) into electrical energy. Modern power systems increasingly incorporate renewable energy sources [7].
2. **Transmission:** High-voltage transmission lines transport electricity over long distances. The focus is on minimizing losses and ensuring the stability of power flow.
3. **Distribution:** Medium and low-voltage networks distribute electricity to end consumers. This stage includes substations and transformers that step down voltage levels [4].
4. **Consumption:** End users, ranging from residential to industrial consumers, use the electricity for various purposes.

2.2 Microgrids and Active Distribution Networks

Microgrids and active distribution networks represent innovative approaches to electricity distribution that offer increased flexibility, reliability, and efficiency. Microgrids are considered essential building blocks for smart grids, offering a decentralized approach to energy management that enhances grid stability and efficiency at both micro and macro levels [8]. Microgrids are localized energy systems that can operate independently or in conjunction with the main grid, incorporating distributed energy resources like solar panels, wind turbines, and energy storage, Active distribution networks, also known as smart grids, are modern electricity distribution systems that incorporate advanced communication, control, and monitoring technologies to enhance grid performance and efficiency [4]. Microgrids can lower peak load prices, engage in demand response markets, and provide frequency management services to the larger grid, thus contributing to economic efficiency [8].

2*.2.1 Load Frequency Control*

In power systems, the balance between generation and load is essential for maintaining system frequency at the nominal value. Any imbalance between generation and load can lead to frequency deviations, which, if not corrected promptly, can result in system instability and potential blackouts. Load Frequency Control (LFC) systems continuously monitor the grid frequency and automatically adjust the output of generators to match the load demand, thereby stabilizing the system frequency [6]. LFC strategies typically involve two main control loops: frequency control and tie-line control. Frequency control focuses on regulating the system frequency by adjusting the output of generators based on frequency deviations, while tie-line control involves coordinating the power exchange between interconnected systems to maintain frequency synchronization [5].

The operation objectives of LFC are to maintain reasonably uniform frequency, to divide the load between generators, and to control the tie-line interchange schedules. The change in frequency and tie-line real power are sensed, which is a measure of the change in rotor angle, δ, i.e. the error $\Delta\delta$ to be corrected. The error signals, i.e. ΔF and ΔP_{tie}, are amplified, mixed and transformed into a real power command signal ΔP_v, which is sent to the prime mover to call for an increment in the torque.

2.2.2 Automatic Voltage Control

Automatic Voltage Control (AVC) plays a key role in regulating voltage levels. An Automatic Voltage Regulator (AVR) is a device used in generators to automatically adjust the voltage output. It takes fluctuating voltages and stabilizes them to provide a constant voltage output. The variation in voltage typically occurs due to changes in load on the supply system, and uncontrolled voltage fluctuations can damage power system equipment. By installing voltage control equipment at various points in the power system, such as near transformers, generators, and feeders, voltage variations can be effectively managed [9].

2.2.3 Architecture of a LFC and AVR systems

Fig. 1 illustrates the control system architecture for a generator, which includes both Load Frequency Control (LFC) and an Automatic Voltage Regulator (AVR). In this system, the LFC regulates the balance of power by adjusting the turbine's steam input through a valve control mechanism. This adjustment compensates for deviations in power (ΔP_{tie}), aligning the generator's power output with the load demand to stabilize frequency. Meanwhile, the AVR is responsible for maintaining voltage levels by monitoring output through a voltage sensor. When deviations in reactive power ΔQ occur, the AVR sends corrective signals to the excitation system and generator field to stabilize the output voltage. By coordinating these components, the control system ensures stable and efficient generator operation, effectively responding to load fluctuations and maintaining power quality in the microgrid.

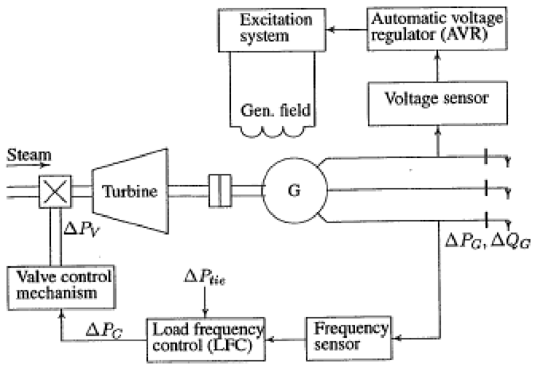

Fig. 1 Schematic diagram of LFC and AVR of Synchronous [5]

The prime mover, brings change in the generator output by an amount ΔP_θ which will change the values of ΔF and ΔP_{tie} within specified Tolerance.

2.2.4 Voltage Regulation

Reactive power control is crucial for balancing reactive power generation or absorption to maintain voltage stability within acceptable limits. By adjusting reactive power levels, system operators can ensure that voltages are kept at desired values, supporting the overall stability of the power system [7]. Voltage regulation plays a key role in controlling voltage levels at different system points to maintain system stability.

Methods such as shunt capacitor switching and shunt reactor installation are utilized to manage reactive power and improve voltage profiles, especially in long high-voltage lines where voltage stability is critical [6].

2.2.5 Droop Control

Droop control is a method used to regulate the output of generators based on changes in system frequency or voltage. The concept of droop control is often applied in primary frequency control, where generators adjust their output in proportion to frequency deviations to help restore system frequency to its nominal value [10]. In voltage control, droop control can also be utilized to regulate voltage levels by adjusting reactive power output in response to voltage variations [9]. It allows multiple generation units to be connected in parallel, sharing loads in proportion to their power rating. In droop control, frequency and voltage "droop" values are assigned to each generation unit in the grid. These droop values represent how much the frequency and voltage are allowed to deviate from their nominal values to account for changes in power demands. The most common type of droop control is conventional droop control. In conventional droop control, frequency and voltage vary linearly with respect to active and reactive power, respectively. For instance, assigning a 1% frequency droop to a converter means that its frequency deviates 0.01 per unit (p.u) in response to a 1.0 p. u change in active power. Reverse droop control is an alternative technique that can be useful in low-voltage microgrids [12].

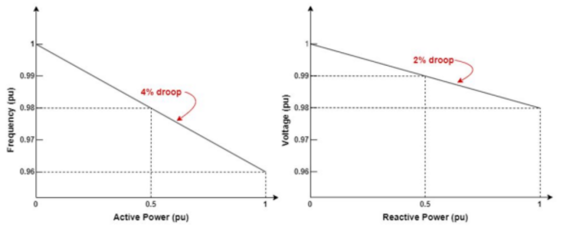

Fig. 2 Frequency and Voltage Droop Curves [12]

2.3 The Swing Equation

The swing equation describes the dynamic behavior of synchronous generators during transient conditions, particularly in response to disturbances such as faults or sudden changes in system conditions. The swing equation is a differential equation that governs the rotor angle and speed of a synchronous generator following a disturbance. It describes the interaction between mechanical and electrical power in the system and is crucial for analyzing the stability of the generator during transient events [6].

For a machine, δ_r is angle between rotor and stator, mmf is F_r and resulting air gap mmf , both rotating at synchronous speed, if the generator armature resistance and leakage flux are neglected, the angle between E and terminal Voltage V, is denoted by δ ,known as the power angle. Consider a synchronous generator developing an electro-magnetic Torque T_e, running at synchronous speed w_{sm}. If T_m is mechanical torque, under steady-state we have,

$$T_m = T_e \quad (1)$$

a disturbance cause departure from steady state ($T_m > T_e$) or ($T_m < T_e$)

$$T_a = T_m - T_e \quad (2)$$

If J is combined moment of inertia of the prime mover and generator, neglecting frictional and damping torques, from law of rotation we have,

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e \quad (3)$$

Where, θ_m is angular displacement and w_{sm} is angular velocity

$$\theta_m = w_{sm}t + \delta_m \quad (4)$$

δ_m is rotor position before disturbance at t=0

$$w_m = \frac{d^2\theta_m}{dt^2} = w_m + \frac{d^2\delta_m}{dt^2} \quad (5)$$

And the rotor acceleration is

$$\frac{d^2\theta_m}{dt^2} = \frac{d^2\delta_m}{dt^2} \quad (6)$$

$$J_{wm}\frac{d^2\delta_m}{dt^2} = P_m - P_e \quad (7)$$

J_{wm} is inertia constant and is related the rotating kinetic energy W_k

2.4 Model of a Synchronous Generator

Synchronous generators play a crucial role in converting mechanical energy into electrical energy through electromagnetic induction. These generators are synchronized with the grid frequency and are essential for maintaining system stability, providing reactive power support, and ensuring the balance between generation and consumption in power systems [6]. In islanded operation, synchronous generators can help maintain system frequency and voltage levels within acceptable limits. Synchronous generators can be controlled and coordinated within the microgrid architecture to ensure optimal operation and response to changes in load or generation. They can also be synchronized with other generators or the main grid during restoration procedures to ensure a smooth transition back to normal operation (Hatziargyriou 2014).

This diagram in Fig.3 illustrates the geometric relationship between the rotating and stationary reference frames in a synchronous machine. It shows the rotor's direct (d) and quadrature (q) axes relative to a fixed reference axis, with the power angle δ indicating the angular displacement between the rotor's d-axis and the reference axis. This representation is crucial for analyzing the dynamic behavior of synchronous machines and understanding power angle relationships, where the angle δ directly influences the power transfer capability of the machine.

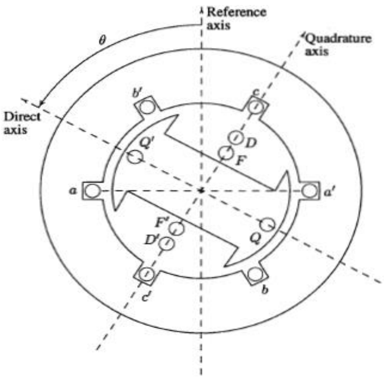

Fig. 3 Schematic of Synchronous Machine [5]

In a three-phase generator, the stator contains three coils aa, bb and cc displaced by 120 electrical degrees. The concentrated full pitch coil shown here maybe considered to represent distributed windings producing sinusoidal mmf waves concentrated on the magnetic axis of the respective phases. An air gap flux of ϑ per pole is revolving, the flux linkage at $\omega t = \frac{\pi}{2}$. Assuming λ_a will vary as angle ωt. Flux linkage becomes

$$\lambda_a = N\vartheta \cos \omega t \tag{8}$$

Voltage induced is obtained by faraday's law

$$e_a = -\frac{d\lambda}{dt} = \omega N\vartheta \sin wt \tag{9}$$

The rms value of generated voltage becomes

$$E = 4.44\, fN\vartheta \tag{10}$$

2.4.1 Generator Model

Equation (11) shows the relationship between rotor angular acceleration ($d^2\delta/dt^2$) and the imbalance between mechanical power input (ΔPm) and electrical power output (ΔPe). The term 2H/ws represents the inertia constant normalized by synchronous speed, essentially describing how the machine's rotating mass responds to power imbalances [13].

Equation (12) appears to be the frequency deviation (ΔΩ(s)) expressed in the s-domain, showing how system frequency changes in response to the power mismatch [ΔPm(s)-ΔPe(s)], scaled by the inertia constant 2H.

$$\frac{2H}{w_s}\frac{d^2\Delta\delta}{dt^2} = \Delta P_m - \Delta P_e \tag{11}$$

$$\Delta\Omega(s) = \frac{1}{2H_s}[\Delta P_m(s) - \Delta P_e(s)] \tag{12}$$

Fig. 4 represents the implementation of equation (12) using discrete simulink blocks.

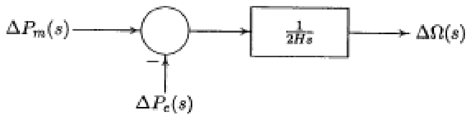

Fig. 4 Generator Model

3. METHODOLOGY

The synchronous generators are modeled to reflect their electrical and mechanical characteristics, including excitation control and dynamic behavior.

3.1 Design Specifications

The parameters in Table 1 were chosen to reflect realistic values commonly found in power system studies, particularly for Load Frequency Control (LFC) and Automatic Voltage Regulation (AVR) in microgrid settings. The MVA ratings for Generator 1 (5.5 MVA) and Generator 2 (5 MVA) represent medium-scale generation units, typical in microgrids, and allow for an analysis of load-sharing dynamics between generators with slightly different capacities. The system frequency is set at 50 Hz, which is the standard frequency in many parts of the world, including Europe, Asia, and Africa, ensuring the study's applicability to real-world conditions. The synchronous machine field current of 50 A provides a standard excitation level necessary for effective voltage regulation, directly impacting the AVR's performance in stabilizing reactive power. Both generators have 4 poles, a common configuration for machines operating at 50 Hz, ensuring a synchronized rotational speed of 1500 RPM. Together, these values provide a practical and standardized foundation for studying the interactions between LFC and AVR within a microgrid environment.

The Model described in Table.1 has the following constant parameters Defined:

Table. 1 Design Parameters

Parameter	Value
Generator 1	5.5MVA
Generator 2	5MVA
Frequency	50Hz
Synchronous Machine Field current	50 A
Poles (Gen1 & Gen2)	4 each

To implement this model, it is essential to define the blocks that make up the simulation, discussed below are the sub-models essential to our design. It is important to note some special blocks which aided our design such as:

1 Discrete-Time Integrator: accumulates a signal over time. It takes a continuous-time signal as input and provides a discrete-time output representing the sum of the input values over each sample interval.

2 Synchronous Machine Measurement: This block measures specific electrical quantities (voltage, current, etc.) of a simulated synchronous machine (generator). It extracts the desired measurement signal from the machine model.

3 Simulink-PS Converter (Simulink to Physical Signal): This block converts a Simulink signal (voltage, current, etc.) into a format suitable for outputting to Simscape or an external device (e.g., real-time hardware).

4 PS-Simulink Converter (Physical Signal to Simulink): This block does the opposite, It takes a physical signal (e.g., sensor measurement) from an external device or from Simscape and converts it into a format readable by Simulink for simulation purposes.

3.2 Implementation of Generator Block

As described in the second chapter, a generator requires controllers to stabilize frequency and voltage, which are known as Governor and Prime Mover respectively, these blocks are fed into a generator model; to implement a generator block, Matlab/Simulink provides an inbuilt model to aid our simulation.

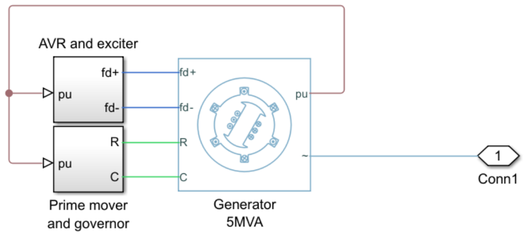

Fig. 5 Generator Block

The generator Model is a closed loop Generator block fed from two control blocks for Automatic Voltage regulation and Load Frequency control, this will ensure regulated voltage and frequency from Active and Reactive power feedbacks. The salient pole synchronous machine block has the following parameters as mention in table 3.1 The parameters are required by the inbuilt block to simulate the generator model, the model also require sub-control blocks to be fed into it, for control of frequency and voltage, these blocks are achieved from the use of basic blocks with Simulink.

3.2.1 AVR and Exciter Block

Both the field voltage and the prime mover rotation rate are managed using a feedback control loop, which is feed to a measurement block on Simulink, this block is able to demultiplex the generator output into synchronous generator per unit outputs.

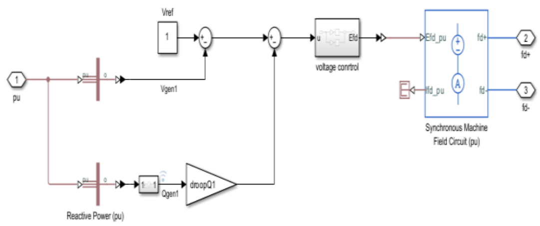

Fig. 6 AVR and Exciter Block

The direct droop method focuses on maintaining a strong correlation between reactive power and inverter output voltage. In our model voltage, a voltage reference is compared with voltage generated and the reactive power fed droop gain block which is interfaced by a discrete time integrator, this droop block is to control adjusts the voltage setpoint based on reactive power variations, stabilizing the system. The error signal is then fed into a sub-model "voltage control" block, within this block is an implementation of a PI-Controller

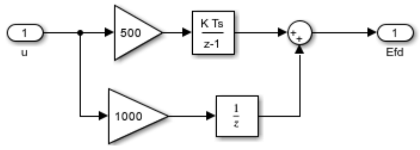

Fig. 7 PI-Controller

The PI controller block sends appropriate control signal to the synchronous machine field circuit, which applies the specified voltage and measures the current in the field circuit of the machine it is connected to which in our case is a salient pole generator.

$$V_{error} = V_{ref} - V_{gen1} \quad (12)$$

$$V_{droop} = DroopControl(Q_{gen1}) \quad (13)$$

$$V_{combinederror} = V_{error} - V_{droop} \quad (14)$$

Where;

V_{ref} = reference voltage, V_{gen1}= generator voltage, Qgen1 = Reactive Power Generated The $V_{combinederror}$ is fed then to a PI controller for control action.

3.2.2 Governor and Prime Mover Block

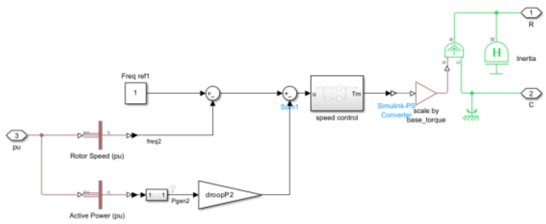

Fig. 8 Governor and Prime Mover Block

Just as described in the AVR model, however this time we are comparing a reference frequency signal with an active power input interfaced with an integrator and the generator frequency, the output is then feed to a speed controller block, the speed controller block is a PI Controller which feeds appropriate control signal in form of torque, this is interface with a Simulink to PS converter, which converts the control signal to physical quantities that simulates the prime mover which simulates rotor rotation in our Generator model.

3.2.3 Solar Block

To implement a solar model, we will have to describe, three important parameters.

1 The Solar output which is a function of irradiance.
2 The MPPT algorithm fed to a DC-DC converter which is crucial for optimizing the power output and efficiency of solar panels.
3 The Inverter which converts solar DC Powar to AC fit for grid

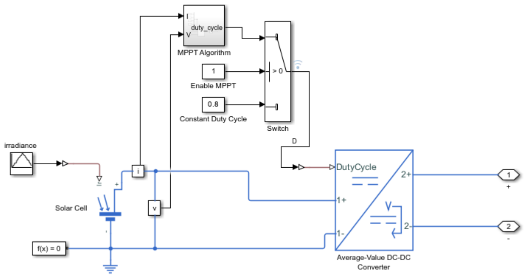

Fig. 9 Solar Generator Block

3.2.4 MPPT Algorithm

The solar cell's output current and voltage are measured and fed into the MPPT algorithm block. This block calculates the optimal operating point (voltage and current) for maximum power output under the current irradiance level. The MPPT algorithm then outputs a duty cycle signal.

3.2.4.1 Principle of operation of MPPT Algorithm

A function implements a Maximum Power Point Tracking (MPPT) controller using the Perturb & Observe algorithm for the PV system. The goal of the MPPT controller is to adjust the duty cycle (D) of a boost converter to maximize the power output from the PV array. This is described by the flowchart in Fig. 10.

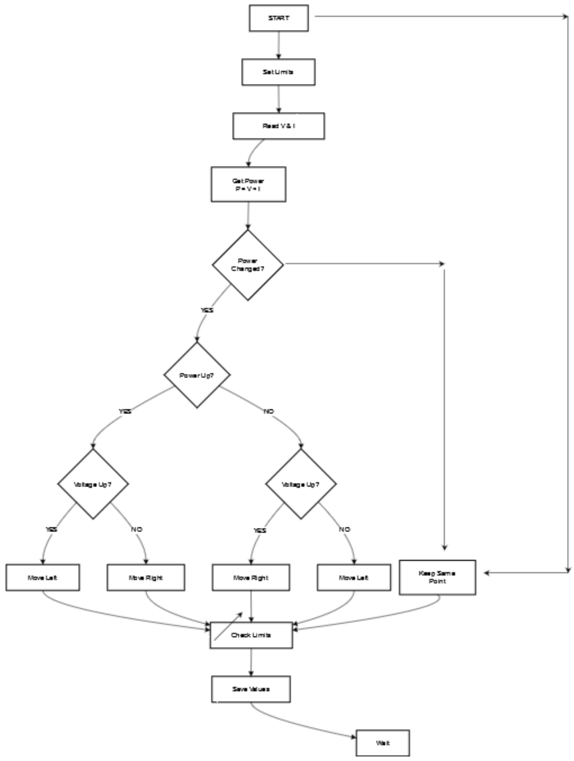

Fig. 10 Flowchart of Perturb and Observer Algorithm

4. RESULTS AND DISCUSSIONS

On Simulink, we implemented three generating stations, two from synchronous generators and one from a Solar generator, below are results from our simulation, we will be utilizing Simulink's Data Analyzer tool for our results.

4.1 MPPT Duty Cycle against Irradiance

From Fig. 11, it can be observed how the duty circle varies with solar irradiation in a full day (24 hours). The comparison in the Fig. 11 is done using normalized data (presented in per unit) During morning hours when there is no sunlight, the MPPT Algorithm has a duty cycle of 1, as the time approaches 3am when sunlight begins to shine, there is a steep drop in duty cycle, as the sun irradiance reaches it's peak at about 1pm the MPPT duty circle falls to 0, at this point Maximum Power is being delivered by the solar Panel to the grid, Fig.11 portrays the Power generated by the Solar Generator.

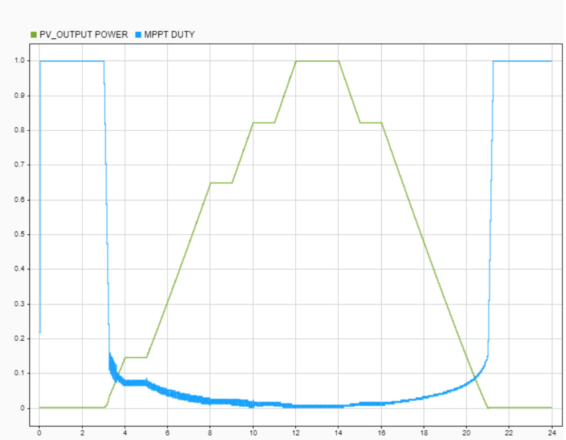

Fig. 11 MPPT Duty cycle and Irradiance

4.2 Synchronous Generator (1)

The synchronous generator is a 5.5 MVA 4pole 50Hz synchronous generator, Fig.12 portrays the Active and Reactive Power produced generator (1) in Purple and Orange respectively in (Per Unit representation). To properly understand the Fig. 4.2, it is important we reiterate that generator (1) is always connected to the grid, however the simulation is set to switch off generator (2) and solar generator at time = 10s, it is also important to state that the switching circuit has an open conductance of 1×10^{-6} ohm, hence a slight possibility of conductance when open, the graph dynamics shows some transient at start of generation which lasted for about 2, the active Power Produced remained at about 0.58 p.u while reactive at about 0.9 p.u, when the switch opens the other generators are cut out and only generator one picks up the load.

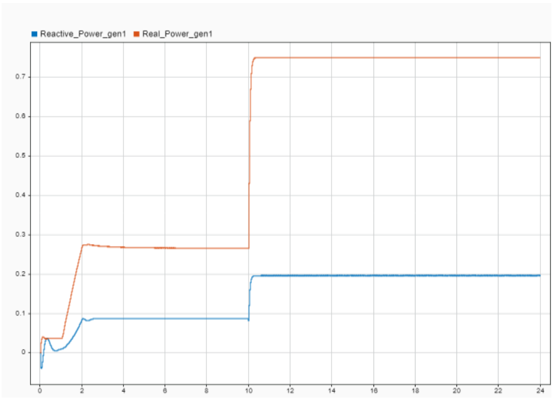

Fig. 12 Generator 1 – Active Power and Reactive Power

4.2.1 Simulation Break Down

From Fig. 12, the Real and Reactive power response of the generator (1) over changes in the network over a time period of 24 hours is explained as follows

1 Initial Transients (0-2):

At the start of the simulation, Generator 1 experiences transient oscillations due to the sudden application of load or initial synchronization process. These oscillations settle down within approximately time=2, indicating the system's initial stabilization.

2 Steady-State Operation (2-10):

After the initial transients, the Active Power (orange line) stabilizes around 0.28 p.u., and the Reactive Power (blue line) stabilizes at almost 0.1 p.u. During this period, Generator 1 is sharing the load with the other generators (Generator 2 and the solar generator).

3 Switching Event (at 10):

At 10 seconds, the switch opens, causing Generator 2 and the solar generator to disconnect from the grid. This leaves only generator 1 connected to the load, requiring it to take over the full power supply.

4 Post-Switching Dynamics:

Immediately after the switch opens, the Active Power output of Generator 1 rises sharply to around 1 p.u., indicating that it is now supplying the entire load. The Reactive Power output also rises sharply, to meet reactive load demand, redistribution of reactive power demand.

4.3 Synchronous Generator (2)

Generator Two is a 3 MVA 4 pole 50 Hz generator, which is disconnected from Load at time = 10, To demonstrate the characteristics of the generator (2), we would be comparing it's active and reactive load for generator (2).

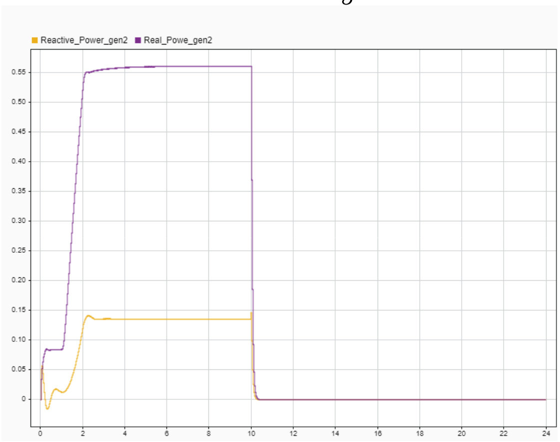

Fig. 13 Generator 2 - Active Power (Purple) and Reactive Power (Orange)

Just as generator (1), the second generator rises with some transients to meet load Active and Reactive load demand, however at time = 10s, when Circuit Breaker opens and cutoff generator two, both active are reactive power generation falls to Zero, indicating disconnection.

This can also be observed from the Fig. 14 which compares active power demands of both generators

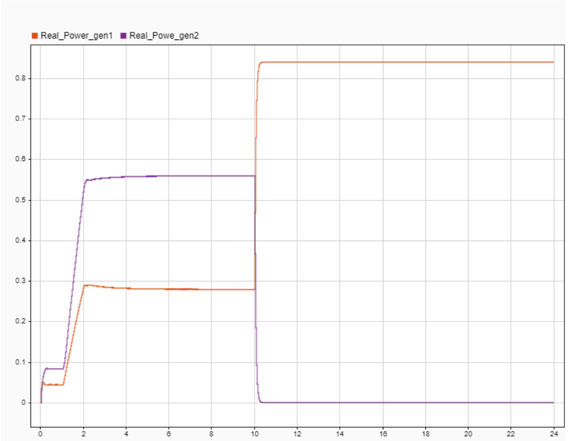

Fig. 14 Comparison of Active Power for synchronous generators

It can be observed, that generator (2) supplies to more real power demanded by the load as distributed by the droop ratio, however, as circuit breaker cuts of load, generator (1) works to meet both demands.

4.4 Aggregate Power transmitted to Loads

If we consider the overall Power transmitted to the Loads by the model represented by the characteristics in Fig. 14Fig. the following properties can be observed.

1 Consistent Delivery of Active Power to loads even after circuit breaker opens.

2 Active power demand is widely larger than reactive Power in the microgrid as designed in the model.

3 Slight Deep is noticed in the Reactive network at time = 10 as circuit breaker opens.

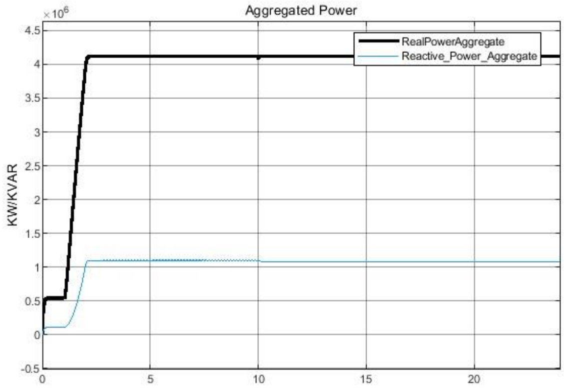

Fig. 15 Aggregate power transmitted to loads

From the results above, we are able to demonstrate how multiple generators function together and how variations are handled by the system. The systems have been modelled in their per unit equivalence, which is a method used in power system analysis and modeling to simplify the representation of electrical quantities. It is particularly useful in the context of large-scale power systems involving generators, transformers, transmission lines, and other equipment, Per-unit values provide a uniform way to represent electrical quantities.

Conclusion

In conclusion, this project has successfully developed a Hybrid Microgrid model incorporating essential control strategies and renewable energy sources. The simulation results have provided valuable insights into the behavior of synchronous and solar generators within a microgrid network and validate the effectiveness of microgrids in maintaining stable power distribution and system reliability.

Microgrid Technology has various applications which could be beneficial in Nigeria such as Rural electrification, Meeting Industrial Demands, Support Urban Energy Management, Nigeria can reduce its dependence on fossil fuels, promoting environmental sustainability.

This study present results for simulations conducted on the Hybrid Microgrid model, showcasing the performance of the generating stations and the overall system under various conditions. By analyzing the data and charts obtained from the simulations, the effectiveness of the implemented control strategies, such as Droop Control and MPPT, in optimizing power generation and distribution within the microgrid network were validated.

The findings from the simulations provide valuable implications for future research and practical applications in the field of microgrid technology. The insights gained from the project can guide further investigations into advanced control strategies, renewable energy integration, and system optimization to enhance the efficiency and sustainability of microgrid systems.

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