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The Role of Energy Management Systems in Addressing Microgrid Challenges

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Abstract

The contribution of renewable energy system in terms of climate change plays a vital roles and the energy scarcity in rural areas are the major concern nowadays. Countries where the grid are not stable and has severe load shedding are the common place to integrate the environmental friendly energy system. Microgird is one of the solution to mitgate such problems either for standalone or grid connected systems. In this research the overview of Microgrid systems are discussed. The propblems and challanges are investigated. The control mechanism of them are discussed and how energy management systems can reduce the associates problems related to microgrids are proposes and critically analysed. In this work, a dispatch strategy has been demonstrated to ensure that the system can reduce the use of diesel generators and increase the utilization of renewable energy sources. The strategy also decreases the excess electricity produced by the system while ensuring its technical feasibility. The system was simulated with and without storage; the results indicate that the version without a battery is more economically and technically feasible while still meeting the necessary constraints.

Keywords: Microgrid, Cyber security, Data collection, Load Scheduling, Sharing energy.

Introduction

The concept of Microgrid (MG) is well-established in the realm of renewable energy systems (RES). It plays a crucial role in integrating distributed energy resources (DERs). The primary challenge with renewable energy sources lies in their unpredictability due to factors such as irradiation, wind velocity, and temperature. After the system is installed, it's essential to monitor its operation, energy production, identify potential faults, and make necessary adjustments to address any issues. This can be achieved by analyzing the data generated by the system. Modern technologies offer a wide range of technical systems. Microgrids were first introduced in 2001 by Bob Lasseter [14]. Monitoring the data and predicting future production levels are also key considerations.

In theory, microgrids should be constantly connected to the utility grid, enabling surplus energy from the microgrid to be fed into the primary grid and any energy deficit in the microgrid to be supplemented by the utility grid. If the grid experiences stability issues, the microgrid (MG) should be capable of operating as an independent, standalone system. The main components of MG include DERs, power converters, energy storage, loads, master controller, intelligent switches, protective devices, communication systems, and control and automation systems. MGs can be categorized into three classes: AC microgrids, DC microgrids, and hybrid AC/DC microgrids. Among these, the AC microgrid is popular due to its plug-and-play approach for all DERs, but it requires additional power conversion devices. Hybrid AC/DC microgrids can be further classified into AC-coupled, DC-coupled, and AC-DC-coupled microgrids. Therefore, a microgrid can be understood as a decentralized network architecture with locally connected production, transmission, regulation, and utilization that can operate independently or in conjunction with other microgrids or the primary grid [13], [9], [16].

Microgrids (MGs) face several challenges, particularly in terms of voltage and frequency deviations [6], power losses, and inefficiencies stemming from load scheduling and the adjustment of Distributed Energy Resources (DERs) according to load requirements. To tackle these issues, extensive research has been conducted to date. Additionally, effective monitoring and observation are crucial for managing MG problems [2], [8], [11]. In this research, we analyzed these issues and utilized Homer Pro, a simulation-based tool, to enhance Energy Management (EM) for a simple MG. For more complex MG systems, addressing the technical feasibility is vital to resolving supply and demand-related challenges.

MGs are used worldwide, but they are particularly valuable in isolated areas, such as islands. The primary objective of deploying MGs in these contexts is to ensure a reliable power supply for appliances and other loads. Regardless of the stability of the public grid, an MG can dynamically adjust its parameters, which is a key feature of this system. Dynamic adjustments are necessary for various factors, including the capacity of connected DERs such as photovoltaic (PV) systems, wind turbines (WT), diesel generators (DG), and the utility grid. Designing a system that incorporates an Energy Management System (EMS) is essential for addressing challenges in areas with unstable grids and for maximizing the use of renewable energy sources (RES).

In this paper, we investigate a method for MG design that tackles issues such as renewable energy fraction, maximizing power supply from RES, load scheduling, minimizing excess electricity production, maintaining the proper load ratio of diesel generators, and operating the system in a fuel-efficient manner. Importantly, the system must also meet power supply requirements while ensuring economic feasibility.

Operating Mode of a Microgrid

An MG can operate in a variety of different modes. The three primary operating modes are a grid-connected mode, which refers to a connection with the power grid; an island mode, which refers to a standalone operation; and a transient operating mode, which is the bidirectional mode when the primary grid is disconnected or stable. The microgrid ensures energy and power control flow in a grid-connected mode by injecting energy from the power utility grid. The power utility grid regulates the network voltage amplitude, frequency, and phase at the specific connection point of standard coupling (PCC), an electrical link between the non-conventional resources and the grid. A synchronization procedure is needed of voltage amplitude, frequency, and phase, of distributed energy resources during the transient operating mode to ensure a smooth transition.

Microgrid Control

In the context of large power systems, three control architectures have been developed: the centralized, the decentralised and the distributed topology. A centralized architecture consists of a single controller which manages and communicates with all the other components. Control decisions are based on the knowledge of all control inputs optimized in a single optimization problem. The main feature of the decentralized architecture is that the control system is composed of several individual controllers. The M.G.s hierarchy follows the architecture of conventional power systems comprising three main layers that correspond to their main control functionalities, namely primary (field level), secondary (microgrid level), and tertiary (grid level) [1].

Control Method 1: Primary Control

Control can be applied locally in D.G. units in the primary layer to regulate the output. P-Q (P=active, Q= reactive) current regulated control can be applied for a grid-connected mode. The main goal of P-Q control is to reduce voltage and frequency drops by using grid-capable frequencies. The P-Q controller provides the reference voltage of the boost inverter, which controls both the active and reactive power. The control is applied to the inverter to deliver output power according to the reference set point. The primary grid-imposed output parameters are voltage, frequency, and phase. The control can be applied in a d-q frame of reference [1], [3],- [9] . Primary control operates at the fastest timescale. It maintains voltage and frequency stability of the M.G. and it ensures proper power sharing among DER in [4], [7]. In [5], a voltage-based frequency controller has been proposed. The load-frequency dependence of an isolated M.G.s is utilized to regulate the system´s frequency. In [12] researchers have considered only MPPT as the primary control objective.

Control Method 2: Secondary Control

The main objective of secondary layer control is to remove steady-state errors in voltage and frequency caused by the primary layer [1]. The main function of secondary control is to perform power quality regulations, to manage voltage/frequency deviations, unbalances, and harmonics, encompassing a synchronization loop between the M.G. and the external grid [10]. Secondary control mitigates voltage and frequency deviations introduced by the primary control. The secondary control objective is to reduce the voltage and frequency deviation produced locally at the D.G.s by adjusting the reference value of primary controllers.

Control Method 3: Tertiary Control

Tertiary control oversees regulating power exchange with the external grid or/and with other M.G.s, which includes advanced functions related to efficiency and economic enhancements constituting a higher management level. Tertiary control is located at the top level of an M.G. hierarchical control system [10]. Extensive reviews have already been done on the hierarchical rules [14]. Tertiary level control provides input to the secondary level control by generating reference parameters and setting the optimal operating points, further improving the system's operation stability [14].

Droop control in MG

Conventional droop-based primary control mentioned is expressed here from the information of [7]. Droop control operates without power sharing. If there is a power flow between two voltage sources U1 and U2 and Z is the value of impedance then considering $Z = Z \prec \theta, U1 = U1 \prec \delta, U2 = U2 \prec 0°$, the active and reactive power flow is obtained [7]:

$$P = \frac{U_1^2}{z}\cos\theta - \frac{zU_1U_2}{z}\cos(\theta+\delta);$$
$$Q = \frac{{U_1}^2}{Z}\sin\theta - \frac{zU_1U_2}{z}\sin(\theta+\delta)$$

If we consider $Z = Ze^{j\theta} = R + jX$ in above equations , it can be written as:

$$P = \frac{U_1}{R^2+X^2}[R(U_1 - U_2\cos\delta) + XU_2\sin\delta];$$
$$Q = \frac{U_1}{R^2+X^2}[-RU_2\sin\delta + X(U_1 - U_2\cos\delta)]$$

$$U_2\sin\delta = \frac{XP-RQ}{U_1}$$
$$U_1 - U_2\cos\delta = \frac{RP+XQ}{U_1}$$

If $X \gg R$ and R can be negligible, and the power angle is small where δ the angle information between two voltage sources which can be controlled by active and reactive power flow. By controlling P and Q, the frequency can be controlled too. $\delta \cong \frac{XP}{U_1U_2}, U_1 - U_2 \cong \frac{XQ}{U_1}$. The general droop is known as $\frac{P}{f} - \frac{Q}{U}$control where (P = active power, Q = reactive power, U = voltage and f = frequency). If, $\omega_{ref} and U_{ref}$ are the nominal frequency and voltage of the grid and $k_p, k_q$are the static droop gain, then it can be achieved as follows [7]:

$$\omega = \omega_{ref} - k_pP$$
$$U = U_{ref} - k_qQ$$
$$k_p = \frac{(\omega_{max} - \omega_{min})}{P_{max}}$$
$$k_q = \frac{(U_{max} - U_{min})}{Q_{max}}$$

In primary control grid connected mode, P-Q current regulated control can be applied [1]. The application applied to the inverter to deliver the required output power which is needed. The control applied in d-q frame reference. The control converts the output to $U_d, U_q(d-qframe)$.Based on reference P and Q, reference current or voltage can be derived to compare with the grid current or voltage in d-q frame and fed into control loop (PI controller as an example). P and Q in d-q frame are given by [1]:

$$P = \frac{3}{2}(V_dI_d + V_qI_q)$$
$$Q = \frac{3}{2}(-V_dI_d + V_qI_q)$$

In that model$V_d, V_q, I_d and I_q are d_q$ components of grid side voltage and current. In steady state,V_d is zero so reference current is derived as:

$$I_{dref} = \frac{2P_{ref}}{3V_d}$$
$$I_{qref} = \frac{2Q_{ref}}{3V_d}$$

In Island mode, (V-F) droop control technique can be applied. The objectives of droop control are to share the load between DGs

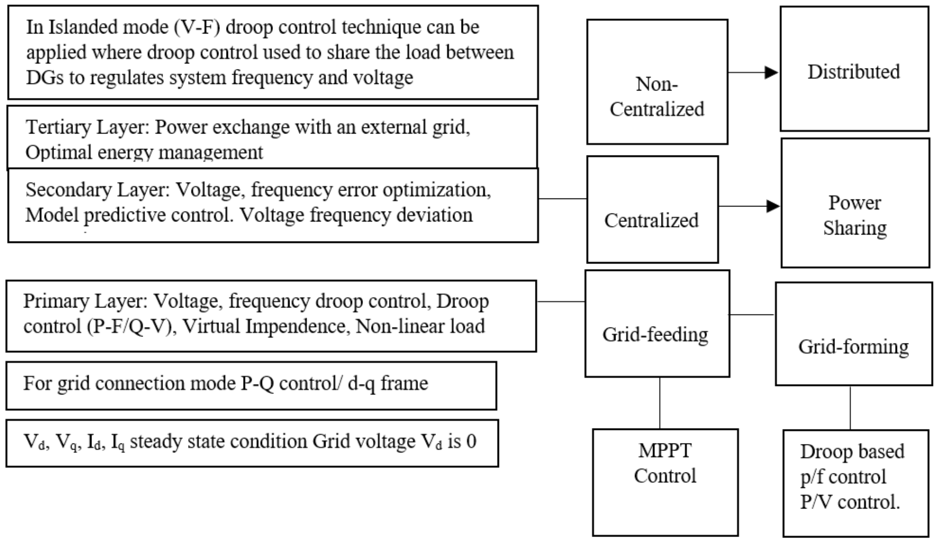

Figure 1: A Sample MG Setup (Control Unit)

and to regulate system frequency and voltage. It is required to provide a reference value of voltage and frequency to the controller. Active power has a relation with frequency while reactive power of DG is controlled by voltage droop equations for active and reactive power:

$$f = f^* + k_P(P - P^*)$$
$$V = V^* + k_Q(Q - Q^*)$$

where $f^*, P^*, V^* and Q^*$ are reference values of frequency, active power, voltage, and reactive power respectively k_P and $k_Q$are droop coefficients. By the above equation one can find out the error from the system and it can be controlled.

To ensure the system's stability, the microgrid's active power flow must be balanced in the M.G.'s grid-connected and islanded operation [15]. Researchers used a single-phase DQ transformation to extract the direct component of the injected current to the VSC (voltage source converter), which is used to control the active power. DQ conversion converts the time de-pendent oscillating components into time-independent non-oscillating quantities. The first step of DQ transformation is to convert the three current and voltage phases into the $\alpha - \beta - 0$ rotating reference frame using the Clarke transformation matrix. The $V_\alpha - V_\beta$and V_0parameters can be converted to the dq_0 reference frame by multiplying $\alpha - \beta - 0$ and V_0 parameters with the park transformation matrix [15]. Where ω is the rotational speed of the DQ reference frame ($100\pi \frac{rad}{sec}$) and t is the time, in seconds, from the initial alignment.

$$\begin{pmatrix} V(\alpha) \\ V(\beta) \\ V(0) \end{pmatrix} = \begin{pmatrix} \frac{2}{3} & \frac{-1}{3} & \frac{-1}{3} \\ 0 & \frac{1}{\sqrt{3}} & \frac{-1}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{pmatrix} \begin{pmatrix} V(a) \\ V(b) \\ V(c) \end{pmatrix}$$

$$\begin{pmatrix} V(d) \\ V(q \\ V(c) \end{pmatrix} = \begin{pmatrix} \sin(\omega t) & -\cos(\omega t) & 0 \\ \cos(\omega t) & \sin(\omega t) & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} V(\alpha) \\ V(\beta) \\ V(0) \end{pmatrix}$$

Design of an Energy Management System for Microgrids MG

In planning the MG system, we have adopted a systematic approach that utilizes HOMER, along with a generated load profile from an island and a MATLAB model. We have established synchronization between the optimal sizing obtained from HOMER, which serves as input for the MATLAB Energy Management System (EMS) model. This MATLAB model simulates real-time information, which is then fed back into HOMER. This dynamic process considers various factors, such as photovoltaic (PV) array output, battery charge and discharge power, generator production, converter size, Levelized Cost of Energy (LCOE), Net Present Cost (NPC), emissions (an environmental consideration), excess electricity (EE), power loss, and more.

HOMER focuses on maintaining power balance and incorporates energy management (EM) through a droop control mechanism, as explained in this paper. It also models grid-forming generators and inverters to maintain frequency stability within the MG system.

Additionally, HOMER considers various dispatch strategies, including Load Following (LF) and Cycle Charging (CC). The LF strategy aims to minimize excess electricity, while the CC strategy ensures that surplus energy is utilized to charge the batteries or serve secondary loads.

Formulas

PV array power output

$$P_{\mathrm{PV}} = Y_{\mathrm{PV}} \cdot f_{\mathrm{PV}} \cdot \frac{G_{\mathrm{t}}}{G_{\mathrm{t,STC}}} \cdot [1 + \alpha_P \cdot (T_{\mathrm{c}} - T_{\mathrm{c,STC}})] \tag{1}$$

Battery charge and discharge

$$P_{\mathrm{discharge,max}} = \eta_{\mathrm{batt,d}} \cdot \left(\frac{Q_1}{\Delta t} + \frac{k \cdot c \cdot Q}{\Delta t} \right) \tag{2}$$

Renewable fraction

$$f_{\mathrm{ren}} = \frac{E_{\mathrm{ren}} + H_{\mathrm{ren}}}{E_{\mathrm{served}} + H_{\mathrm{served}}} \tag{3}$$

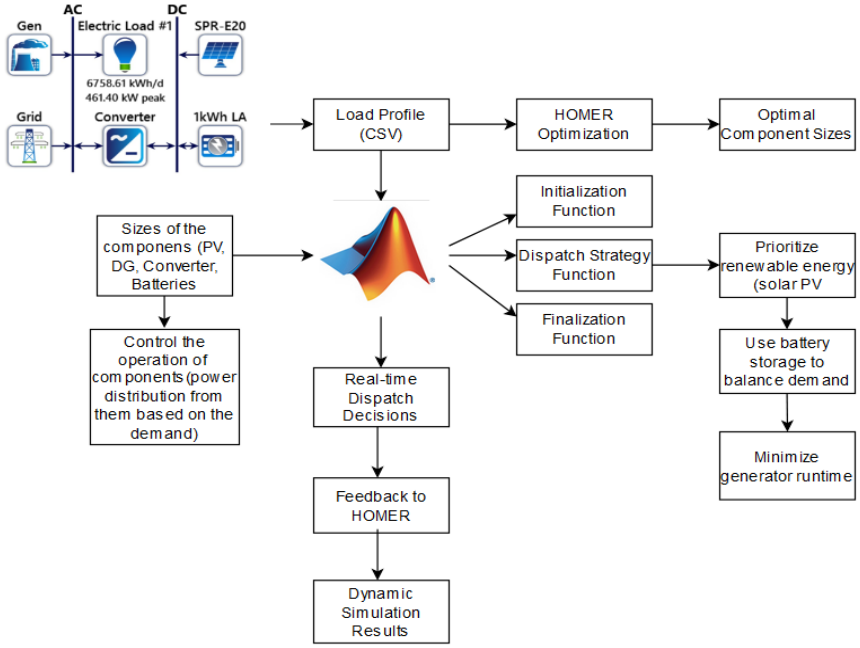

Figure 2: Homer-Matlab-EMS Integration

Net present cost (NPC)

$$\mathrm{NPC} = \sum_{t=1}^{N} \frac{C_t}{(1+r)^t} \tag{4}$$

Levelized cost of energy (LCOE)

$$\mathrm{LCOE} = \frac{\mathrm{NPC}}{\sum_{t=1}^{N} \frac{E_{\mathrm{served},t}}{(1+r)^t}} \tag{5}$$

Emissions

$$E_{\mathrm{total}} = \sum_j (F_j \cdot e_j) \tag{6}$$

Generator fuel consumption

$$F = F_0 \cdot Y_{\mathrm{gen}} + F_1 \cdot P_{\mathrm{gen}} \tag{7}$$

Excess electricity

$$f_{\mathrm{excess}} = \frac{E_{\mathrm{excess}}}{E_{\mathrm{prod}}} \tag{8}$$

Power balance equation

$$P_{\mathrm{gen}} + P_{\mathrm{ren}} + P_{\mathrm{batt}} = P_{\mathrm{load}} + P_{\mathrm{loss}} \tag{9}$$

Grid-forming inverter (droop control)

$$f = f_0 - K_{\mathrm{droop}} \cdot (P_{\mathrm{output}} - P_{\mathrm{set}}) \tag{10}$$

Battery frequency support

$$P_{\mathrm{batt}} = -K_f \cdot (f - f_0) \tag{11}$$

Load following (LF) dispatch

$$P_{\mathrm{gen}} = \min(P_{\mathrm{load}}, P_{\mathrm{gen,max}}) \tag{12}$$

$$P_{\mathrm{batt,charge/discharge}} = P_{\mathrm{renewable}} - P_{\mathrm{load}} \tag{13}$$

Cycle charging (CC) dispatch

$$P_{\mathrm{gen}} = P_{\mathrm{gen,max}} \tag{14}$$

$$P_{\mathrm{surplus}} = P_{\mathrm{gen,max}} - P_{\mathrm{load}} \tag{15}$$

$$P_{\mathrm{batt,charge}} = \min(P_{\mathrm{surplus}}, P_{\mathrm{batt,max}}) \tag{16}$$

In the formula for PV array power output, P_{PV} represents the power output of the PV array in kW, Y_{PV} is the rated capacity of the PV array under standard test conditions (kW), and f_{PV} is the derating factor accounting for system losses. G_{t} refers to the solar irradiance on the PV array in kW/m^2, while $G_{\mathrm{t,STC}}$ is the solar irradiance under standard test conditions 1 kW/m^2. The formulas used in this paper (1-11) are based on the guidelines provided in the HOMER Pro manual.

In the formula 2, $P_{\mathrm{discharge,max}}$ represents the maximum power the battery can discharge in kW, $\eta_{\mathrm{batt,d}}$ is the battery discharge efficiency, Q_1 refers to the available energy at the beginning of the time step in kWh, and Δt is the time step length in hours. In addition c is the storage capacity ratio, and Q is the total battery capacity in kWh.

In the formula 3, f_{ren} represents the fraction of energy supplied by renewable sources, E_{ren} is the total renewable electricity production in kWh/year, and H_{ren} is the total renewable thermal production in kWh/year. E_{served} refers to the total electricity demand served in kWh/year, while H_{served} is the total thermal demand served in kWh/year.

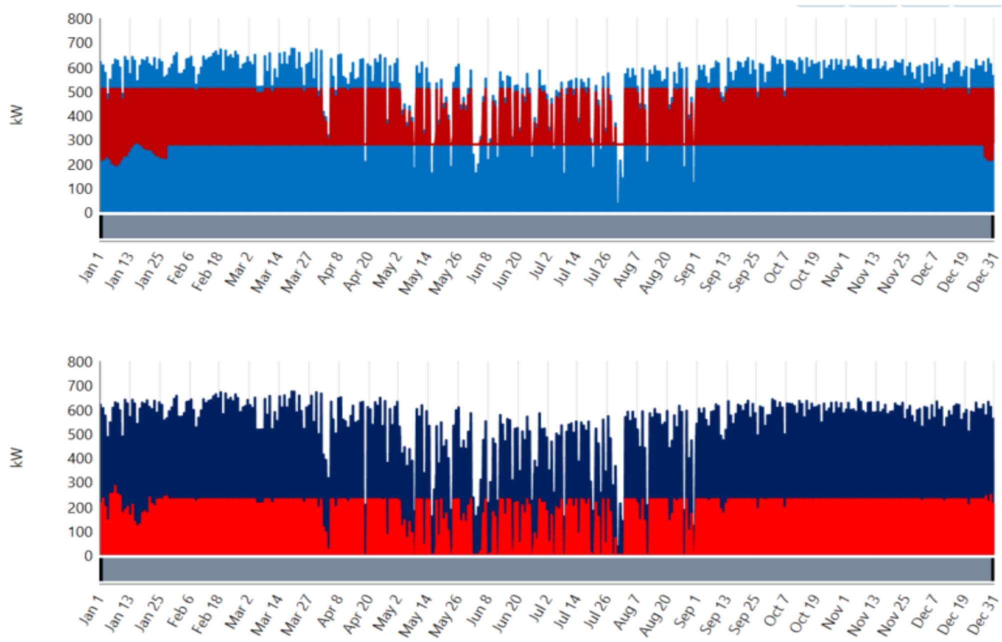

Figure 3: Time series detail analysis with EMS process

Similarly in the formula 4, NPC represents the total lifetime cost of the system, C_t is the cost incurred in year t (e.g., fuel, maintenance, replacement), r is the discount rate, and N is the project lifetime in years.

In the formula for LCOE represents the cost of energy in terms of e.g., \$/kWh. NPC is the total system cost, $E_{\text{served},t}$ is the electricity served in year t in kilowatt-hours (kWh), r is the discount rate, and N is the project lifetime in years.

In the formula for emissions, E_{total} is the total emissions (e.g., CO_2, NO_x) in kg/year, F_j is the fuel consumed by component j (e.g., diesel generator) in liters or kilograms, and e_j is the emission factor for component j in kilograms of pollutant per unit of fuel.

In the formula 7, F represents the total fuel consumed in L/h, F_0 is the fuel curve intercept coefficient in liters per hour per kilowatt of rated capacity (L/h/kW), F_1 is the fuel curve slope in L/h/kW, Y_{gen} is the generator's rated capacity in kW, and P_{gen} is the generator's output power in kW.

In the formula for power balance, P_{gen} is the power produced by the generator in kW, P_{ren} is the power produced by renewable sources in kW, P_{batt} is the power supplied by or stored in the battery in kW, P_{load} is the electrical load demand in kW, and P_{loss} represents the power losses in the system in kW.

Grid-forming generators or inverters maintain the voltage and frequency stability of the MG. The parameter f represents the frequency of the grid in Hz, f_0 is the nominal frequency (e.g., 50 Hz or 60 Hz), K_{droop} is the droop coefficient, P_{output} is the power output of the generator or inverter in kW, and P_{set} is the power setpoint in kW.

In the formula 11, P_{batt} represents the power supplied by the battery in kW, K_f is the frequency response coefficient of the battery system, f is the measured frequency in Hz, and f_0 is the nominal frequency in Hz.

In the LF strategy, P_{gen} is the power output of the generator in kW, P_{load} is the electrical load demand in kW, and $P_{\text{gen,max}}$ is the maximum generator capacity in kW.

In the CC strategy, P_{gen} is the generator's power output in (kW, $P_{\text{gen,max}}$ is the generator's maximum power output in kW, P_{surplus} is the surplus power generated in kW, and $P_{\text{batt,charge}}$ is the power used to charge the battery in kW.

Results and Discussions

In this paper, a demonstration simulation has been conducted using the MATLAB EMS function and HOMER, as illustrated in Figure 2. The simulation utilized a load profile from an island. The LCOE for the island taken as 0.14 €/kWh. It has been determined that by implementing the dispatch strategy, the LCOE can be reduced to 0.10 €/kWh, with a system size of 603 kW of photovoltaic (PV) power and a 508 kW system converter.

Figure 3 presents two plots: the upper plot shows the PV output power represented by a blue line, corresponding to the total electrical load, which is indicated by a red line. The lower plot illustrates the total renewable power output in blue and total grid sales in red, based on the simulation and dispatch strategy.

The results revealed a total excess electricity generation of 31,723 kWh annually. The total PV production achieved was 1,379,928 kWh per year, while total grid purchases amounted to 1,546,725 kWh per year. The system managed to achieve grid sales of 360,626 kWh annually, which represents 12.8% of the total electricity consumption.

It is important to note that the system design does not incorporate any storage as a Distributed Energy Resource (DER) but rather relies solely on PV systems and the utility grid. The system operates according to a dispatch mechanism that prioritizes PV generation and functions in a fuel-saving mode throughout the simulation process.

Conclusion

This research highlights the benefits of a custom control strategy in terms of system sizing. Homer CC and LF offer a load scheduling strategy that directs surplus energy to lower-priority tasks, such as charging the storage bank. In the context of LF, these lower-priority tasks are serviced by renewable energy sources. The advantage of such a custom strategy is that it ensures the system output aligns with the specific requirements of the load demand.

In this work, we have incorporated custom load demands, renewable energy output, battery state of charge (SOC), battery capacity, and constraints such as the generator's minimum output and battery SOC. The renewable energy source utilized is photovoltaic (PV), which serves as the main energy source. Results indicate that this configuration yields the maximum size of PV as a distributed energy resource (DER). Additionally, if the SOC is sufficient, the battery should meet the load requirements, meaning the system did not count battery output as one of the DERs during the simulation.

Future work should test this system design and control strategy in a real-time scenario to serve as proof of concept.

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