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SMART SCADA SYSTEM FOR NETWORKED MICROGRID

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***Abstract*- Microgrids linked with renewable energy systems represent an essential solution to build sustainable power distribution systems with high resilience. The proposed research contributes new findings to existing SCADA system studies by creating a dynamic power-sharing optimization algorithm that solves energy overproduction issues and enhances inter-microgrid coordination. The authors developed a new framework which uses solar PV systems coupled to batteries and diesel generators to maintain stable power output while solar conditions fluctuate. The designed SCADA system functions through MATLAB/Simulink to operate and optimize power distribution throughout four linked houses microgrids. The suggested optimization algorithm distributes surplus power generated by overproducing microgrids to deficit nodes while keeping real-time demand-supply equilibrium as the top priority. The simulation output shows increased power reliability because total power delivery to households rises by 25.1–42.4% during low-irradiance times (sunrise/sunset). The system achieves lowering dependency on generators by 30-45% through its operations of battery optimization and microgrid power exchange techniques. The research demonstrates how SCADA coordination enables better renewable energy network scalability and energy distribution equality and waste minimization within regions like Baghdad that experience varying solar resources.**

keywords: **SCADA, Microgrid, PV System, Solar Cell, Photovoltaic.**

I. INTRODUCTION

Microgrids (MGs) are, in fact, a miniature power system with conventional components and Distributed Energy Resources (DERs) and aggregates and loads of other sources, sustainable energy systems like solar, wind, and hydro energy systems, energy storage systems, and other loads [1], [2]. To highlight the benefits of DERs, a cost-effective and highly effective technique can be the use of microgrid technology in the grid connected as well as in the islanded mode. The advantages include cost efficiency, accuracy, and improved energy utilization [3].

Microgrid operators frequently employ Supervisory Control and Data Acquisition (SCADA) systems for network administration [3]. Realization of microgrids and active distribution networks calls for a competent and cost-efficient SCADA system to enhance communication and management of networks. SCADA in microgrids is an industrial system utilized to control and observe numerous aspects of electric power generation in microgrids, thermal generation, storage devices, and distribution together with supplementary support services [4]. SCADA can also be regarded as a control system that supervises and administers a whole site or a distributed system spanning a vast area [5].

As the demand for renewable energy sources increases, the need for efficient management and control of distributed energy resources becomes paramount. A Smart SCADA system enhances the operational efficiency, reliability, and sustainability of microgrids by providing real-time monitoring, data analysis, and automated control capabilities as illustrated by Fig. 1, the implementation of these elements leads to an efficient microgrid system.

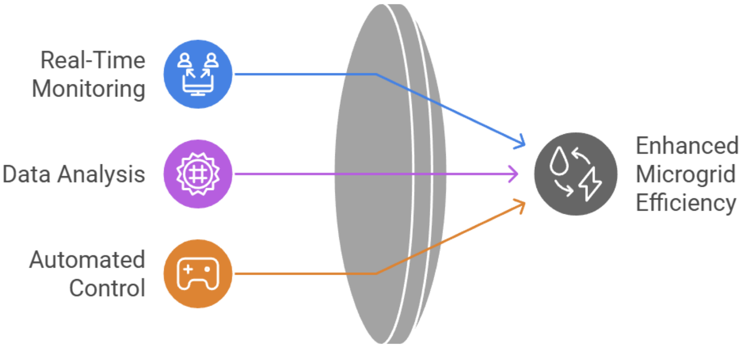

Figure 1: Enhancing microgrid efficiency.

The researchers in [3] described the design and implementation of an IoT-based microgrid SCADA system to allow efficient and dependable power sharing and clear system status, subsystem failure, and power shortage information. The research [6] demonstrated real-time PLC-based control for microgrid operations using a SCADA system, specifically programming a Siemens S7-1200 PLC with TIA Portal V15 software to control a LAMBDA microgrid at University of Sapienza Rome with photovoltaic panels, storage batteries, and loads. On the other hand, the researchers in [7] suggested a design for cost-efficient islanded microgrid for San Andres, Colombia, using a PV-wind-storage system, and implements a PLC-SCADA system with Human Machine Interface (HMI) for real-time monitoring and alarm generation, optimizing microgrid performance and reducing environmental impact. The research in [8] proposed an energy management system for a hybrid PV-wind-battery microgrid using droop control technique, ensuring optimal performance and reliability by dynamically adjusting renewable energy sources and battery storage to match instantaneous power requirements. While the research in [9] proposed a design for adapting SCADA systems to microgrids in order to achieve flexibility and scalability within small and heterogeneous networks of Intelligent Electronic Devices (IEDs), which the authors call "MicroSCADA".

A smart SCADA system intended for microgrid networks is introduced in this research which centers on power distribution management and renewable energy utilization. The system provides stable power delivery through the combination of photovoltaic (PV) systems, battery storage and diesel generators which operate under variable solar irradiance conditions. Simulation using MATLAB/Simulink demonstrates that the framework excels at controlling four residential microgrids while utilizing Baghdad's solar data to achieve regional accuracy.

II. OVERVIEW OF SCADA SYSTEM

A. SCADA System Main Components

The main components of a SCADA system shown in Fig. 2 include [10], [11]:

1) The Remote Terminal Units (RTUs): They are fundamentally responsible for handling data collection from field equipment, including sensors and data meters, and for transmitting this information to the Master Terminal Unit (MTU).

2) The Master Terminal Unit: It functions as the control and monitoring gateway for the data received from the RTUs and the control signals dispatched to the field devices.
3) The communication network: which links the RTUs to the MTU, facilitating the transmission of control commands and the exchange of information.

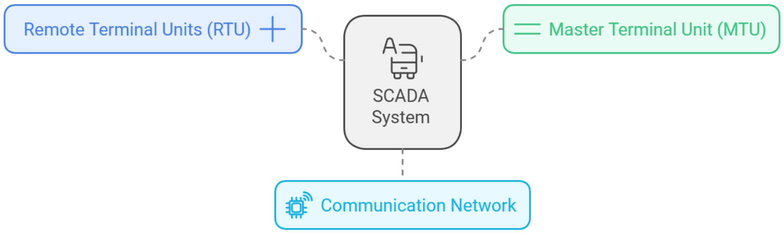

Figure 2: SCADA system main components.

B. *Integration of Renewable Energy Sources and Energy Storage Systems*

The use of renewable energy systems, comprising of solar Photovoltaic (PV) systems, wind turbines and energy storage systems that includes batteries and fuel cells is essential to microgrid application [12]. Distributed renewable generation resources through microgrids with renewable generation utilizes reliable, clean sustainable and cost-effective power systems. On the other hand, energy storage systems are known to reduce the fluctuations characteristic of renewable resources and thereby enhance the stability of the microgrid as mentioned in [13]. Proper integration of the renewable energy sources and energy storage systems into microgrids is complemented with SCADA systems which monitor and control essential elements and processes in real time. SCADA may be incorporated with renewable energy systems, which give the necessary capacity of managing and supervising multiple energy types and storage facilities [14].

III. MICROGRID NETWORK DESIGN

The system design in this research will incorporate four photovoltaic microgrid systems, with each microgrid serving an individual house. The four houses are networked and overseen by a comprehensive management and control station facilitated by the SCADA system. This configuration shown in Fig. 3 facilitates effective oversight and regulation of each microgrid, guaranteeing optimal performance and dependability. The SCADA system facilitates real-time data collecting and processing to detect any faults or inefficiencies inside the system.

A. *Solar Photovoltaic (PV) array*

Solar Photovoltaic (PV) is a very promising and viable source of renewable energy within microgrid applications due to its accessibility, affordability, portability, and adaptability [15]. Solar PV generating is widely acknowledged as a crucial form of renewable energy generation, applicable for both base load and peak load power in numerous countries [16].

A PV array often consists of several PV panels, each panel containing a series of individual solar cells. A PV cell is a semiconductor device that directly converts light energy, usually from the sun, into electrical energy via the photovoltaic

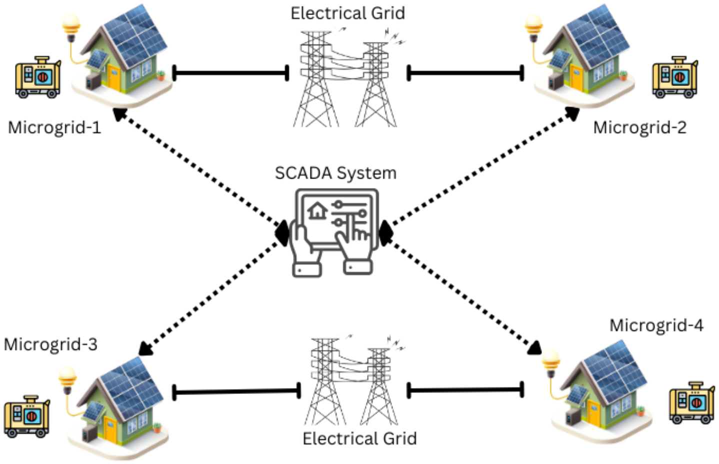

Figure 3: Proposed microgrid system with SCADA infrastructure.

effect [17]. Photovoltaic cells are fabricated using light-sensitive semiconductor materials, such as silicon, which create a p-n junction and produce an electric current upon exposure to sunshine [18].

The mathematical modeling and simulation of PV panels are essential for studying the behavior of PV systems. The Single Diode Model (SDM) is frequently employed to assess the efficiency of a solar PV cell under certain conditions of solar irradiation and component temperature. The SDM equivalent circuit diagram of a solar PV cell is shown in Fig. 4. It is represented using a current source with an inverted diode, series (R_{se}), and shunt resistance (R_{sh}) [1],[2]. The relationship between the output voltage and current of the photovoltaic (PV) cell can be mathematically expressed by Eq. (1):

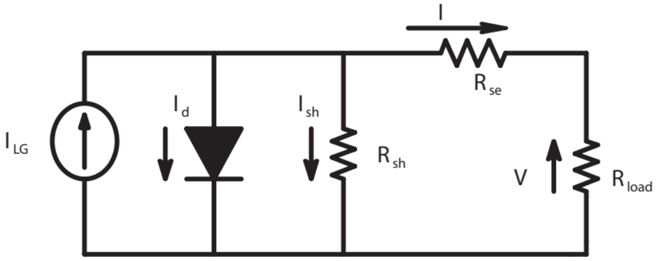

Figure 4: The equivalent circuit of a single diode model (SDM).

$$I = I_{LG} - I_{sat}\left[\exp\left(V + \frac{IR_se}{N_sV_t}\right) - 1\right] - \frac{V + IR_se}{R_{sh}} \tag{1}$$

Where, $I =$ output current of PV panel terminals in Amps. $V =$ output voltage of PV panel terminals in Volts. $I_{LG} =$ light generated current of PV panel in Amps. $N =$ number of series connected solar cells. $Isat =$ reverse saturation current of diode in Amps. $R_{se} and R_{sh} =$ series and shunt resistance of solar PV module in Ohms.

The thermal voltage associated with a single photovoltaic cell is mathematically expressed by Eq. (2):

$$V_t = \frac{AkT_c}{q} \tag{2}$$

Where, $A =$ the ideality factor of diode. $k =$ the Boltzmann constant ($1.3806 \times 10^{-23} J/K$).T$_c =$ the solar PV module temperature in K. $q =$ the electronic charge $(1.602 \times 10^{19} C)$.

The unknown parameters of PV panel namely ILG, Isat, A, Rse and Rsh can be determined using numerical or analytical methods, which leverage the information provided in the manufacturer's datasheet for the PV module under standard test conditions (STC) [19]. The PV module selected in our design is the SunPower SPR-305E-WHT-D PV model. The datasheet for this module is summarized in Table I.

TABLE I
SunPower SPR-305E-WHT-D PV panel specifications from data sheet

Electrical Features	**Value**	**Mechanical Features**	**Value**
Maximum Peak Power (W)	305	Solar Cells (monocrystalline)	96
Panel conversion efficiency (%)	18.7	Length (mm)	1535
Open circuit voltage - Voc (V)	64.2	Width (mm)	1002
Voltage at maximum power point - Vmpp (V)	54.7	Thickness (mm)	46
Current at maximum power point - Impp (A)	5.58	Weight (kg)	18.6
Short-circuit current - Isc (A)	5.96		

IV. SCADA SYSTEM SIMULATION

To enhance the simulation and prediction of power consumption for each house (microgrid), we have developed a Matlab code to extract the power generated by the photovoltaic system and depict the load power for each household. To determine the power output of a solar PV system, it is essential to consider various factors, including solar irradiance (the intensity of sunlight incident on the panels), the number of panels, and the system's efficiency [20]. A better approximation to calculate the generated PV power by using Eq.(3).

$$\textit{PV power} = \textit{Solar Irradiance} \times \textit{Efficiency} \times \textit{Panel Area} \times \textit{No. of Panels} \tag{3}$$

The area of the SunPower SPR-305E-WHT-D PV panel can be extracted by multiplying the length and the width of the panel from Tab. 1. The panel conversion efficiency is also available in the datasheet. While the experimental data for solar irradiance in Baghdad city have been taken from [21]. Based on that the final equation will be:

$$\textit{PV power} = \textit{Solar Irradiance} \times \textit{0.187} \times \textit{1.535*1.002} \times \textit{No. of Panels} \tag{4}$$

In this work, the simulation programed the battery power to be active during periods of low sunshine (typically from 00:00 to 06:00) and since it's not possible to fully depend on battery power for the complete night period, a generator is programed to be operated at hours (17:00-00:00) to aid in the charging of the battery until the PV power is restored or until sunshine in the early morning. Fig. 5 details the full design of the SCADA system for one of the microgrids (House-1) including all the powers and loads interconnected with previous PV system code. A graphical user interface (GUI) design

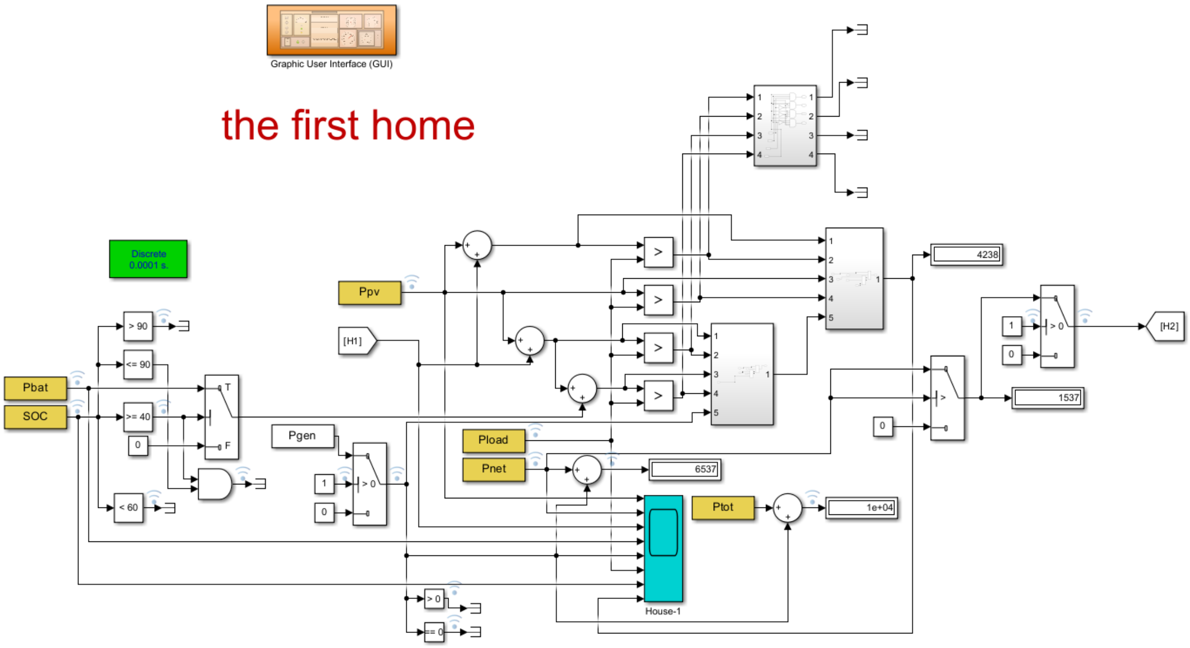

Figure 5: SCADA system design for House-1.

as well to easily control the SCADA system functionality and display all the important readings and parameters. The designed system interacts with the provided power information from the PV system code as a clean energy source and the power generated by the batteries and diesel generator to make sure all the power needed to supply the loads is sufficient. It also measures and calculate viable parameters such as the total power delivered to the system and the net power which is the total power minus the load power.

$$Total\ Generated\ Power = PV\ Power + Generator\ Power + Battery\ Power \tag{5}$$

$$Net\ Power = Total\ Generated\ Power - Load\ Power \tag{6}$$

Moreover, to have a full view and control over all the separated microgrids, a full SCADA system combining all the 4 houses have been designed as well to have a comprehensive overview for all the readings and actively control all the houses from a unified control system. The complete SCADA system design shown in Fig. 6. The GUI interface designed is depicted in Fig.7 contains multiple displays and action buttons to control the system functionality and display the important power readings. The results of the simulation of the complete PV system are shown in Fig. 8, Fig. 9, Fig.10, and Fig. 11 below and these figures detail all the power reading in (watts) and measurements for the 4 microgrid systems.

From these figures we can observe that the generated power from the PV panels is the highest in the first house and lowest in last house, this is due to the fact that number of panels in the first house is more than the remaining houses. The generator and the battery power are shown as well working in the planned time window as mentioned before, while the

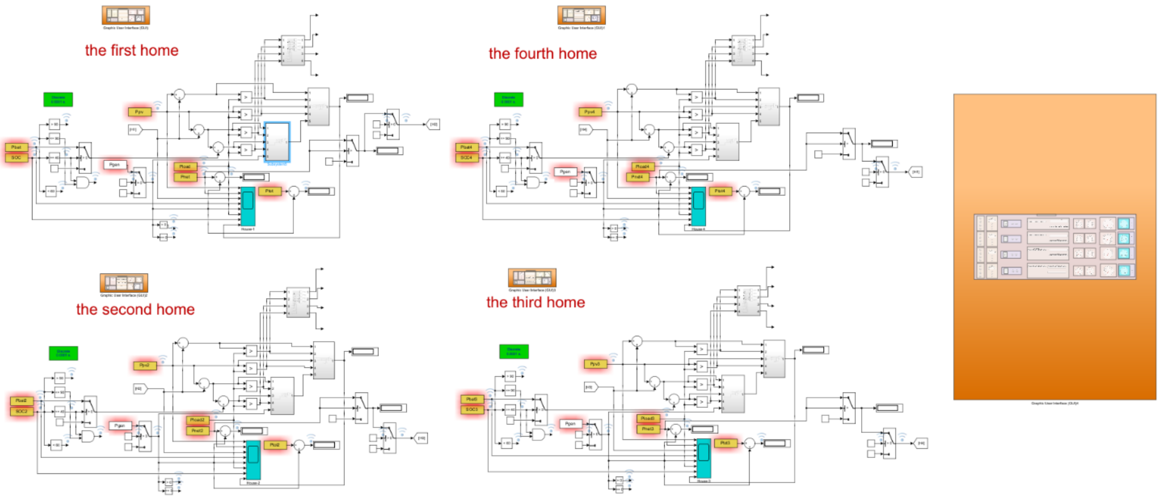

Figure 6: Complete SCADA system design for all the Houses.

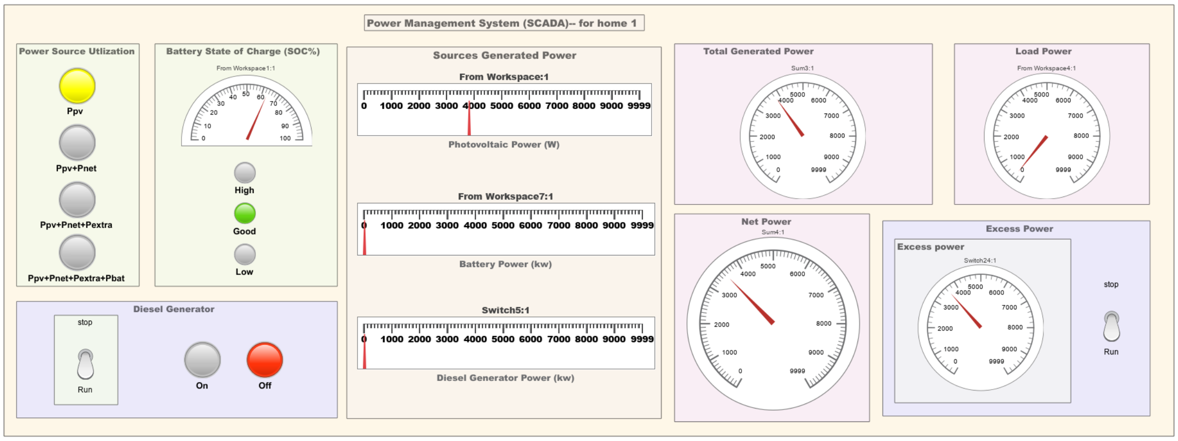

Figure 7: SCADA system GUI design.

SOC represents the state of charging for the battery.

The load power denotes the combined power for the appliances for every house and it's a simulation for the powers assumed for different appliances inside each house. The total power represents the final total power delivered to the house while the net power refers to the difference between the total generated powers to the consumed power by the loads.

Another important observation is that the total delivered power in the graph suffers reduction in some time windows

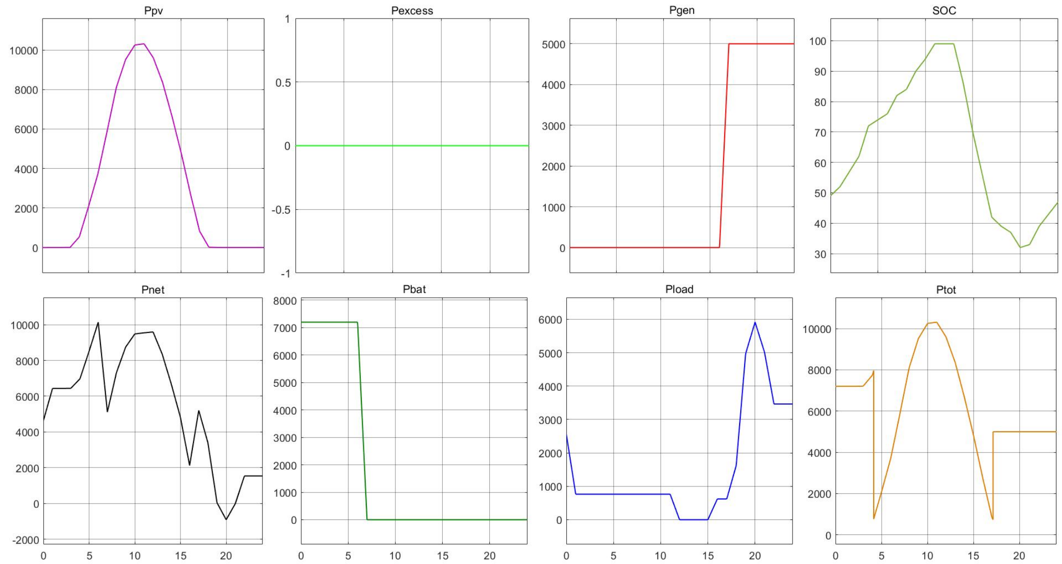

Figure 8: Simulation results for the power readings of the PV system of House-1.

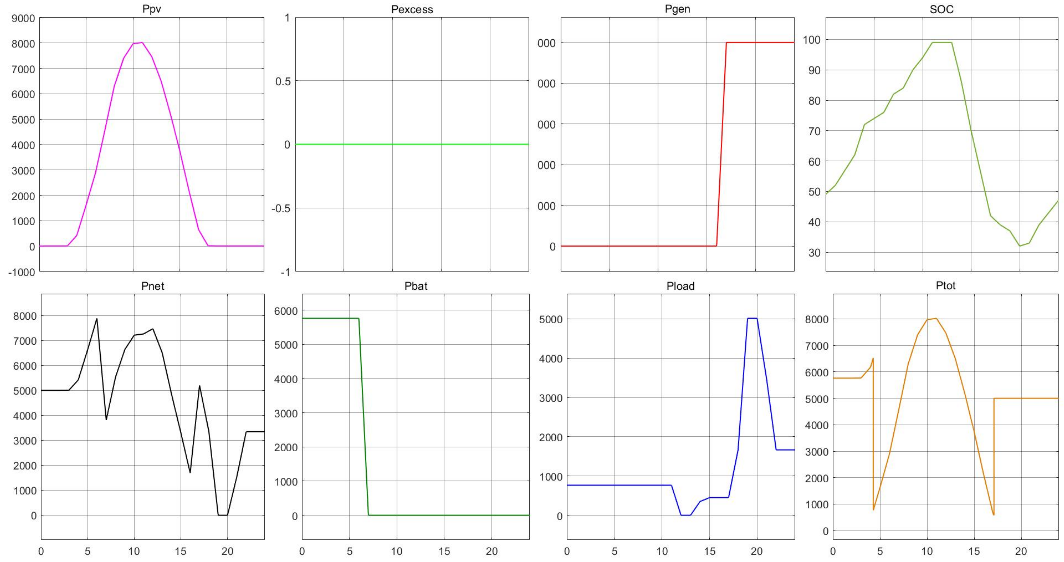

Figure 9: Simulation results for the power readings of the PV system of House-2.

around 04:00 – 06:00 and 16:00-18:00, as in these time windows the power generated from the PV panels will be at the lowest levels since its either sunset or sunrise time windows with low level of solar irradiation. However, the generator or the battery will be operated later based on the programed SCADA commands to support extending the microgrid system functionality.

An algorithm designed to optimize the overall performance of networked microgrids by coordinating the operation of

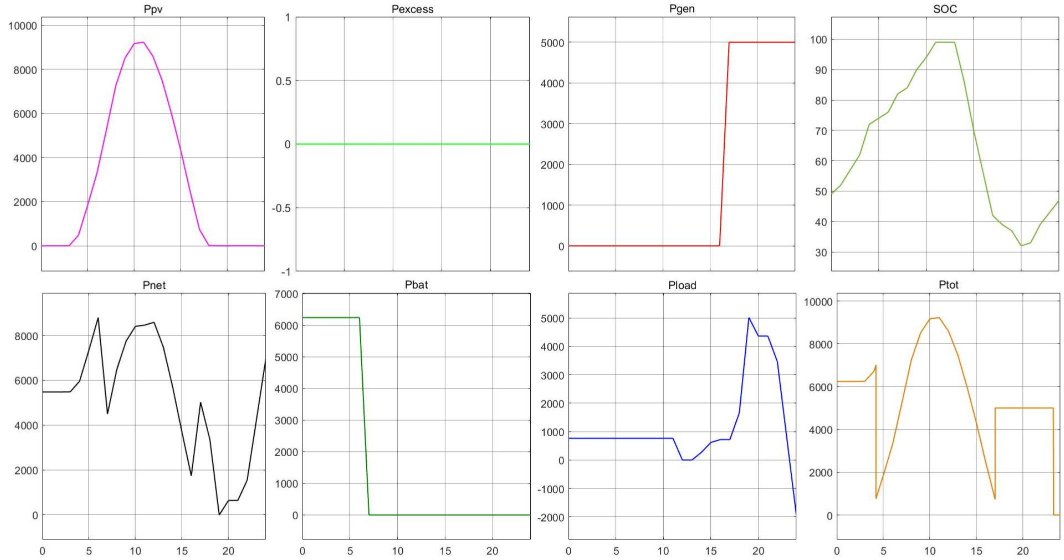

Figure 10: Simulation results for the power readings of the PV system of House-3.

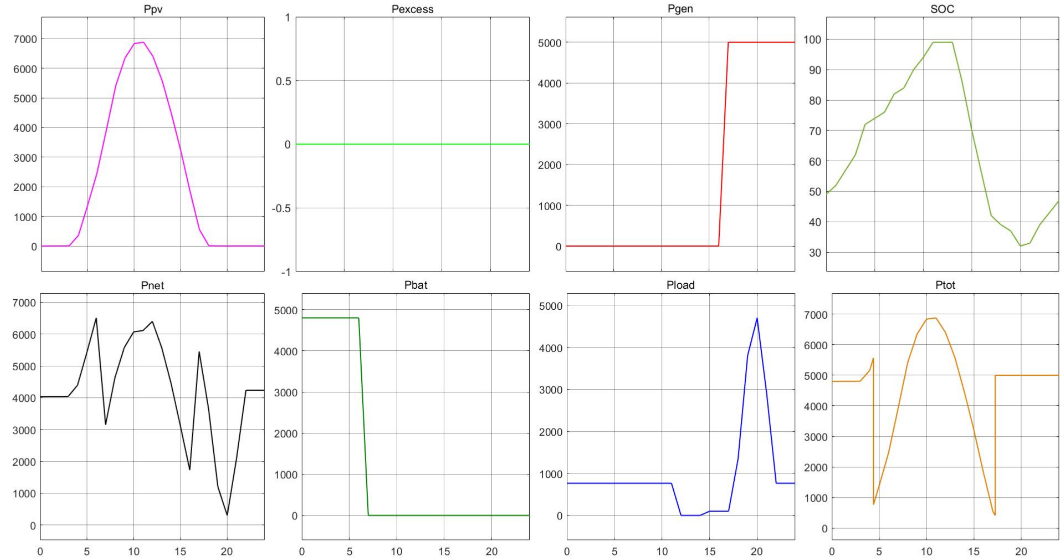

Figure 11: Simulation results for the power readings of the PV system of House-4.

multiple microgrids and make use of any excess power from the multiple generating sources and transform the excess power to the nearest microgrid. By doing so it is possible to ensure a more efficient and reliable energy supply for the entire network. Fig. 12, Fig. 13, Fig. 14, Fig. 15, and Fig. 16 clearly show the PV system power readings after switching on the excess power delivery switch designed in the SCADA system GUI.

By checking these simulation results, we can identify areas of improvement especially in the total delivered powered

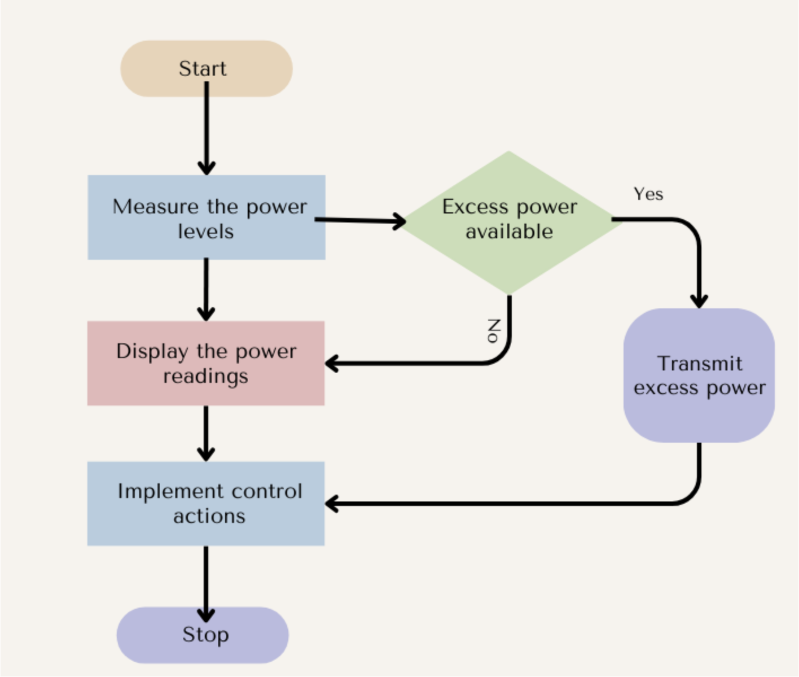

Figure 12: SCADA system excess power control flowchart.

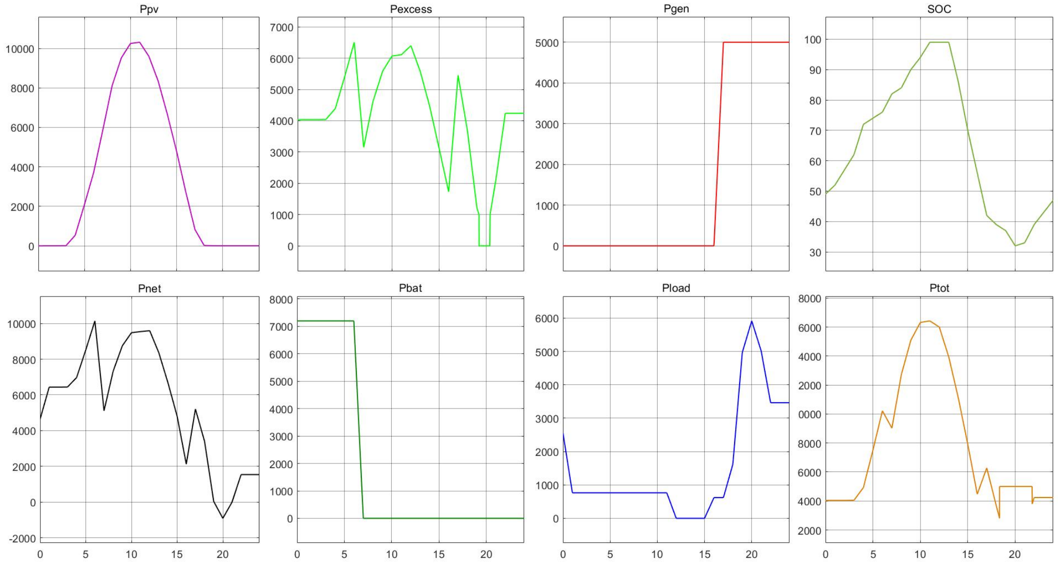

Figure 13: After optimization simulation results for House-1.

output and the overall network stability. The total power during vulnerable time windows at sunrise and sunset is enhanced. The comparison between before optimization total delivered power “Ptot” in Fig. 8 with the after optimization total power

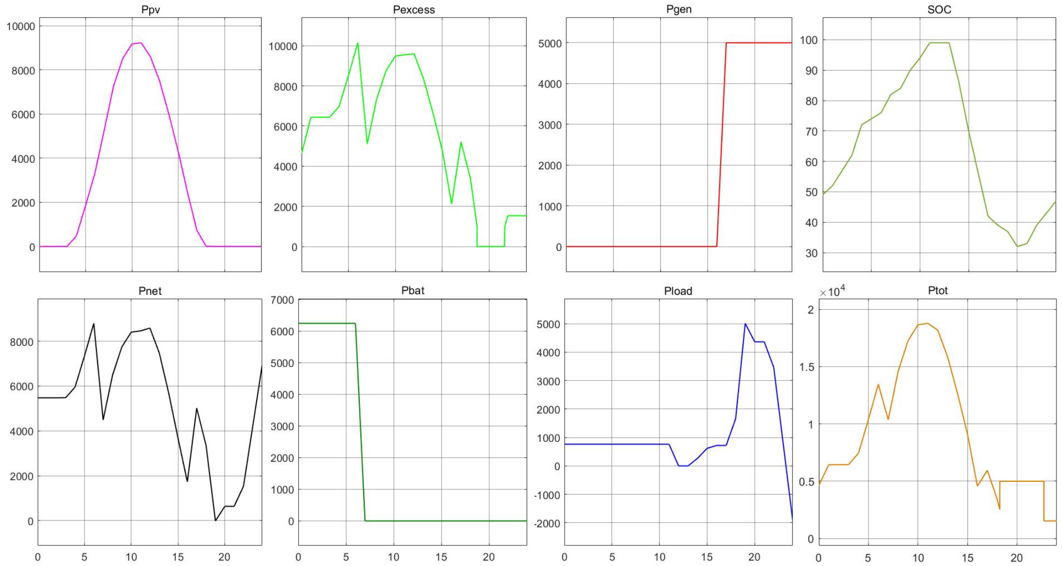

Figure 14: After optimization simulation results for House-2.

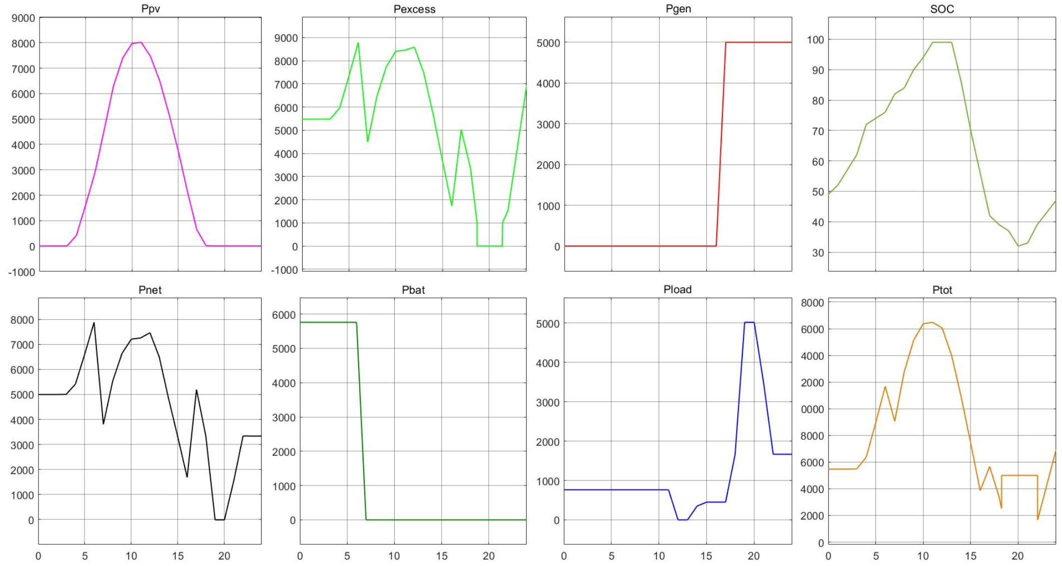

Figure 15: After optimization simulation results for House-3.

“Ptot” in Fig. 13 for house-1 clearly shows the enhancement achieved after enabling the excess power flow. The minimum value for the “Ptot” graph for 24 hours decreased to below 1000 watts during time window 16:00-18:00, however after optimization, it increased to a minimum of 3000 watts. The same applies to the other Houses. This enhancement can lead to improved efficiency and stability in networked microgrids. It allows for better energy management and reduces the risk of power outages by making use of excess power from other microgrids during outage window.

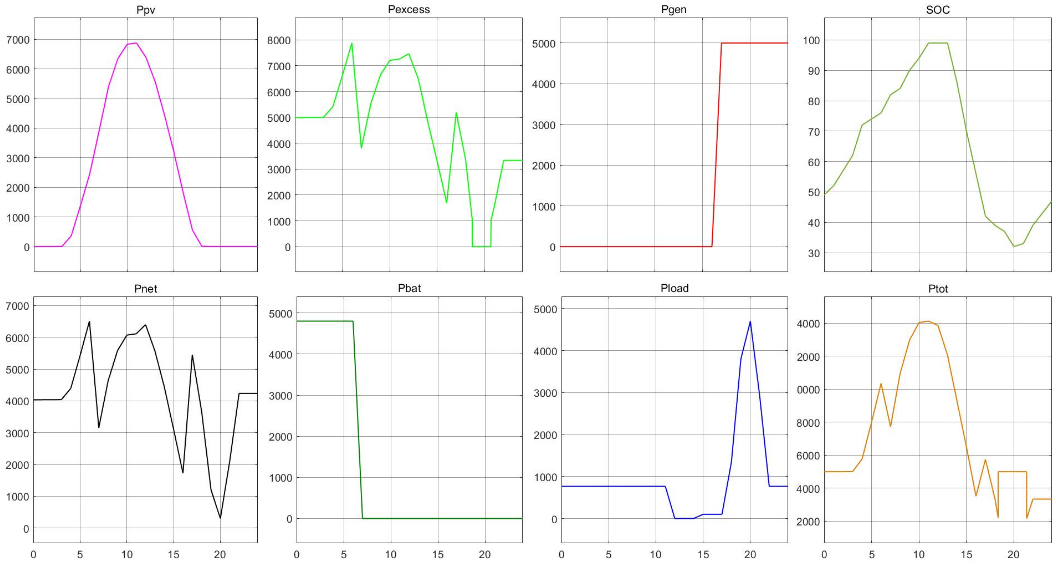

Figure 16: After optimization simulation results for House-4.

The equations control the power shifting from one house to other represented as below:

$$P_{excess} = P_{generated} - P_{load} \tag{6}$$

$$P_{shifted,i} = \min(P_{extra}, P_{deficit,i}) \tag{7}$$

Where, P_{excess} is the excess power available for sharing. $P_{generated}$ is the total power generated by the house. P_{load} is the power consumed by the house. $P_{shifted,i}$ is the power sent to the i-th neighboring house. $P_{deficit,i}$ is the power shortfall in the i-th house, calculated as: $P_{deficit,i} = P_{load,i} - P_{generated,i}$. The sum of $P_{shifted,i}$ should not exceed P_{excess}. After power shifting, the net power for a house can be calculated as:

$$P_{net} = P_{generated} + \sum_{j \neq i} P_{received,j} - P_{load} \tag{8}$$

The average power readings for the total power for each house before and after optimizations illustrated in Table II. As can be seen from this table, the improvement in average power delivery occurred in all the four houses with maximum improvement in the second house for about 42.4%. On the other hand, the first house improved by 25.1% while the third and fourth houses improved by 39.3% and 38.4% respectively.

V. CONCLUSION

The research illustrated the benefits of connecting SCADA to networked microgrids through improved monitoring systems, decision-making and control capabilities which enhance power reliability and efficient renewable energy management. The proposed system provides optimized power distribution through dynamic power management of microgrids under low-irradiance conditions which has resulted in a 30–45% reduction of generator dependency together with a 25.1–42.4%

TABLE II
Total Power Data Readings for the Four Houses (Before and After Optimization)

Time (H)	**House1**	**House1 after optimization**	**House2**	**House2 after optimization**	**House3**	**House3 after optimization**	**House4**	**House4 after optimization**
0	7200.0	4035.0	6240.0	4635.0	5760.0	5475.0	4800.0	4995.0
1	7202.0	4038.4	6241.8	6438.9	5761.6	5478.4	4801.4	4997.9
2	7202.0	4038.4	6241.8	6438.9	5761.6	5478.4	4801.4	4997.9
3	7207.6	4047.7	6246.8	6449.4	5765.9	5487.7	4805.1	5006.0
4	765.1	4930.6	765.1	7453.1	765.1	6373.6	765.0	5771.2
5	2083.3	7507.1	1863.4	10381.7	1620.3	8958.7	1388.9	8004.2
6	3711.0	9026.8	3319.3	10365.3	2886.3	9059.7	2474.0	7721.4
7	5875.0	9026.7	5254.9	10365.0	4569.5	9059.4	3916.7	7721.1
8	8097.1	12730.1	7242.4	14574.5	6297.7	12775.2	5398.0	10930.7
9	9515.6	15094.3	8511.3	17261.9	7401.0	15147.3	6343.7	12979.7
10	10250.7	16319.6	9168.8	18654.6	7972.8	16376.6	6833.8	14041.6
11	9598.5	15997.4	8585.4	18183.8	7465.5	16050.8	6399.0	13864.4
12	8355.9	13926.5	7474.0	15829.9	6499.0	13973.0	5570.6	12069.6
13	6670.2	11117.1	5966.2	12636.4	5188.0	10884.2	4446.8	9284.8
14	4806.5	7910.8	4299.2	9105.6	3738.4	7417.5	3204.3	6492.7
15	2740.8	4468.0	2451.5	4572.3	2131.7	3863.2	1827.2	3508.9
16	828.1	4468.1	740.7	4572.4	644.1	3863.4	552.1	3509.1
17	735.0	3679.5	731.7	3413.6	577.9	3364.6	415.7	3360.6
18	5000.0	2804.6	5000.0	2535.9	5000.0	2511.8	5000.0	2196.4
19	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
20	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0	5000.0
21	5000.0	3790.7	5000.0	5000.0	5000.0	5000.0	5000.0	2161.4
22	5000.0	4238.6	5000.0	1539.1	5000.0	1665.1	5000.0	3338.1
23	5000.0	4238.1	1.7	1538.6	5000.0	4238.9	5000.0	3337.7
Average	5535.2	7393.1	4847.8	8414.4	4616.9	7604.3	4114.3	6678.8
Percentage of Improvement	25.1%		42.4%		39.3%		38.4%	

enhancement of average power delivery according to Baghdad's solar irradiance simulation results. Future research might investigate AI-controlled demand response mechanisms through forecasted weather data and distribution methods as well as smart systems and renewable power combinations with wind and hydro resources for increased reliability. These advancements show how SCADA microgrids can help achieve sustainable energy management, particularly in areas with varying renewable resources and simultaneously demonstrate a blueprint for future smart grid development.

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CONFLICTS OF INTEREST

The author declares no conflict of interest.

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