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Dynamic Modeling and Simulation of an Isolated Hybrid Power System Designed for Urban Areas in Pakistan

Muhammad Kashif , Mohammad Tariq Iqbal and Mohsin Jamil
Department of Electrical and Computer Engineering
Faculty of Engineering and Applied Science
Memorial University of Newfoundland, St. John's, NL, A1C 5S7
mkashif22@mun.ca, tariq@mun.ca, mjamil@mun.ca

***Abstract*— This paper presents the dynamic modeling and simulation of an isolated hybrid energy system for a residential neighborhood in Karachi, Pakistan. The proposed system is a hybrid solar-battery energy setup integrated with a shared neighborhood diesel generator. The case study models a house with a daily energy demand of 15 kWh, using HOMER Pro and MATLAB/Simulink to assess dynamic performance under different resistive and inductive load modeling, reflecting the actual load of the house, and varying irradiance levels during different weather conditions. The system includes a 7.61 kW PV array, a 12-battery bank (140 Ah, 48V), an MPPT controller, a DC-DC buck converter, and a shared diesel generator limited to 2 kW per house, converting 48V DC to 220V AC via a DC-AC inverter and step-up transformer. Simulation results show stable power output, effective load response, and quick recovery from voltage transients. The shared diesel generator reduces battery requirements, cutting capital and operational costs. This study highlights scalable hybrid systems as cost-effective, sustainable solutions for urban and rural areas, reducing fossil fuel dependency and enhancing energy resilience in Pakistan.**

Keywords*— *solar energy, hybrid power systems, dynamic simulation, HOMER PRO, MATLAB Simulink, battery storage, Optimization, MPPT(Maximum Power Point Tracking)

I. Introduction

Energy is a fundamental driver of economic stability and social progress, essential for global development [1]. In countries like Pakistan, energy demand is rapidly increasing due to industrial growth, urbanization, and population expansion. According to the International Energy Agency (IEA), around 675 million people are projected to remain without electricity access by 2030, illustrating both progress and the enduring challenge of achieving universal energy access in developing regions [2]. This gap emphasizes the need for sustainable and accessible energy solutions to foster socioeconomic advancement and improve quality of life. Pakistan faces significant energy shortages due to factors such as generation shortfalls, inefficient power transmission, and outdated distribution infrastructure, leading to prolonged load-shedding across the country. Interestingly, the generation deficit is not caused by capacity limitations but is largely attributed to reliance on imported oil and fossil fuels, which places considerable pressure on the Pakistani rupee due to the exchange rate with the USD.[3] Additionally, legacy agreements with rental power projects require capacity payments regardless of actual energy production, adding financial strain. As a result, the removal of subsidies, coupled with the imposition of additional taxes and duties, has led to higher electricity costs for consumers, who now endure both expensive and unreliable power supplies [4].

To address these challenges, renewable energy systems have emerged as viable alternatives to traditional grid power from utility companies. The most common solutions are on-grid and off-grid systems, each with distinct advantages and limitations. While on-grid systems are cost-effective, they lack reliability during grid outages. Conversely, off-grid systems provide power independent of the grid but require extensive and costly battery storage to sustain energy throughout the night and during cloudy periods with low solar output. Recognizing this gap, this study designs a hybrid system integrating solar, battery storage, and a shared diesel generator. This approach offers a cost-effective, grid-independent solution that alleviates consumers from government taxes altogether and provides reliable backup power through the shared diesel generator. A case study was conducted for seven houses in an urban locality of Karachi, with this paper focusing on dynamic simulation on MATLAB Simulink and modeling to evaluate the system's feasibility and performance.

II. Literature review

This study reviewed several papers focusing on the dynamic simulation and optimization of hybrid power systems. Ozogbuda *et al.* conducted dynamic simulations of a PV hybrid system with battery and generator backup for a remote area in Edo State, Nigeria. Their model, which included a 1.23 kW PV array, a 4.8 kW generator, and a 48V battery bank, demonstrated stable performance using MATLAB Simulink. The system maintained efficiency and reliability by utilizing PV as the primary source, supplemented by generator power during low irradiance periods, effectively meeting the peak load demand of 1.26 kW and daily consumption of 3.4 kWh [5]. Wajahat Khalid *et al.* developed a dynamic simulation and optimization model for rural off-grid hybrid systems. Using PVsyst and HOMER Pro, they optimized a hybrid configuration to meet a daily load of 137.48 kWh with a peak load of 33.54 kW. The simulation outcomes, validated through hardware-in-the-loop (HIL) testing, confirmed the system's reliable power delivery, scalability, and emission reductions. The hybrid setup demonstrated cost-effectiveness with an energy cost of $0.158 per kWh, indicating its practical viability for rural areas [6]. In their research, Muzaffar *et al.* designed an off-grid DC solar system to meet a daily load of 7.81 kWh for a household in Pakistan. Using 36 Canadian Solar PV panels (325 W each) and a 48V battery bank, their MATLAB simulations showed that the system could reliably handle fluctuating load demands, maintaining stability across seasonal variations. This setup underscores the system's potential to deliver grid-independent, sustainable power in remote areas [7]. Mansoor *et al.* conducted a comparative techno-economic analysis of on-grid and off-grid hybrid systems for the remote Jamshoro District in Sindh, Pakistan. By using HOMER for optimization, they found that an on-grid hybrid system with a 150 kW PV array, a 110 kW wind turbine, and a fuel cell was the most cost-effective solution. This configuration outperformed standalone systems in terms of both net present cost and levelized cost of energy, ensuring reliable and sustainable power for the region [8].

The off-grid solar system designed for a rural household in Pakistan by Asif ur Rehman et al. includes four 140 W solar panels, a 24 V battery bank with four 125 Ah batteries, and a 1 kW inverter. Simulation results indicate this system effectively meets the household's energy needs, generating approximately 729 kWh annually, providing a sustainable, grid-independent energy solution [9].

In summary, the reviewed studies underscore the effectiveness of hybrid renewable energy systems as reliable and sustainable solutions for areas with unreliable or costly grid access. These systems offer promising alternatives for both rural and urban regions, particularly in developing countries where traditional infrastructure may not adequately meet energy demands.

III. System Details

A site is selected for this study at 24.919904 latitude and 67.145514 longitude, located within a residential neighborhood in urban Karachi, consisting of seven closely situated houses. The site location is shown in Figure 1.

Fig 1. Selected Site Location

The system design, component selection, sizing, and optimization were conducted using HOMER Pro. The schematic diagram of the system, depicting all major components, is presented in Figure 2.

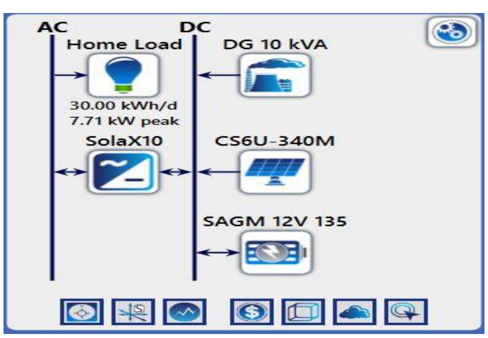

Fig 2. Schematic of the designed system

In the proposed system, there are a total of seven houses, each equipped with an individual solar system tailored to its specific energy demand, along with access to a shared diesel generator for backup during nighttime and cloudy days. Figure 3 illustrates the solar system configuration, including component details for each house based on its respective energy requirements.

Sensitivity	Architecture					Cost				DG 10 kVA					CS6U-340M		SAGM 12V 135	
Home Load Scaled Average (kWh/d)	CS6U-340M (kW)	DG 10 kVA (kW)	SAGM 12V 135	SolaX10 (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)	Capital Cost ($)	Production (kWh/yr)	Autonomy (hr)	Annual Throughput (kWh/yr)
15.0	7.61	2.00	12	0.576	CC	$15,563	$0.296	$553.54	$8,407	48.0	68.5	21.9	38.4	40.7	1,576	9,017	25.8	2,115
20.0	8.72	2.00	12	0.736	CC	$20,438	$0.298	$886.94	$8,972	154	183	60.1	123	112	1,806	10,331	19.3	2,778
25.0	15.0	2.00	16	1.01	CC	$24,792	$0.276	$967.47	$12,285	54.0	67.0	21.8	43.2	40.6	3,108	17,777	20.6	3,531
30.0	18.3	2.00	16	1.12	CC	$28,392	$0.275	$1,176	$13,185	65.0	82.0	26.7	52.0	49.6	3,782	21,635	17.2	4,127
35.0	19.1	2.00	20	1.29	CC	$32,653	$0.272	$1,353	$15,165	86.0	115	37.1	68.8	69.1	3,957	22,636	18.4	4,839
40.0	28.8	2.00	24	1.48	CC	$39,278	$0.286	$1,567	$19,015	72.0	84.8	27.9	57.6	51.9	5,965	34,124	19.3	5,419
45.0	29.3	2.00	20	1.65	CC	$42,761	$0.278	$1,913	$18,037	158	187	61.5	126	114	6,066	34,699	14.3	6,105

Fig 3. System design for each house

For House 1, the energy demand is 15 kWh/day. Canadian Solar CS6U-340M modules are selected for this study, with an operating current (I_{mp}) of 8.97 A and an operating voltage V_{mp} of 37.9 V. The configuration consists of 11 parallel strings, each with 2 modules in series, resulting in a total of 22 modules. Figure 4 presents the I-V and P-V curves of the selected module at different temperatures.

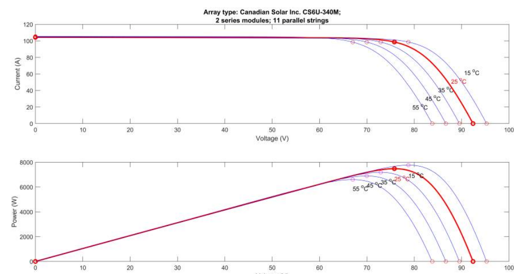

Fig 4. I-V and P-V curves of the PV Array

Tables 1 and 2 provide technical specifications of PV module and the battery used in the design.

Table 1

PV Panel Specifications

Parameter	Values
Model	CS6U–340M
Manufacturer	Canadian Solar
Panel Type	Monocrystalline
Nominal Power(P_{max})	340 W
Operating Voltage (V_{mp})	37.8V
Operating Current (I_{mp})	8.87A
Operating Temperature	-40°C ~ +85°C
Module Efficiency	17.49 %

Table 2

Battery Specifications

Parameter	Values
Model	Trojan SAGM
Nominal Voltage	12 V
Nominal Capacity	1.68 kWh
Maximum Capacity	140 Ah
Roundtrip Efficiency	85 %
Max. Charge Current	27 A
Max. Discharge Current	300 A
Bus Voltage	48 V
Cycles @50% DoD	1700 cycles

IV. Dynamic Simulation

A. MPPT

The performance of photovoltaic (PV) cells is significantly influenced by solar irradiance, the sun's position, and weather conditions, all of which impact output due to the non-linear relationship between the current-voltage (I-V) and power-voltage (P-V) characteristics. At any moment, there exists a unique maximum power point (MPP) where the PV module delivers peak power. To optimize energy conversion, a Maximum Power Point Tracker (MPPT) is employed to continually adjust PV operation to this MPP. MPPT technology plays a critical role in modern PV systems, ensuring consistent delivery of maximum power to loads and batteries, thereby enhancing overall system efficiency and reliability. Numerous MPPT algorithms have been developed, each with distinct advantages and limitations. Common approaches include Perturb and Observe (P&O), Incremental Conductance (INC), Constant Voltage (CV), and Hill Climbing (HC), as well as advanced methods like Fuzzy Logic Control (FLC), Neural Network (NN) MPPT, Particle Swarm Optimization (PSO), and Genetic Algorithm (GA) [10].

This study implements a modified INC algorithm due to its robust tracking capabilities, reliable performance under fluctuating irradiance and temperature, and straightforward implementation. The algorithm dynamically adjusts the duty cycle (D) of the DC-DC buck converter based on real-time changes in power (d_p) and voltage (d_v), ensuring that the system remains close to the MPP. To maintain system stability and prevent overshoot, the duty cycle is bounded between a minimum (Dmin = 0.1) and maximum (Dmax = 0.9)..

The Incremental Conductance (INC) algorithm operates on the principle that the derivative of power with respect to voltage (d_p / d_v) at the Maximum Power Point (MPP) is zero, as shown in Equation (1).

$$\frac{d_p}{d_v} = 0 \tag{1}$$

By examining the relationship between the instantaneous conductance and the incremental conductance of the PV array, as described in Equations (2)–(4), the INC algorithm determines if the MPP has been reached and adjusts the duty cycle of the converter accordingly.[11]

$$\frac{d_i}{d_v} = -\frac{1}{V} \tag{2}$$

$$\frac{d_i}{d_v} > -\frac{1}{V} \tag{3}$$

$$\frac{d_i}{d_v} < -\frac{1}{V} \tag{4}$$

From Equation (1), we can derive the following relationship:

$$1 + \frac{d_p}{d_v} = 0 \tag{5}$$

In summary, when Equation (3) holds true, the algorithm increases the voltage to move toward the MPP from the left. Conversely, if Equation (4) is true, it decreases the voltage, moving the operating point to the right of the MPP. The Incremental Conductance method is effective for tracking the MPP under rapidly changing irradiance conditions because it can dynamically detect changes in the slope direction, allowing the PV system to consistently operate near the MPP. Figure 5 illustrates the MPPT configuration for the photovoltaic system.

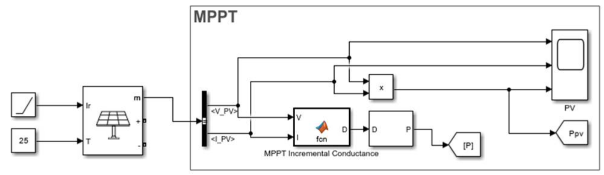

Fig 5. MPPT model in Matlab

B. Buck Converter

A buck converter is a highly efficient DC-DC converter commonly used to step down voltage from a higher input to a lower output level, maintaining stability and low ripple in output voltage, making it ideal for applications requiring regulated power. In this study, the converter adjusts the voltage from the PV array to match the system's DC link voltage requirement of 48V, with the output voltage (V_o) consistently set below the input voltage (V_i). This voltage reduction is achieved by modulating D of an insulated-gate bipolar transistor (IGBT) switch, which controls the proportion of time the switch remains on.

The essential components of the buck converter include the IGBT switch, an LC smoothing filter (inductor L and capacitor C, snd a discharge diode, which collectively ensure stable output. The rapid switching of the IGBT, governed by a pulse-width modulation (PWM) controller, allows controlled intervals of energy transfer, smoothing the output voltage to a consistent DC level. The duty cycle, a scalar between 0 and 1, is carefully adjusted to maintain desired voltage levels, directly affecting the power delivered to the load. Important equations describing the operation of Buck converter are as follows [12]:

$$V_o = DV_i \tag{6}$$

$$L = \frac{V_o \times (V_i - V_o)}{\Delta I_L \times f_s \times \Delta V_o} \tag{7}$$

$$C_{out} = \frac{\Delta I_L}{8 \times f_s \times \Delta V_o} \tag{8}$$

Where ΔI_L is the inductor ripple current, representing the oscillating component in current flow, typically characterized by its alternating nature. Based on these equations, the inductor and capacitor values are calculated as 2.2 mH and 19.55 μF, respectively. Figure 6 shows the buck converter circuit.

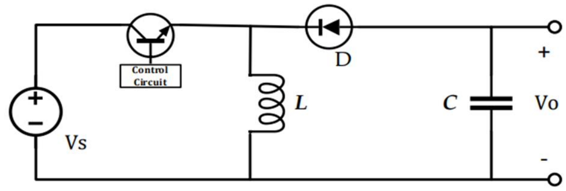

Fig 6. DC-DC Buck Converter

The individual models of the major system blocks are combined and presented in Figure 7, which illustrates the dynamic modeling of the complete system.

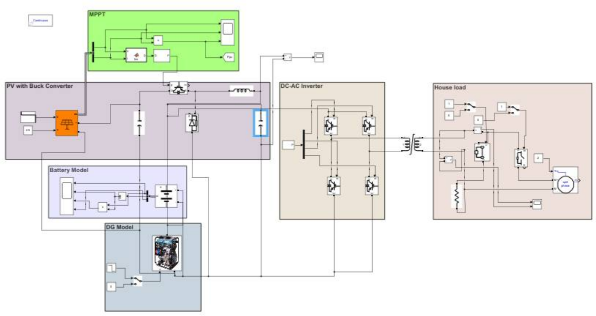

Fig 7. Complete System Modeled in Matlab Simulink

V. RESULTA AND ANALYSIS

The complete PV system configuration includes 11 parallel strings, each with 2 modules connected in series. Irradiance levels are set at 1000 W/m², 800 W/m², and 300 W/m², representing ideal, sunny, and low-light conditions, respectively. Given that PV power output is heavily influenced by fluctuating weather conditions—such as irradiance and temperature—analyzing the impact of these variations on PV output and, consequently, on the overall power system performance is crucial. The system's dynamic response is evaluated by subjecting it to variable irradiance levels.

The battery bank comprises 12 batteries of 140 Ah each, providing a backup duration of 20.16 hours and connected to the 48 V DC bus. The initial state of charge is set at 50%. To support the load during nighttime or periods of low solar irradiance (e.g., cloudy or rainy weather), a shared diesel generator (DG) is integrated with each household's power supply, with MATLAB modeling addressing synchronization constraints between the DG and PV system. The designated house can draw a maximum of 2 kW from the DG, ensuring continuous power flow and stability in variable load conditions. Figure 8 illustrates the PV system's voltage, current, and power responses under varying irradiance conditions.

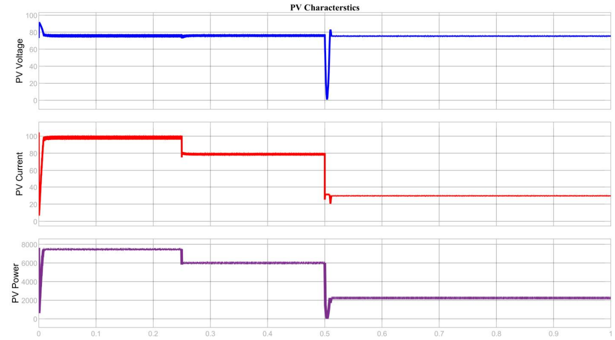

Fig 8. PV voltage, current and power

The system's response time and behavior are satisfactory, with the MPPT controller effectively reaching the maximum power point (MPP) despite significant weather fluctuations, ensuring maximum power generation from the PV array in all scenarios. The battery provides supplemental power when PV output is insufficient and recharges during periods of surplus PV power. To maintain battery levels efficiently, the Cycle Charging (CC) methodology is adopted, prioritizing battery charging from the diesel generator (DG) whenever solar output is unavailable and battery charge is low. The DG supplies any power deficit, with excess power directed to recharge the battery bank. Battery characteristics under these conditions are shown in Figure 9.

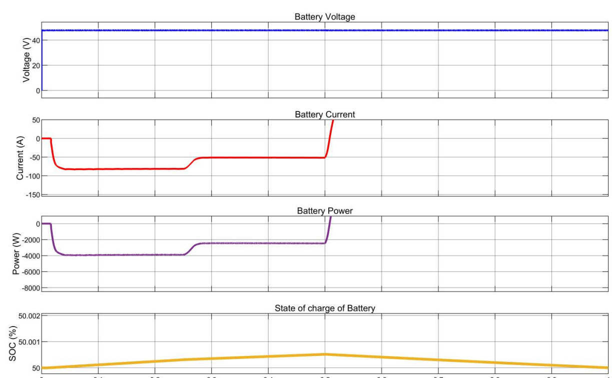

Fig 9. Battery Bank Voltage, Current and SOC

The total load requirement for the house is 15 kWh/day, primarily comprising resistive loads such as fans, lights, a TV, and a fridge, along with a smaller inductive component from the motor pump used for the water tank.Figure 10 shows the stable load voltage V_L and and load current I_L, with the system operating at the local standards of 220 V and 50 Hz.

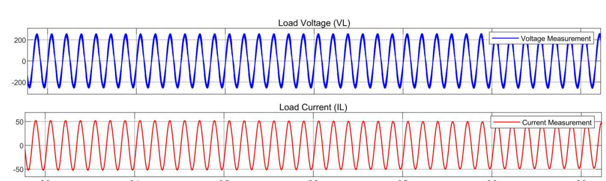

Fig 10. Volatge and Current delivered to the load

VI. Conclusion

The dynamic simulation results of the designed hybrid PV-battery-diesel system demonstrate its robust performance in addressing the energy needs of a residential neighborhood in Karachi. The MPPT algorithm effectively tracks the maximum power point under fluctuating irradiance conditions, optimizing PV output to ensure reliable power delivery. The battery system, with a 20.16-hour backup, seamlessly supplements the PV array during low irradiance periods, while the shared diesel generator supplies additional power when needed, maintaining grid independence. The Cycle Charging (CC) strategy further enhances efficiency by prioritizing battery charging from the generator during low solar availability, thereby reducing reliance on large battery banks and minimizing operational costs. Overall, this system offers a sustainable and cost-effective energy solution, underscoring the feasibility of hybrid renewable systems to meet residential energy demands while reducing dependency on fossil fuels and alleviating economic pressures associated with traditional energy sources.

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Conflict of Interest Declaration

The authors declare that there is no conflict of interest related to this research.

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