Optimal Energy Solution for Multi Residential Buildings: Combining Grid Connected PV System with Demand Response and EV's

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ABSTRACT - As energy demands continue to rise in urban multi-residential complexes, the integration of renewable energy sources with smart grid technologies becomes essential for sustainable, cost-effective, and efficient energy management. This study proposes a comprehensive energy solution for multi-residential buildings by combining a grid-connected photovoltaic (PV) system with a storage battery, electric vehicles (EVs), and demand response (DR) strategies. The system achieves significant reductions in grid dependency, energy costs, and carbon emissions. Through MATLAB Simulink modelling the technical feasibility and performance benefits of such an integrated framework are clearly demonstrated. This work provides a solid foundation for future research and policy formulation in the domain of smart residential energy systems.

***Key Words*:** Grid-Connected PV System, Demand Response, Electric Vehicles (EVs), Vehicle-to-Grid (V2G), Smart Energy Management, Multi-Residential Buildings, Energy Optimization, Renewable Energy Integration.

1. INTRODUCTION

The global energy landscape is undergoing a significant transformation, driven by the urgent need to reduce greenhouse gas emissions, ensure energy security, and transition to more sustainable energy sources. One of the primary contributors to energy consumption in urban areas is the residential building sector, particularly multi-residential complexes, which consume a substantial portion of electricity for lighting, heating, cooling, appliances, and now increasingly, electric vehicle (EV) charging.

Traditionally, these buildings rely heavily on centralized, fossil-fuel-based power grids that are not only environmentally damaging but also vulnerable to fluctuations in fuel prices and demand peaks. As urban populations grow, so does the strain on existing grid infrastructure, leading to challenges such as peak load issues, voltage instability, and high energy costs. Therefore, developing optimal energy solutions for these buildings is essential to address environmental, economic, and operational challenges.

Recent advancements in renewable energy technologies, especially solar photovoltaic (PV) systems, offer a viable alternative to meet residential energy needs in a clean and sustainable manner. When installed on rooftops or nearby land, grid-connected PV systems can significantly offset a building's energy consumption by providing a local source of electricity. However, solar energy is inherently intermittent – its production varies with weather and time of day, which makes integration and management a critical issue.

To complement PV systems, the concept of Demand Response (DR) has emerged as a powerful tool for energy optimization. DR allows consumers to adjust or shift their electricity usage in response to real-time signals such as electricity price fluctuations or grid load conditions. For example, certain household appliances or HVAC systems can be scheduled to operate during off-peak hours, reducing stress on the grid and lowering electricity bills.

Simultaneously, the increasing adoption of electric vehicles (EVs) introduces both challenges and opportunities. On one hand, uncontrolled EV charging can increase peak loads and cause stress on the electrical system. On the other hand, EVs equipped with vehicle-to-grid (V2G) capabilities can act as mobile energy storage systems, providing electricity back to the building or grid during high-demand periods.

2. METHODOLOGY

The block diagram represents an optimal energy management system for a multi-residential building, integrating grid-connected photovoltaic (PV) systems, demand response (DR), and electric vehicles (EVs). The system efficiently manages power generation, storage, and distribution by incorporating renewable energy sources, battery storage, and vehicle-to-grid (V2G) technology.

It ensures that energy demand is met in an optimal manner while minimizing grid dependency and maximizing the use of solar power.

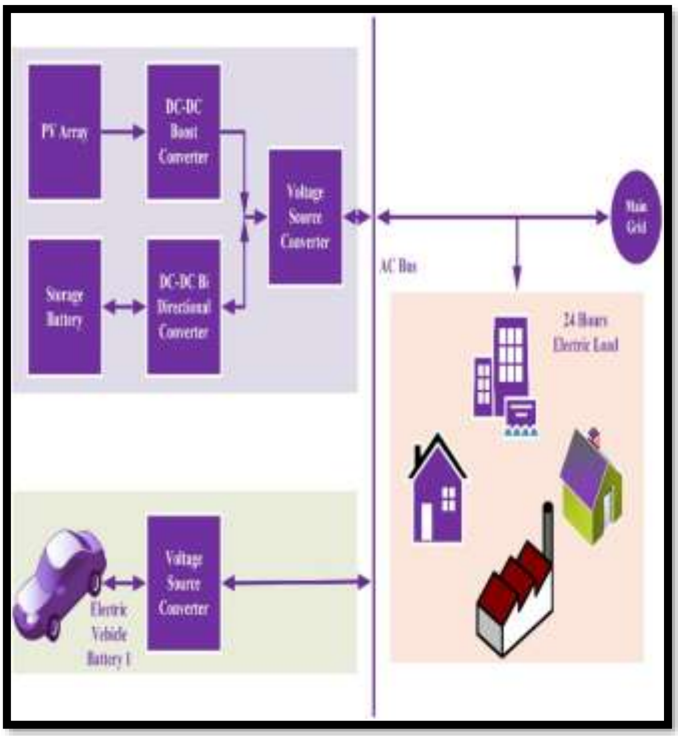

Fig-1: Block Diagram of Optimal Energy Solutions for Multi-Residential Buildings: Combining Grid-Connected PV Systems with Demand Response and EV's

3. WORKING PRINCIPLE

The solar PV panels act as the primary renewable energy source, generating DC power that is converted to AC by inverters and synchronized with the main grid. Surplus solar energy can either charge the battery or be exported to the grid. When solar energy is insufficient (such as during cloudy weather or night-time), energy stored in the battery or imported from the grid meets the load demand. Smart controllers using Proportional-Integral (PI) algorithms continuously manage voltage and frequency to maintain system stability. Battery management ensures optimal charging and discharging based on load requirements and solar availability. The microgrid intelligently switches between different power sources, prioritizing renewable energy, enhancing reliability, and minimizing reliance on the main grid. A closed-loop control system for regulating the output voltage delivered to a DC load. Initially, the input voltage from a DC link (likely from a solar PV or other DC source) is compared with a reference voltage set at 400V. The difference, or error signal, is processed through a Proportional-Integral (PI) controller to minimize the deviation from the desired setpoint. The output of the PI controller determines the duty cycle (D) for a DC-DC converter. This duty cycle is then fed to a pulse generator, which controls the switching of a power electronic device (such as a MOSFET) to adjust the output voltage. A feedback path monitors the load current (Idc_Load), ensuring system stability under varying load conditions. The ultimate goal of this system is to maintain a constant, regulated DC output voltage to supply the connected DC load efficiently and reliably.

The control and power flow within a solar photovoltaic (PV) system that also includes load management and battery storage.

The PV module generates DC electricity based on sunlight availability, which is measured by sensors monitoring voltage (Vabc) and current (Iabc). These signals are converted from the three-phase (abc) frame into the direct-quadrature-zero (dq0) frame for easier control. Real (P) and reactive (Q) powers are then calculated. The generated power is intelligently distributed: it can either directly supply the load, charge the battery, or feed into the grid depending on demand and generation conditions. If there is excess solar energy, it charges the battery or is exported to the grid. If solar generation is insufficient, the battery or grid supplements the load. Various multiplication and conversion blocks measure and display the amount of power in kilowatts for PV generation (PPV), load consumption (PL), and grid support, ensuring efficient energy management in the system.

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4. RESULTS

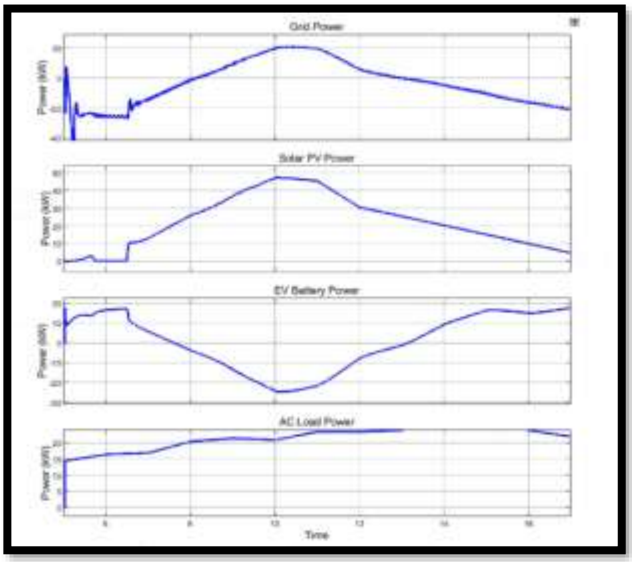

Fig-2: Grid, Solar PV, EV Battery and AC Load Power Waveform

The Grid Power graph represents the power exchanged between the microgrid and the main utility grid over time (in seconds). At the beginning of the simulation, there are visible fluctuations which indicate initial transients as the system stabilizes. Initially, the grid supplies power to the system (seen in positive values), suggesting that the PV output and battery are not yet sufficient to meet the load demand. Shortly afterward, the grid power drops below zero reaching nearly -40 kW indicating that the microgrid is exporting surplus energy to the grid.

This likely results from high PV generation and possible battery discharge. As time progresses, the curve rises steadily, showing increased grid consumption as demand potentially rises or renewable output drops. The grid power then stabilizes after reaching a peak around 20 kW, suggesting a balance is achieved between generation, storage, and consumption. This graph highlights how the grid acts as both a backup power source and an energy sink, dynamically adjusting based on real-time power flow and demand conditions.

The Solar PV Power graph demonstrates the real-time power output from the solar photovoltaic array over the simulation time (in seconds). Initially, the PV system generates minimal power close to 0 kW likely simulating early morning or overcast conditions. As time advances, the output gradually increases, climbing from 10 kW up to nearly 50 kW, representing the midday peak when solar irradiance is strongest. The power output then symmetrically declines, forming a bell-shaped curve typical of daily solar generation. This pattern reflects the natural variation of solar energy availability and shows the PV system's dependence on sunlight conditions. The peak generation period aligns well with possible battery charging and grid export, while the lower generation ends signal periods when the battery or grid would support the load. This curve is vital in energy management planning, as it informs scheduling for storage and load control strategies to optimize self-consumption and reduce grid dependency.

The EV Battery Power graph illustrates the charge and discharge cycles of the electric vehicle battery over the time period in seconds. In the early stage, the power is positive peaking around 20 kW indicating that the battery is charging, likely due to excess power from the solar PV or from grid energy during off-peak periods. Soon after, the curve dips below zero, reaching -30 kW, indicating that the battery is discharging. This discharge likely supports load demand during solar shortfall or grid unavailability. The curve then shows cycles of charging and discharging, highlighting the battery's responsive nature to system conditions. This behaviour reflects a smart battery management system designed to optimize usage by charging during low-cost or high-generation periods and discharging during high-load or low-generation periods. The graph confirms the EV battery's dual role as both a load and energy source, enhancing system flexibility and promoting cost-efficient, clean energy usage.

The AC Load Power graph reflects the total power consumed by the system's alternating current loads throughout the simulation (in seconds). Unlike the other dynamic plots, this graph remains relatively steady, starting slightly below 15 kW and gently rising to about 20 kW.

This stability suggests a constant or smoothly varying load, which could represent residential or commercial building loads where appliances or equipment operate on predictable schedules. The minor fluctuations might be due to periodic operation of smaller appliances or internal load management. The consistent power demand acts as a reference point for the PV system, battery, and grid to balance supply. When PV generation exceeds this load, the surplus can be stored or exported, while during deficits, the grid or battery compensates.

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This stability is crucial for developing effective control algorithms and ensuring the reliability of supply, making it a key variable in energy management systems.

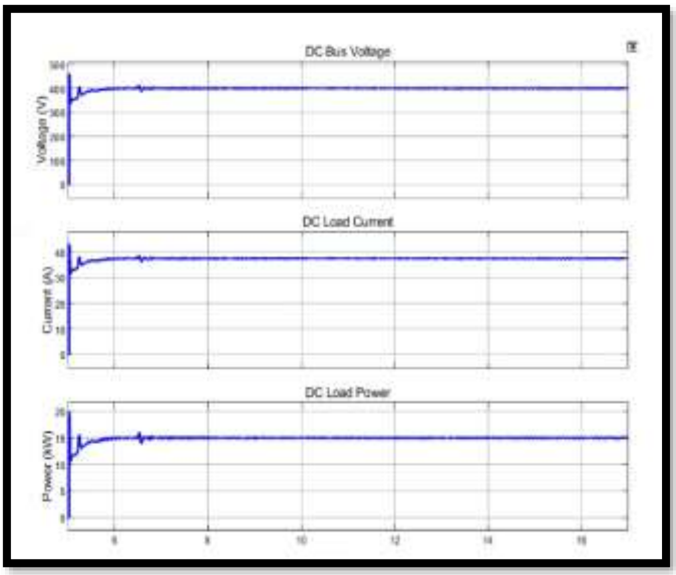

Fig-3: DC Bus Voltage, DC Load Current and DC Load Power Waveform

The DC Bus Voltage graph illustrates the voltage stability of the DC bus in the power system over a time period measured in seconds. Initially, there is a transient response as the system powers on, where the voltage momentarily rises and then quickly settles. After around 6 seconds, the voltage stabilizes at approximately 400 V and remains constant for the remainder of the simulation.

This stable voltage profile indicates effective voltage regulation, which is critical for maintaining the performance and protection of all DC-powered equipment connected to the bus. The transient behaviour is brief and expected due to switching actions or controller engagement during start-up. The absence of voltage drops or fluctuations in the later period confirms that the DC source and voltage controller are functioning as intended, maintaining a regulated voltage under a steady load.

The DC Load Current graph shows the current drawn by the DC load throughout the same time window. At the beginning, a short transient is seen, where the current quickly ramps up from zero to about 38 A, corresponding to the initial application of the load or activation of the power system. This ramp-up is smooth and settles into a nearly flat line, showing minimal fluctuation. The stable current draw suggests that the load connected is constant and that the system is not experiencing major variations in load demand during this period. This is beneficial for control systems and converters, as consistent current reduces dynamic stress and allows for more efficient operation. The graph further implies that the power electronics interfacing the DC load are operating in steady-state conditions, maintaining reliability and energy balance.

The DC Load Power graph, which is the result of multiplying the DC bus voltage and the load current, represents the actual power being delivered to the DC load. It starts with a sharp but controlled increase as the system reaches operational conditions and then levels off at a power value of about 15 to 18 kW. This behavior mirrors the trends in the voltage and current graphs, reaffirming system stability.

The brief disturbance at the beginning corresponds to the initial synchronization or load switching but is quickly damped. Once stabilized, the power curve is smooth and consistent, indicating efficient energy delivery. The sustained level of DC power signifies that the system has reached a steady-state mode, and both the source and load are well-matched. Such power stability is crucial in DC microgrids, EV charging stations, and industrial DC systems where fluctuations could disrupt operations.

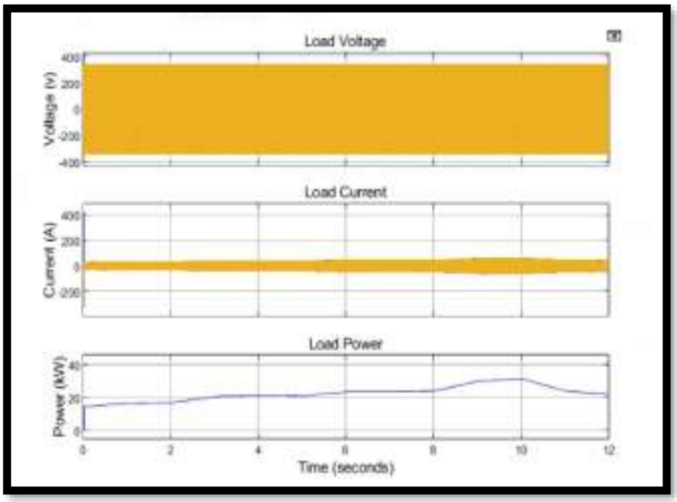

Fig-4: Load Voltage, Load Current and Load Power Waveform

The graph "Load Current" shows the alternating current (AC) being drawn by the load, measured in amperes (A). Similar to the voltage waveform, the current also appears sinusoidal, maintaining regular oscillations over time. However, unlike voltage, the amplitude of the current waveform slightly varies across the 12-second window. These fluctuations indicate changes in the load demand or operational conditions of the system. Around 0 to 4 seconds, the current amplitude is lower, possibly due to minimal load usage or inactive devices. From 4 seconds onward, the current magnitude slightly increases, peaking around 200 A at certain points, particularly between 8 and 10 seconds. This implies that more devices or systems were turned on, increasing current demand. The current remains within a symmetrical AC range of approximately ±200 A, reflecting proper power flow without distortion or faults. This behaviour ensures that the load is operating under a balanced condition with effective current regulation.

The graph "Load Power," shows the real power consumed by the load in kilowatts (kW). This graph exhibits a relatively smooth curve that increases gradually over time, demonstrating the dynamic nature of load demand. Initially, between 0 and 2 seconds, the load power is just under 20 kW. This value slowly rises, reaching about 25 kW by 4 seconds and slightly above 30 kW around 6 seconds. A noticeable peak appears between 9 and 10 seconds, where the power reaches nearly 40 kW before slightly dropping again. These changes reflect typical load behaviour in a residential or commercial energy system, where the demand increases due to additional appliances or processes being activated and then slightly reduces as some loads are turned off. The power curve is smooth and does not show any abrupt spikes or drops, indicating a steady and controlled load environment. This ensures the system is functioning efficiently without overload or unexpected shutdowns.

The three graphs together provide a comprehensive view of the electrical characteristics at the load side of the system. The Load Voltage remains stable and sinusoidal, suggesting a healthy voltage supply. The Load Current follows a similar pattern but with slight variations in amplitude, indicating fluctuating demand. Lastly, the Load Power graph confirms these changes in demand, with a steady increase in power usage over time and a peak that mirrors the current pattern. This data supports the conclusion that the load is functioning reliably and efficiently under stable electrical conditions.

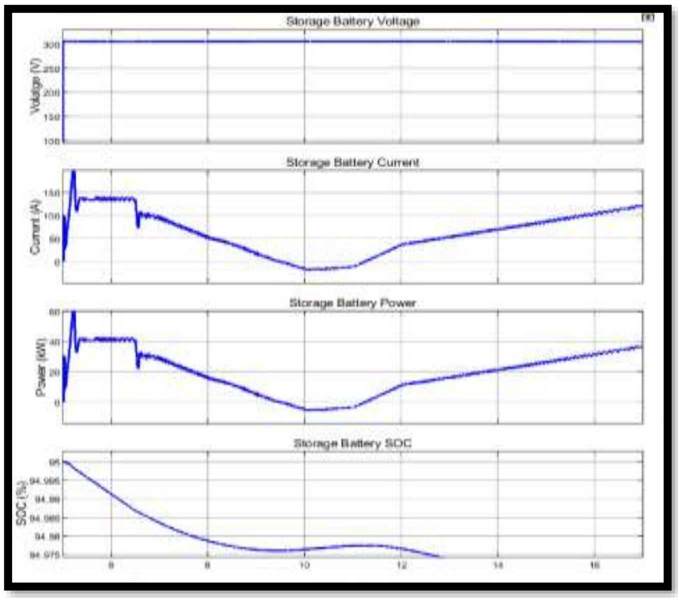

Fig-5: Storage Battery Voltage, Current, Power and SOC Waveform

The storage battery current graph represents the battery current in amperes (A). It begins with a peak of over 150 A at around 5 seconds, indicating strong initial charging. This value decreases over time, reaching close to zero by 10 seconds, indicating the battery is either idle or transitioning into discharge. After 10 seconds, the current begins to rise again in the positive direction, indicating a return to charging.

The smooth nature of the graph indicates controlled operation, and the direction of current helps determine the mode of battery operation — positive for charging and negative for discharging (though this graph only shows positive values, suggesting charging or very mild discharging not shown as negative).

This storage battery power graph shows the battery power in kilowatts (kW). The power graph mimics the current profile since power is a product of voltage and current. Initially, the power is high, reaching about 55 kW during initial charging, and then gradually decreases, bottoming near 0 kW around 10 seconds, where battery activity is minimal. After that, it starts increasing again up to 30 kW by 16 seconds, indicating a return to active charging. The smooth transition between these phases reflects efficient power management and regulation by the control system. The absence of negative power values indicates that this storage battery is either not discharging during this period or the power direction convention used shows only charging events.

The SOC graph shows the State of Charge (SOC) as a percentage, which represents the remaining capacity of the battery. Starting at around 95%, it gradually decreases as the battery discharges, reaching a minimum of around 94.975% at about 10 seconds. After this point, the SOC curve slightly flattens and shows a very small upward trend, consistent with the charging phase seen in the current and power graphs.

Although the changes in SOC are small, they are significant in indicating how energy is cycled in and out of the battery in this short simulation period. The high SOC throughout suggests that the battery remains mostly full, likely because it is being used for short-term balancing rather than deep cycling.

These four graphs together provide a comprehensive view of the storage battery's behaviour in a smart grid or hybrid energy system. The battery begins in a charging state, briefly enters a resting or minimal-use phase, and then returns to charging. Voltage remains stable, current and power follow expected trends, and SOC decreases slightly, indicating minor discharging followed by recharging. This reflects intelligent battery use for peak shaving, load balancing, or backup support.

5. CONCLUSIONS

The system demonstrates stable and efficient operation, as indicated by the analysis of load and battery parameters. The load voltage remains constant and balanced, while the load current stays steady with minor variations, leading to a relatively consistent load power output. The storage battery voltage maintains stability throughout the operation, while the battery current and power show smooth charging and discharging patterns. The battery's State of Charge (SOC) experiences only minimal fluctuations, staying within a narrow range, which indicates effective energy management and no risk of deep discharge or overcharging. Overall, the results confirm that the system maintains a healthy load and battery performance, ensuring reliable and efficient energy supply and storage under the given operating conditions.

Future Scope: This project involves expanding the system into real-time applications using embedded controllers and integrating advanced technologies like AI for predictive energy management. It can be enhanced with Vehicle-to-Grid (V2G) features, allowing EVs to support the grid during peak hours. Scalability to community microgrids, inclusion of smart contracts for peer-to-peer energy trading, and optimization for cost, battery life, and grid support further increase its value. This system has the potential to become a smart, sustainable solution for future decentralized and clean energy networks.

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