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Integrating PEVs into Smart Home Energy Management: A Vehicle-to-Home Backup Power Solution with Solar power system

T Ravi Sankar Reddy[1], **and I Kumaraswamy**[2*]

[1]*Research scholar, Mohan Babu University, Tirupathi, ravisankarshoba@gmail.com*
[2]*Associate Professor, Sree Vidyanikethan Engineering College, kumaraswamy.i@vidyanikethan.edu*

***Correspondence:** kumaraswamy.i@vidyanikethan.edu

ABSTRACT- This study focuses on leveraging the capabilities of plug-in electric vehicles (PEVs) to serve as an alternative power supply for suburban demands during disruptions, encompassing backup solutions, particularly in emerging or deprived regions. This initiative is part of an overarching strategy to establish household microgrids. Importantly, this utilization of PEVs for backup power is engineered to have no adverse impact on their primary function as electric vehicles. The proposed Vehicle-to-Home (V2H) system integrates seamlessly with solar photovoltaic (PV) charging. This synergy transforms the entire setup into a nano grid, a self-contained energy ecosystem. In a specific capacity, the plug-in electric vehicle (PEV) operates as a household load, utilizing its battery that gets charged either from solar photovoltaic (PV) systems or grid connections. The pivotal focus, however, remains on maximizing solar energy utilization, thereby reducing dependence on grid-based charging. To achieve this, a multi-faceted approach is adopted. Throughout daylight hours, various charging modes such as slow DC charging, fast DC charging, constant voltage, and constant current charging are employed to tap into and leverage solar energy resources effectively. The primary goals of this initiative include addressing various aspects: reducing household energy expenses, decreasing dependence on the conventional grid, enhancing power supply reliability to meet suburban demands during load shedding and power outages, and optimizing the utilization of solar energy from rooftop photovoltaic arrays. Essentially, this study aims to creatively integrate plug-in electric vehicles (PEVs), solar photovoltaics (PV), and smart grid technologies to improve energy resilience and efficiency in residential settings.

General Terms: Buck-boost Converter, Bidirectional AC-DC Converter, CC-CV Boost Converter, Energy Storage Unit, DC-Link.

Keywords: Electric vehicles; plug-in electric vehicles; photovoltaic; Vehicle-to-Home.

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1. INTRODUCTION

We ask Electric vehicles (EVs) are a type of automotive vehicle equipped with a substantial battery pack that facilitates traction using electricity, resulting in a notable reduction in the consumption of fossil fuels. Additionally, plug-in electric vehicles (PEVs) and plug-in hybrid electric vehicles (PHEVs) exhibit superior fuel conversion efficiency compared to conventional vehicles [1]. With decreasing mileage and per-unit costs (measured in Rs/km), the adoption of PEVs has experienced significant growth in recent times. Projections indicate that global PEV sales could reach an impressive 3.8 million units by 2020 [2]. These vehicles play a crucial role in decreasing reliance on fossil fuels by utilizing high-voltage (HV) batteries to power their operations. However, considering the volume of private vehicles, the energy consumption required for charging has a discernible impact on the utility grid. This may necessitate the construction of new power plants, including hydroelectric, nuclear, and coal-based facilities, leading to economic and policy-related challenges, as well as additional complexities. The adoption of renewable energy sources on a global scale offers a promising strategy for reducing greenhouse gas emissions, particularly CO_2. Various studies have explored CO2 reduction through diverse approaches such as solar cookers, water heaters, dryers, biofuels, improved cookstoves, and hydrogen utilization [3]. Investigations into the development and diffusion of different renewable energy technologies (RETs) in various countries, notably across European nations, have been documented [4]. The integration of renewable energy sources presents its own set of challenges. Extensive research has delved into the intricate aspects of Integrated Renewable Energy Systems (IRES) for power generation [5], addressing issues related to sizing methodologies, integration, storage systems, and control mechanisms for managing power flow. A range of control strategies, including distributed, centralized, and hybrid systems, has been explored for effective power flow management within IRES [6]. The declining cost and payback period of solar photovoltaic (PV) technology, attributed to rapid advancements, have made PV modules more economically viable, driving their adoption in various applications. By harnessing solar PV systems on rooftops, homeowners can not only achieve cost savings but also reduce energy loss attributed to transmission [7]. Solar photovoltaic systems have emerged as one of the most widespread and feasible energy technologies globally. Consideration has been given to employing solar PV systems within hybrid setups, integrating them with complementary energy sources to provide cost-effective heating and air conditioning [8]. Given the reduction in PV costs and policy incentives targeting greenhouse gas emissions and energy security, solar PV has emerged as an increasingly viable energy source [9]. Renewable energy sources, however, exhibit inherent intermittency, rendering energy storage solutions essential for ensuring continuous supply during periods without sunlight or wind. Traditional energy storage research has largely concentrated on large-scale systems, although smaller-scale storage devices have rapidly gained prominence over the past decade [10]. With the rising popularity of EVs and PHEVs, these vehicles have been considered as potential storage solutions for household households. Although EVs and PHEVs typically require battery replacement every decade, replaced batteries still retain around 70% of their state of health (SoH). Given the power demands of vehicles, a 30% decrease in SoH results in noticeable effects, as more frequent recharging becomes necessary [11]. In a notable development, GM and ABB proposed repurposing discarded Chevy Volt batteries into distributed energy storage systems, benefiting both industries and communities [12]. Projections suggest that by 2050, around 60% of personal vehicle sales will comprise electric vehicles (xEVs), translating to an 18% upsurge in the electric load on the grid [13]. Various optimization strategies have been proposed for xEVs connected or disconnected from homes to ensure efficient energy use [14] and to address scenarios such as blackouts and grid outages [15].

xEVs possess the potential to function as a Vehicle-to-Home (V2H) energy source, supplying power to homes during interruptions, similar to a standalone emergency generator [16]. The effective utilization of xEVs necessitates a comprehensive understanding of their interactions with the grid, renewable energy sources, and user transportation schedules. These xEV batteries could be employed to support homes or the power grid when connected. The concept of Vehicle-to-Building (V2B) further extends their utility, although considerations of battery depreciation costs arise [17] The emergence of new technologies, such as vehicle-to-home (V2H), vehicle-to-vehicle (V2V), and vehicle-to-grid (V2G), has presented novel opportunities for grid integration [18]. xEVs find common application in load management for homes, ensuring household privacy and confidentiality of smart meter data [19]. Research has proposed xEV-assisted battery load management algorithms, offering optimal charging and measurement muddling, demonstrating the flexibility of EVs in comparison to other household load-based energy storage systems [20]. To enhance the utilization of PV-generated electricity, V2H systems with rooftop solar PV and xEV batteries have been explored, with the added benefit of remaining operational during blackouts [21]. The advantages of xEVs over traditional backup generators include more efficient engine-generator operation, substantial battery storage to manage temporary load fluctuations, reduced emissions, and heightened customer interest [22]. Integrating fixed battery storage with solar PV systems for homes, utilizing available xEVs and integrating them into the home, offers potential economic benefits. Key factors influencing the profitability of energy storage systems include xEV battery size, daytime availability, and household consumption patterns. Ensuring the reliability, efficiency, and capability of batteries to deliver power and energy as required necessitates accurate performance assessment and life prediction [23]. Microgrid concepts have garnered attention, investigating their benefits and disadvantages, architecture, and control schemes [24]. Analysing microgrid demands through communication technology utilizing common information models (CIM) is reliant on branch theory [25]. In summary, this research underscores the potential of utilizing EVs as backup power sources within household microgrids in developing and underdeveloped regions. The proposed Vehicle-to-Home (V2H) approach integrates solar PV-based EV charging, creating a comprehensive nano-grid system. By strategically charging EVs through a combination of slow DC charging, fast DC charging, constant voltage, and constant current charging during daylight hours, the dependency on the electric grid is reduced. This approach holds promise for enhancing energy resilience, reducing fossil fuel dependency, and maximizing solar energy utilization in household settings.

2. ENVISIONED SYSTEM ARCHITECTURE AND DESIGN

The essential intention of this endeavor is to enhance and showcase advancements in technology and systems that empower an electric vehicle to function as a Vehicle-to-Home (V2H) system while parked at the owner's residence, effectively serving as a backup energy source. This innovation aims to utilize the vehicle's power infrastructure as a standby energy reservoir for the household, particularly during instances of load shedding and blackouts. The central focus of this research is to validate the practicality and feasibility of employing electric vehicles for V2H operations, thereby demonstrating their potential as dependable backup power supplies. Furthermore, the V2H system could play a pivotal role in addressing challenges related to market acceptance and cost concerns in the wider adoption of electric vehicles.

Drawing on existing research, this project intends to create a comprehensive model for V2H technology. This model integrates various components such as the vehicle's battery, rooftop solar photovoltaic (PV) array, emergency backup power systems, DC and AC loads within the home, as well as grid power. Through careful consideration of previous work in this field, a refined model will be developed to establish a robust V2H framework that optimizes energy usage and addresses energy supply contingencies for household settings.

The envisioned system presents a fusion of both stand-alone and grid-connected configurations, illustrated in Figure 1. This innovative approach draws advantages from both stand-alone and grid-connected setups, offering a comprehensive array of benefits. An additional advantage is its cost-effectiveness, as it relies on a solitary standalone inverter, which incurs minimal expenses. The incorporation of the photovoltaic (PV) system into the utility grid not only ensures affordability but also guarantees a dependable power supply.

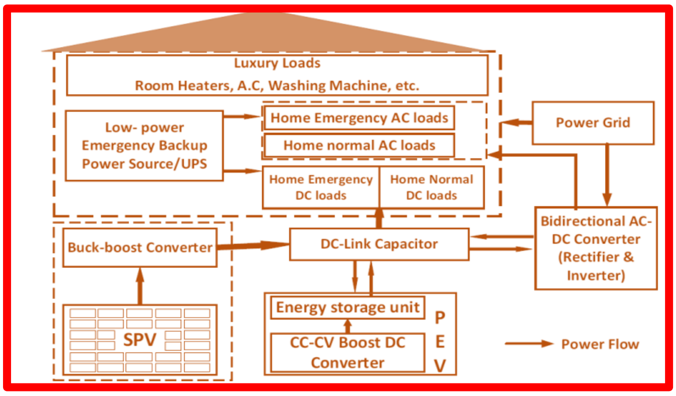


Fig.1. An intricate block diagram detailing the power flow within the proposed system

2.1 V2H Operational Modes

The V2H system encompasses six distinct operational modes, each predicated on the direction of power flow. The exploration of these modes involves the creation of corresponding block diagrams and an analysis of the electrical flow direction, elaborated upon in the subsequent sections.

2.1.1. Home Powered by Grid Supply

In this operational mode, depicted in *fig.2*, the unavailability of Plug-in Electric Vehicles (PEVs) or their low State of Charge (SoC) renders this source inaccessible. Furthermore, the solar PV source remains unavailable due to conditions such as partial shading, cloudy weather, or nighttime, precluding its power contribution. Consequently, the grid assumes the role of supplying power to the household loads, encompassing both AC and DC loads.

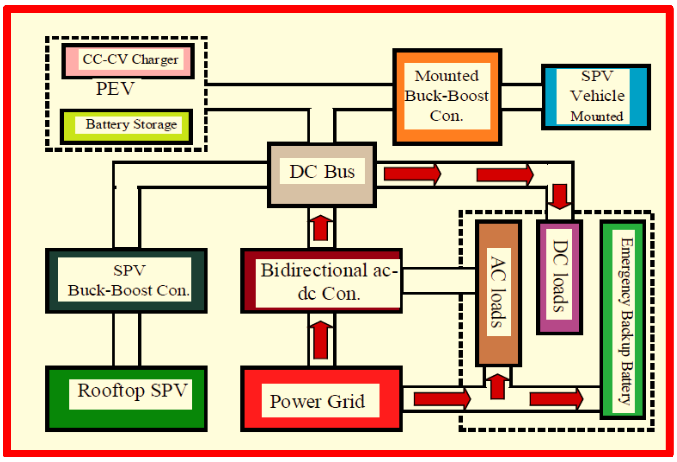


Fig.2. Home Powered by Grid Supply

$$P_{generation} \geq P_{demand} \qquad (1)$$

During high solar insolation, system expression is:

$$P_{pv} \geq P_{load} + P_{EV\,BatteryCharging} \qquad (2)$$

Also, during low insolation

$$P_{EV\,BatteryCharging} \geq P_{load} - P_{pv} \qquad (3)$$

Similarly, during night when the battery gets discharged

$$P_{grid} \geq P_{load} \qquad (4)$$

Thus, during the availability of grid power supply and very low level of EV battery the proposed system works on:

$$P_{Grid} = P_{load} + P_{EV\,BatteryCharging} - P_{pv} \quad (5)$$

2.1.2. Seamless integration with the grid - Charging via Grid Connection

The Plug-in Electric Vehicle (PEV) is linked to the home. However, owing to an urgent requirement for charging driven by the low State of Charge (SoC) of the PEV, the grid furnishes power to both the PEV and the suburban loads. It's important to highlight that in this mode, the power availability from the PV source is not taken into account, and the plug-in electric vehicle (PEV) undergoes swift charging, operating at 43A. As depicted in *fig. 3*, the power flow direction is from the grid to both the household loads and the PEV.

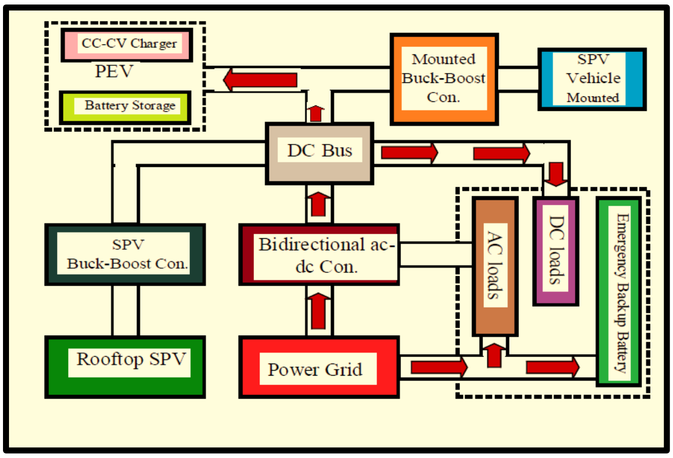


Fig.3. Direct Grid Transfer - Charging via Grid Connection

2.1.3. Solar based Charging - Rectification via Grid Connection

In this operational mode, the residence draws power from the grid, while solar photovoltaic (PV) energy is harnessed to charge the Plug-in Electric Vehicle (PEV). This configuration enables a deliberate choice for slow battery charging, attributed to the inherent limitations of solar PV in generating high current levels required for fast charging. The power flow dynamics are visually represented in *fig.4*.

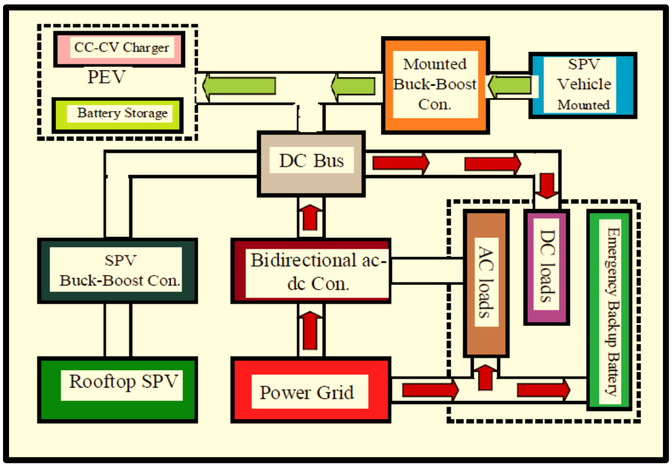


Fig.4. Solar based Charging - Rectification via Grid Connection

2.1.4. PV-Home Connection - Plug-in Electric Vehicles Charging

In this operational configuration, the PV system serves a dual role by providing power for both charging the PEV and fulfilling the energy needs of the household loads. The solar PV array generates an ample 1250W of power, efficiently dividing it between the battery charging requirement in slow mode (350W) and the household load demand of 820W. The intricate dynamics of power flow are visually depicted in *fig. 5*, portraying the direction of energy transfer from the solar PV source to both the PEV and the household loads.

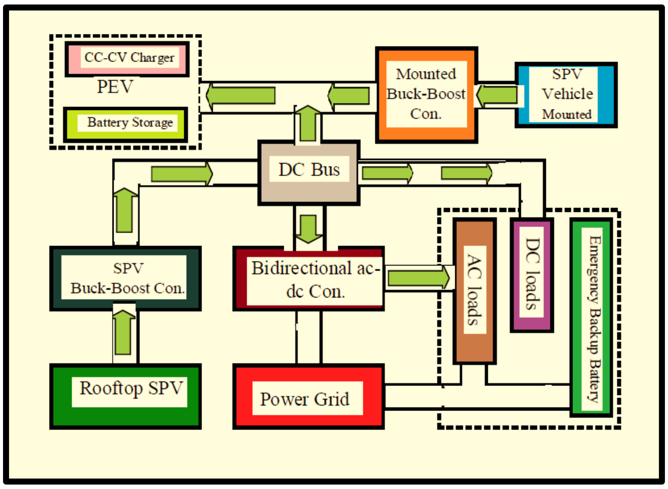


Fig.5. Solar PV-Home Connection - Charging Plug-in Electric Vehicles

2.1.5 PEV-Enabled Power Distribution

Within this mode, visually represented in *figure 6*, both the solar photovoltaic (PV) source, potentially hindered by factors like partial shading or cloudy conditions, and grid-based power are unavailable. Consequently, the Plug-in Electric Vehicle (PEV) takes on the role of providing power to the suburban loads via the DC bus. These suburban loads encompass both AC and DC loads within the household, comprising standard usage loads while excluding luxury load applications, which remain disconnected from the envisioned V2H system.

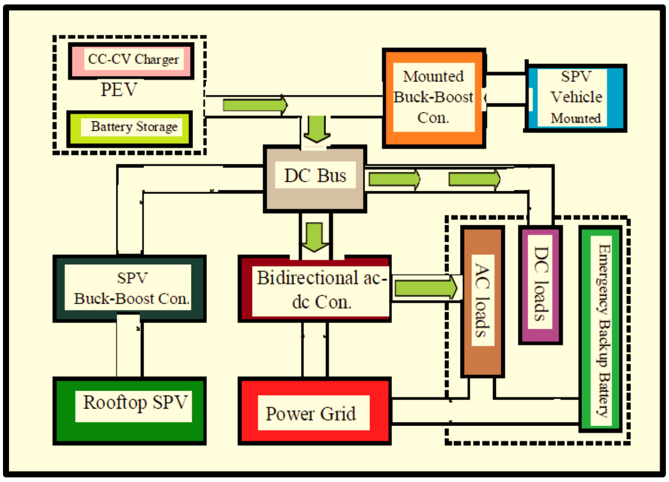


Fig.6. PEV-Enabled Power Distribution

2.1.6. Integrating Battery Backup

Within this operational mode, any other potential power sources are rendered inaccessible due to various reasons. Consequently, the crucial power supply for the household emergency loads is facilitated by the emergency backup battery. These household standby loads encompass a range of both alternating current (AC) and direct current (DC) requirements, delivering a holistic solution for essential energy demands. A visual representation of this mode is depicted in *fig.7*.

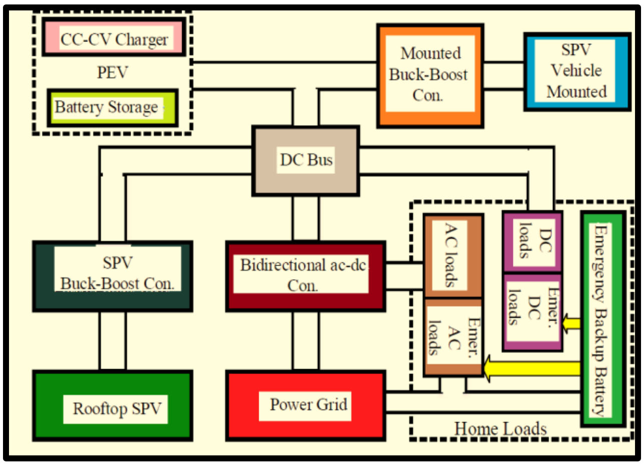


Fig.7. Integrating Battery Backup

2.2 Design Consideration

The assessment of the suggested framework was conducted using Simulink®/MATLAB®. The comprehensive illustration of the entire model can be observed in *figure 8*. Within this representation, the direct current (DC) loads within the household setup, plug-in electric vehicle (PEV), solar photovoltaic (PV) system, and emergency backup source are interconnected with the DC link capacitor. On the opposite side of the converter, the power grid and household alternating current (AC) loads are linked. Elaboration on each component is provided in the following sections.

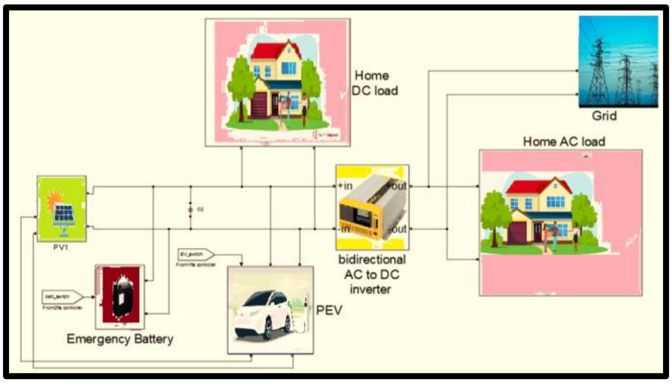


Fig. 8. portrays the Simulink/MATLAB representation of the envisioned framework designed for the V2H

2.2.1. Integration of Solar Photovoltaic (PV) System

The PV integration involves a duo of PV arrays. The foremost array boasts a peak potential of 1200Wp, while the secondary array contributes 400 Wp. The primary array establishes a connection with the DC link through a buck-boost converter, employing a closed-loop proportional-integral (PI) controller to uphold a steady 24V output. As for the secondary array, it interfaces with the plug-in electric vehicle (PEV) charger through a control switch. Both C1 and C2 denote DC link capacitors, and the incorporation of ideal switches orchestrates control over these energy sources. The buck-boost converter takes charge of channeling power into the DC link, duly furnishing a 24V DC voltage output.

In *fig. 9.* the i-v and p-v characteristics of PV1, as depicted in *fig. 9*, are showcased under two distinct temperature settings while maintaining a constant irradiation level of 1000W/m2. This visual representation encompasses key parameters such as open-circuit voltage (Voc), short-circuit current (Isc), maximum power point (Pmpp), current at maximum power point (Impp), and voltage at maximum power point (Vmpp).

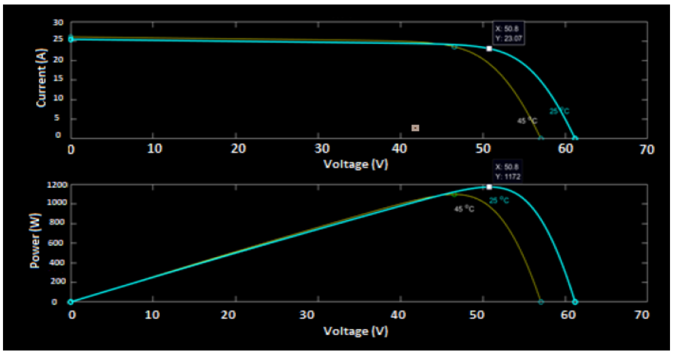


Fig. 9. PV, IV curve featuring a combination of two modules in series and two parallel strings

2.2.2. System for Storing Emergency Backup Batteries

Within this module, a 200 Ah, 24 V lead-acid battery governs the dispensation of power to critical loads during emergencies. A commercially available AC/DC/AC inverter, designed for household applications, assumes the responsibility of charging the battery when the grid is operational. In the event of battery utilization, the controller's role is pivotal, discerning whether to transmit an 'on' or 'off' directive (1 for 'on' and 0 for 'off') to the switches.

2.2.3. EV Battery & Charge Controller

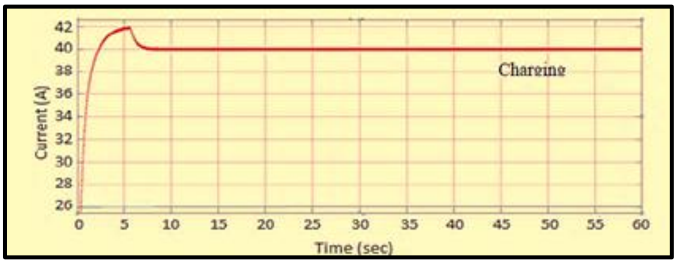
The PEV battery storage module consists of a lithium-ion battery, a battery charger, and control switches specifically designed for battery charging and discharging functions. The storage unit itself boasts a substantial 4.8 kWh capacity. An integral aspect of the PEV battery storage segment is the onboard battery charger. This charger, meticulously designed, employs a boost converter configured to administer constant current (CC) and constant voltage (CV) charging strategies for the battery. The charger's versatility extends further—it adeptly harnesses both photovoltaic (PV) and grid power sources, offering two distinct charging modes: rapid charging (45A) taps into grid power, while leisurely charging (13A) capitalizes on solar PV energy. The controller, intricately linked to the battery's state of charge (SoC), orchestrates the transition between CC and CV modes as needed. Figures 10 and 11 exhibit the expeditious and gradual charging processes of the battery within the constant current (CC) charging mode.

2.2.4. Bidirectional Converter

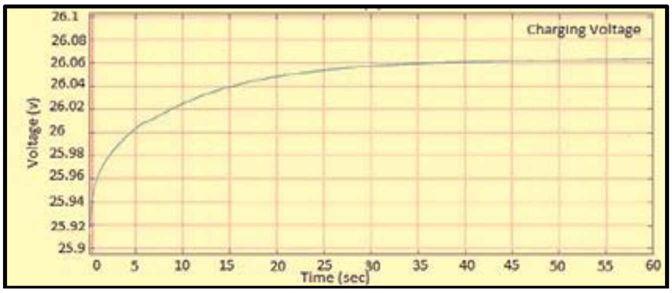
A 24V converter, complemented by a 24V/220V transformer, adroitly adjusts voltage levels whenever shifts in energy direction are necessitated. During step-down conversion, the transformer adeptly reduces AC voltage, and by halting signals to the IGBTs gate, it seamlessly operates akin to a bridge diode—effectively rectifying AC voltage into DC. Alternatively, in the step-up conversion mode, a quartet of pulses is dispatched to the IGBTs by the PWM generator, enacting the transformation of DC input into AC, while the transformer propels the AC voltage upwards.

2.2.5. Computation of Grid Supply and Household AC and DC Loads

The grid system embodies a singular-phase 220V AC source that interfaces with the household load through judiciously positioned control switches. These switches, serving as conduits of connection or disconnection, manage the interaction between household loads and the AC source. The household setup encompasses 700W AC loads and 120W DC loads, with the former being of RLC type and the latter adopting a resistive configuration.

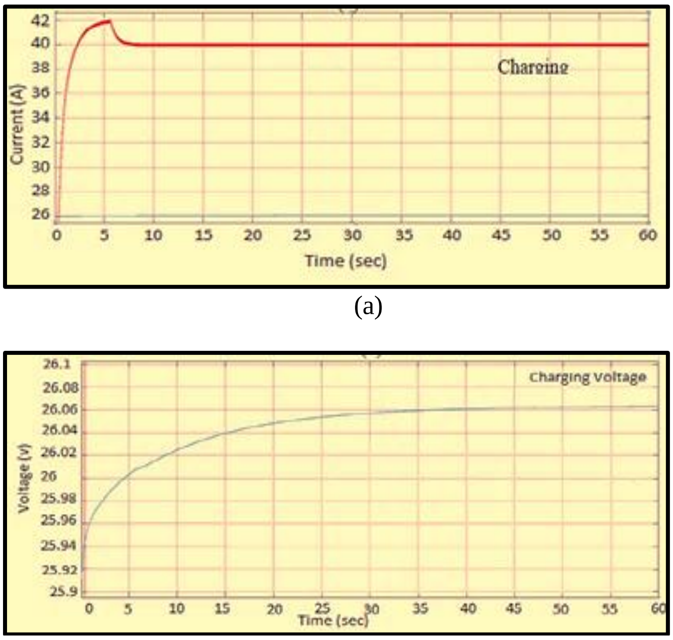


(a)



(b)

Fig. 10. the rapid charging procedure (40A) conducted under the constant current (CC) mode is delineated, encompassing both the charging current (a) and the charging voltage (b)



(a)

(b)

Fig. 11. Elucidates the process of leisurely charging (13A) within the constant current (CC) mode, presenting both the charging current (a) and the charging voltage (b)

3. SIMULATION, RESULT AND DISCUSSIONS

3.1. Home Powered by Grid Supply

The solar PV, PEV, and emergency backup battery sources all yield zero output power. In contrast, the grid seamlessly furnishes a power output of 830W, effectively catering to the demands of the household loads. The power consumption profile is characterized by three distinct curves within the P_load spectrum. Specifically, the yellow curve signifies the power attributed to the DC loads, while the blue curve corresponds to the power drawn by the AC loads. The culmination of both DC and AC load powers is strikingly represented by the red curve. The intricacies of this power distribution scenario are vividly depicted in *figure 12* depicts the power output of every source in addition to the extravagant power of household loads, all within the scope of mode I as mentioned in section 2.1.1.

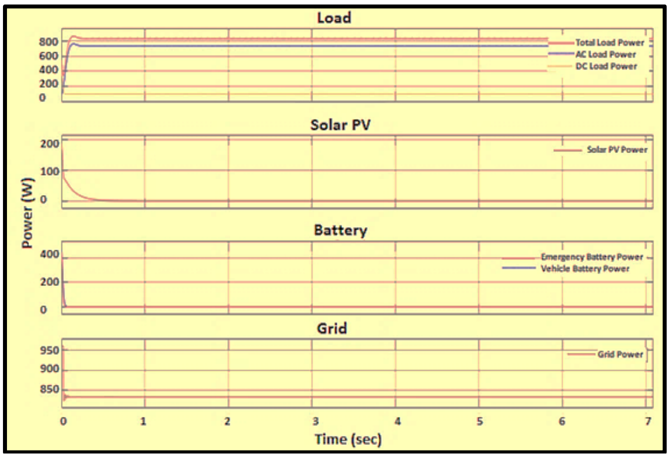


Fig.12. The output power profiles of individual sources alongside the power consumption pattern of the household

3.2. Direct Grid Transfer - Charging via Grid Connection

Figure 13 provides a comprehensive portrayal wherein the grid seamlessly contributes a substantial 2158W of power to sustain a household load of 820W, while simultaneously allocating 1043W to expedite the rapid charging of the battery. Notably, the power value (-1043W) assigned to battery power consumption distinctly signifies its active charging status. This scenario unfolds in the absence of PV source availability, consequently reflecting a power curve of zero. In addition, there is no power being stored in the emergency battery backup.

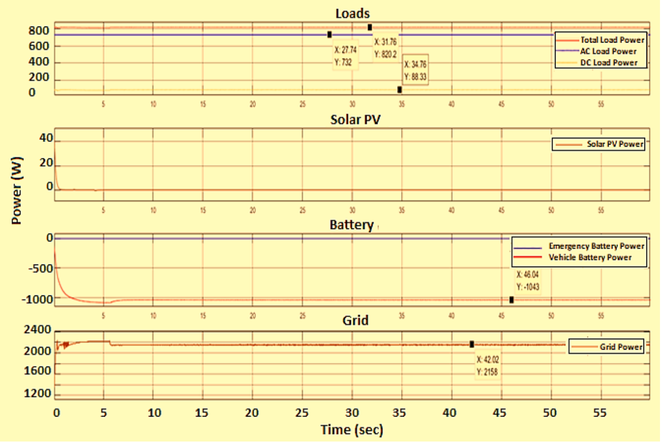


Fig.13. The generated power from each source alongside the power consumption of household loads

3.3 Solar based Charging - Rectification via Grid Connection

Figure 14, the dynamics shift to a scenario where solar PV output plays a pivotal role. Here, the battery experiences a 330W influx of power from solar PV during the gradual charging phase, while the grid continues to empower household loads with 830W of sustenance. The solar PV array is also instrumental in generating 350W of power, primarily dedicated to fueling the battery charger for its charging process.

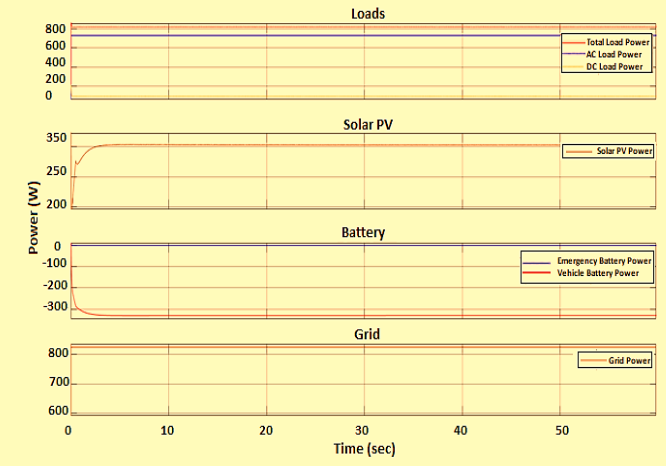


Fig. 14. The power outputs of individual sources alongside the power consumption pattern of household loads

3.4 Solar PV-Home Connection - Charging Plug-in Electric Vehicles

Figure 15 distinctly illustrates a scenario where solar PV emerges as a substantial contributor, effectively channeling power to both household loads and the PEV. Notably, the solar PV source contributes an impressive 1200 W of power, while the cumulative demand from the household loads nears the 800 W mark. In this equilibrium, the PEV seamlessly draws upon 350 W from the solar PV array. The unmistakable negative power value attributed to the vehicle battery convincingly signifies its ongoing charging process.

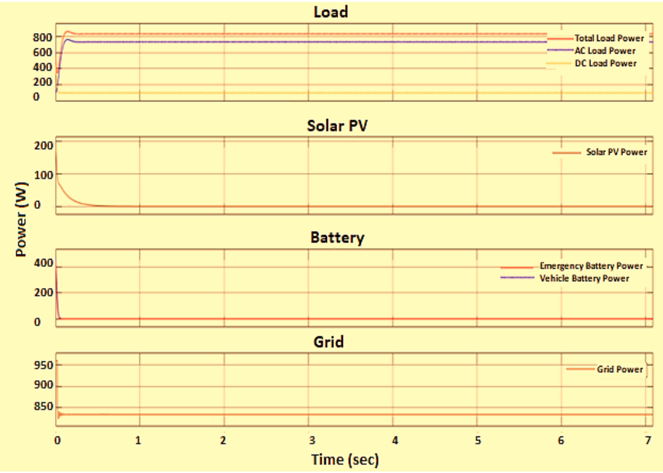


Fig. 15. The power output from the solar PV, the power absorbed by household loads, and the power draw from the PEV

3.5 PEV-Enabled Power Distribution

Figure 16 offers a succinct visual representation of power dynamics, vividly portraying the power output profiles of both the PEV and the household loads. Specifically, the PEV efficiently furnishes a commendable 830W of power, effectively catering to the energy demands of both household DC and AC loads.

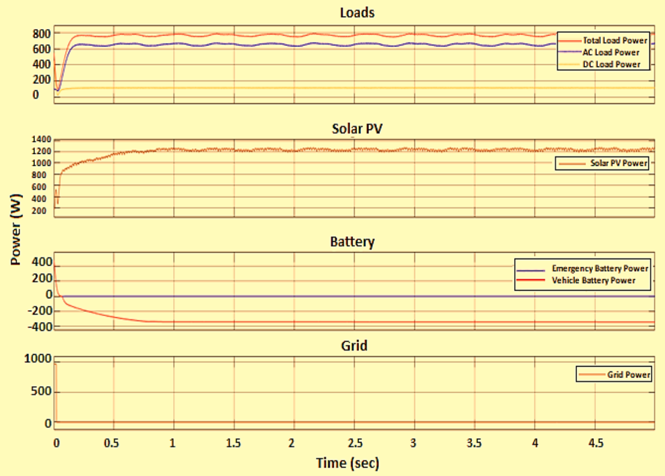


Fig. 16. The power output profile of the PEV in tandem with the power consumption pattern of the household loads

3.6 Integrating Battery Backup

Figure 17 vividly encapsulates a distinctive scenario wherein the energy demands of the household loads are exclusively met through the agency of the emergency backup battery. Intriguingly, neither of the other power sources contributes any measure of power to the household load during this depicted period.

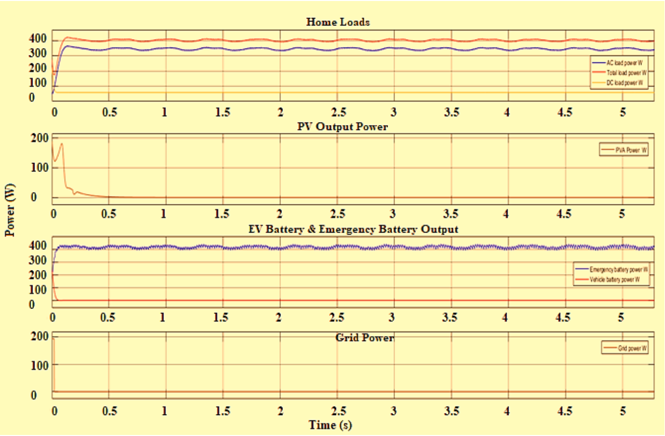


Fig. 17. The power output from the emergency backup battery in conjunction with the power consumption of critical household emergency loads.

Table. 1 Comparisons with recent research article

Ref.	Settling time (Sec)
[4]	0.5
[8]	0.6
[9]	0.62
[10]	0.45
[12]	0.76
Proposed	0.2

4. CONCLUSION

This study places significant emphasis on harnessing Plug-in Electric Vehicles (PEVs) as crucial backup power sources for domestic loads, particularly in developing and underdeveloped nations. The proposed framework seamlessly integrates into the household setup, functioning as a household nano-grid, all while preserving the PEV's primary role as an electric vehicle. This integration is achieved through the implementation of a Vehicle-to-Home (V2H) system. The innovation extends to include solar photovoltaic (PV)-based charging of the vehicles, granting the entire system nano-grid capabilities within this framework, the PEV functions as a household load, drawing its charge from both the grid and solar PV. Notably, the solar PV array takes precedence as the preferred charging source, thereby reducing dependence on the grid. During daylight hours, a combination of gradual DC charging and swift DC charging is employed, utilizing constant voltage and constant current charging methodologies to optimize the utilization of solar energy. The versatility of the V2H system is encapsulated in six distinct operational modes, customized to meet the specific needs of a typical Indian household. These operational modes serve as the basis for modeling and simulating the proposed V2H system.

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