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Enhanced Grid Stability and Demand-Side Optimization through Deep Neural Network-Controlled Vehicle-to-Grid (V2G) Peak Shaving and Load Shifting

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Abstract - Modern power networks face both opportunities and problems from the quick adoption of electric vehicles (EVs) and the growing use of non-conventional resources. To keep the grid stable, controlling peak demands and making sure energy is distributed efficiently provide a significant challenge. By enabling bidirectional power transfer between EVs and the grid, vehicle-to-grid (V2G) technology provides a workable option. As a result, EVs become mobile energy storage devices that may optimize energy consumption and lessen grid stress by recharging during off-peak hours (load shifting) and discharging electricity during peak demand (peak shaving).This study suggests a Deep Neural Network (DNN)-based Demand Side Management (DSM) approach for a grid-connected V2G energy storage system. By training the DNN to forecast short-term power use and user behaviour, EV charging and discharging cycles may be controlled in real time. Through advanced V2G operations, the model ensures optimal energy exchange by considering criteria including EV availability, battery State-of-Charge (SOC), grid load patterns, and power price. MATLAB/Simulink simulation results with various residential and business load profiles over a 24-hour period show how successful the suggested approach is. Peak grid power peaked at 166.5 kW without DNN management, however peak shaving based on DNN lowered this to 100 kW. The demand was further spread using load shifting, which produced a smoother load curve. The suggested DNN-based DSM strategy is a viable option for next-generation smart grids as it greatly improves grid stability, lowers operating costs, and makes it easier to integrate renewable energy.

Keywords**:** Deep Neural Network, Demand Side Management, Electric Vehicles, Grid-Connected System, Load Shifting, Peak Shaving, Vehicle-to-Grid

1. Introduction

Modern power networks are increasingly integrating non-conventional resources and EVs, which has led to the necessity for advanced DSM techniques. EVs may function as storage devices or V2G, technology, which permits bidirectional energy transfer between EVs and the grid. Energy from EVs sent to the grid at high demand (peak shaving), and charging can be planned for times of low demand (load shifting). This boosts the use of input resources, lowers peak demand pressure, and greatly improves grid stability. By facilitating services like peak shaving, frequency management, and voltage stability, EVs' participation in V2G frameworks highlights their potential to act as dynamic grid support systems. Because V2G provide bidirectional flow, EVs return stored power to the grid at high demand, easing pressure and improving both the environment and the economy. In addition to highlighting its benefits like lower grid stress and cost savings, a thorough analysis of V2G for peak shaving also highlights its drawbacks, such as battery deterioration and inconsistent user engagement, and offers suggestions to enhance deployment [1].

EV aggregators with V2G capabilities are included into an optimization-based approach for load shifting in grids to flatten demand curves. Tested on an IEEE 37-bus distribution grid, this model highlights the flexibility of V2G in demand response by demonstrating efficient load shifting and congestion management driven by hourly energy price signals [2]. V2G applications in microgrids and public infrastructure further show how effective they are in controlling peak demands. EV charging and discharging schedules are optimized using an algorithm created for public facilities to reduce peak loads while taking user mobility requirements and battery state-of-charge limitations into account. Better use of non-conventional resources is made possible by the algorithm, which has been tested in three parking situations and validates that V2G efficacy varies on EV numbers and parking length [3].

Peak shaving is improved by a user-friendly V2G scheme that provides both centralized and decentralized operating phases, tailoring techniques to the individual preferences of each EV user. In China, a case study demonstrates that global and split schedule optimization models lower charging expenses, resulting in a 5.89% reduction in peak power use as compared to traditional charging [4].

To optimize grid operations and offer more peak shaving and load balancing, an adaptive control approach for PEV charging/discharging was tested on a residential transformer with 1,000 customers. It uses real driving data to dynamically update reference operating points [5]. V2G facilitates peak shaving and valley filling scenarios by use of advanced EMS. When used on a grid-linked microgrid with module and EV charging stations, a tree-based decision method optimizes EV charging and discharging to smooth load curves. Utilizing changes in power prices and user lifestyle habits, the system efficiently fills off-peak times and lowers peak demand when tested with varying industrial and residential loads [6].

Peak shaving is optimized using a two-stage V2G control technique that first determines the target peak reduction levels offline using PEV mobility models and load projections, then modifies the discharging rates in real time. This method, which has been tested on a residential distribution transformer using actual PEV mobility data, reduces computing complexity and provides competitive peak shaving performance when compared to ideal alternatives. It also addresses the effects of nighttime load through offline charging scheduling [7].

With an adaptive modified multi-objective whale optimization method optimizing network effects and costs for both EV users and utilities, EV integration with PV modules reduces grid reliance. The model's practical effectiveness is validated by simulations that use actual EV travel patterns, which provide better load profiles, voltage stability, and lower energy losses [8]. By giving precedence to charging EVs with low SOC and discharging during high loads, an optimum priority-based V2G scheduling method reduces grid load variation. It balances grid and customer demands by reducing peak-to-off-peak load variance from 5 MW to 1.5 MW in a commercial-residential region with 1,300 EVs [9].

Environmental advantages and the integration of renewable energy are also supported by V2G systems. V2G offers up to 700 MW (11% of linked EV capacity) for peak shaving in a Latvian power system case study, lowering CO_2 emissions by about 100 kg per passenger car and showing great promise for sustainable grid operations [10]. Concerns regarding deterioration are raised by the increased battery cycling in V2G services, though. Calendar aging's impact on lithium inventory loss is highlighted in research that uses a physics-based digital-twin model to compare the advantages of V2G against battery lifetime. According to the results, environmental temperature and battery chemistry have a crucial role in determining V2G compatibility [11].

A coordination technique for numerous EV aggregators was tested on IEEE 13-node and Seoul distribution networks to ensure EVs can support peak shaving and valley filling while meeting driving demands. To smooth load profiles, it employs upper-level linear power distribution and lower-level min-max optimization [12].

DNNs have demonstrated great potential in the prediction and optimization of intricate, nonlinear systems, such as patterns of electricity consumption. A DNN-based DSM model is created in this situation to forecast changes in demand and adjust the EVs' charge/discharge schedule appropriately. The model carries out peak shaving through coordinated V2G operation and intelligently adjusts loads by learning past consumption patterns and grid behaviour. This strategy guarantees energy efficiency, lessens grid congestion, and promotes a more intelligent and robust grid architecture.

2. Proposed Grid connected EV system

EVs act as dynamic energy storage linked to the main power grid in a V2G integrated power distribution system, as shown in Fig. 1. To transmit energy at a feasible low voltage to different consumer loads, a step-down transformer (34.5/0.4 kV) receives power from the main grid, which has a 154 MW capacity at 34.5 kV. In order to show how power is supplied to local households and companies, these loads are divided into residential and commercial sectors (Load-1 through Load-5).

The EV battery system is linked to the grid via an AC/DC converter. To charge the EV battery, the converter converts grid-supplied AC into DC, and vice versa. Stable DC voltage and seamless energy exchange are ensured by the DC link capacitor between the converter and the EV battery. The bidirectional flow, in which the EV battery may release energy back into the grid during times of high usage and the grid recharges the battery during off-peak hours, is the fundamental component of V2G operation. The energy feedback loop is represented by the dashed magenta arrow above, emphasizing how EVs improve grid flexibility, load balancing, and peak shaving by acting as both distributed energy sources and consumers.

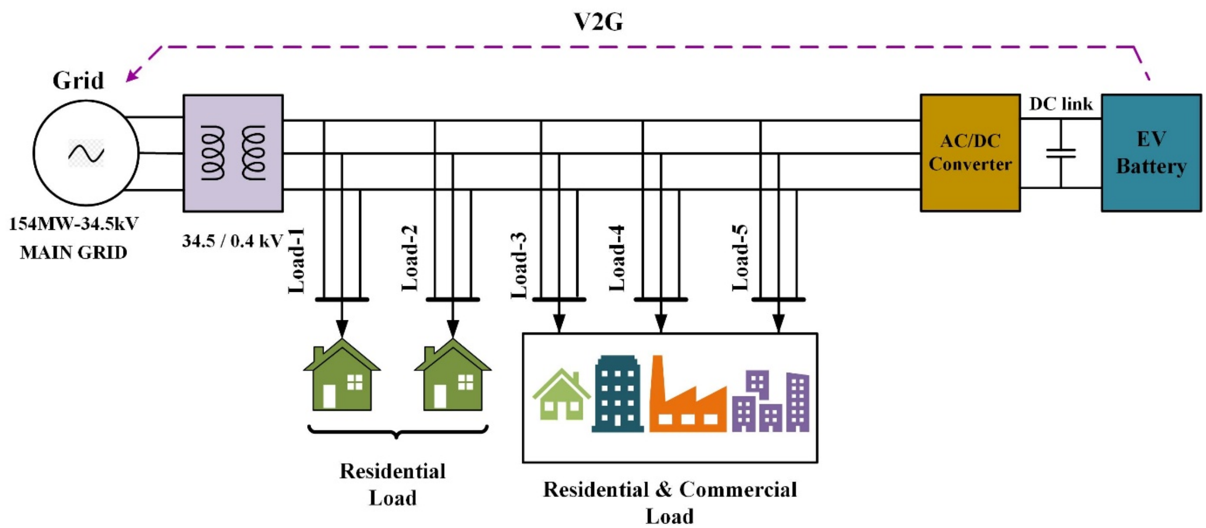

Fig. 1: Proposed System Architecture

2.1. Peak Shaving

Two essential features of V2G systems are peak shaving and valley filling, which work to flatten the load curve by lowering the peak energy demand and making use of the extra capacity during times of low demand. By boosting electricity consumption during off-peak hours, which are usually when energy demand and costs are very low and are sometimes referred to as the "valley" of the load curve, valley filling is a demand-side energy management technique that supplements peak shaving. This operational approach increases the utilization rate of base load generation during off-peak hours and reduces the requirement for extra power generation during peak hours. Because V2G delays the installation of new generating units and related infrastructure and lowers the need for peak load, power production businesses gain a great deal from this process. Delaying investments in transmission and distribution infrastructure also helps grid operators. However, grid operators and EV customers bear the majority of the expenditures associated with the V2G deployment.

2.2. Benefits for EV owners

There are two main costs for EV customers to contribute in V2G. the price of charging during off-peak hours. the expense of battery deterioration brought on by repeated cycles of charging and draining. Let's allow daily discharge (kWh) to be denoted by E_{allow}, battery depth-of-discharge by δ, battery cycle life by L_{cyc}, discharge efficiency by η_{dis}, daily driving distance by R_d, and vehicle efficiency (km/kWh) by η_{veh}. The capacity for daily discharge is thus provided by

$$E_{allow} = \frac{C_b.\delta - \frac{R_d}{\eta_{veh}}}{\eta_{dis}} \tag{1}$$

The unit storage cost for the EV user is,

$$C_{user} = \frac{C_{bat}}{\delta L_{cyc}} + C_{val} \tag{2}$$

Where C_{val} is the valley-time electricity price. The total number of participating EVs is estimated by:

$$N_{ev} = \frac{P_{total} T_h}{E_{allow}} \tag{3}$$

Where, P_{total} is total annual V2G peak power support, T_h average daily discharge duration (hours) Total user-side cost over T_y years, considering discount factor i is,

$$C_u = \sum_{t=1}^{T_y} \frac{C_{user} P_{total} T_h N_d}{(1+i)^t} \tag{4}$$

Where N_d is the number of days per year of V2G participation.EV users' revenue from selling power at peak time C_{peak}:

$$B_u = \sum_{t=1}^{T_y} \frac{C_{peak} P_{total} T_h N_d}{(1+i)^t} \tag{5}$$

2.3. Benefits of Grid

Installing and maintaining V2G infrastructure, including control systems and chargers, is the responsibility of grid companies. Assume that N_{ev} is the number of participating EVs and C_{infra} is the infrastructure cost. C_{mgmt} is the yearly cost of project management. The grid operator's overall expense is then,

$$C_g = C_{infra} N_{ev} + \sum_{t=1}^{T_y} \frac{C_{mgmt} + C_{val} \cdot P_{tot} \cdot T_h \cdot N_d}{(1+i)^t} \tag{6}$$

Grid operators benefit from lower capacity expansion expenses, which are projected to be:

$$B_g = \sum_{t=1}^{T_y} \frac{C_{cap} \cdot P_{total} + C_{line} \cdot P_{total} \cdot T_h \cdot N_d}{(1+i)^t} \tag{7}$$

where C_{line} is the cost per kWh of postponed transmission expansion and C_{cap} is the cost per kW of averted generation.

2.4. Benefits for Power Producers

Producers of power save money, lower operational costs as a result of making the most use of base load plants and less investment in peaking power units. Let $\Delta\, C_{op}$ be the savings from utilizing base load rather than peak power, and let $C_{gen.}$ be the unit cost of peak load power capacity. The advantage then is,

$$B_p = \sum_{t=1}^{T_y} \frac{C_{gen.} P_{total} + \Delta\, C_{op}. P_{total}. T_h. N_d}{(1+i)^t} \tag{8}$$

The following is the net economic advantage of peak shaving based on V2G:

$$G = B_u + B_g + B_p - C_u - C_g \tag{9}$$

2.5. Load Shifting

Relocating consumption from periods of peak demand to off-peak hours is known as load shifting, and it is a demand-side energy management approach. When it comes to load shifting in grid-connected systems, EVs are essential, particularly when combined with V2G technology. EVs are charged during periods when electricity rates and demand are low, usually at night. These cars can release stored energy back into the grid later, during peak hours when demand and power costs are high. In doing so, the load curve is flattened, and peak demand stress is successfully reduced by redistributing energy use throughout the day.

Load shifting in V2G networks is advantageous to EV owners as well as grid operators. Without having to rely on expensive peaking power plants or make significant investments in new infrastructure, grid managers are able to better balance supply and demand. However, battery deterioration, energy efficiency losses, and charging/discharging restrictions must also be taken into consideration in this economic model. Thus, to optimize load shifting's advantages while reducing its disadvantages, intelligent scheduling and optimization techniques like DNNs are employed.

When incorporating variable non-conventional resources like wind and PV, load shifting is particularly crucial. The grid may use more clean energy and less fossil fuel by rearranging loads to coincide with periods of strong renewable power. Thus, load shifting improves overall grid dependability by serving as a link between sporadic renewable production and steady demand in the context of smart grids and energy storage systems.

3. DNN based Control logic for Inverter connected to EV battery

A DNN-based control system intended for DSM in a V2G operation is shown in Fig. 2. To create the ideal power references, Pref and Q_{ref}, the DNN gets inputs such as the time of day and the EV battery's state of charge. To create current references (I_{dref}, I_{qref}), these references are compared to the real power outputs, Pact and Q_{act}. The errors are then treated using PI controllers. The inverter output is controlled by comparing the reference and actual currents after a transformation block transforms the measured three-phase voltages and currents into dq0 coordinates. To improve response accuracy, the control loop uses feedforward decoupling to reduce coupling between the d and q axes. After being converted back into V_{abc}, the voltage commands (V_d, V_q) are delivered to a PWM generator, which generates the switching pulses for the inverter that is attached to the EV battery. The EV and the grid can exchange energy intelligently and efficiently thanks to this setup. By charging the battery at off-peak hours and discharging it through high-demand times, the technology facilitates valley filling and peak shaving, which eventually stabilizes the grid and increases energy efficiency. This model continuously adjusts to real-time situations using DNN-based prediction and control, ensuring dependable V2G participation and optimized battery utilization.

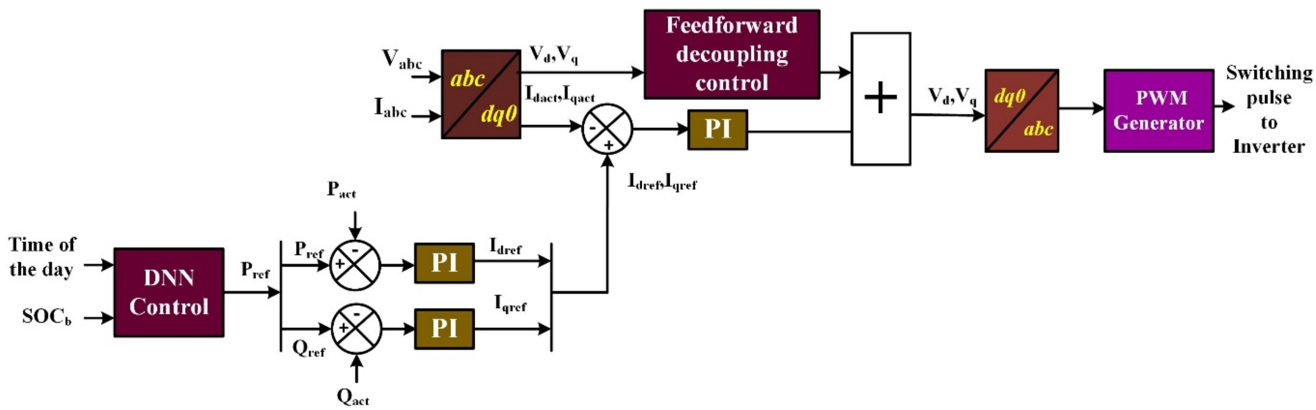

Fig. 2: DNN based Control for Inverter connected to battery

4. Results & Discussions

The proposed Peak shaving and Load shifting for V2G is performed in MATLAB/Simulink. Totally 5 residential and 3 commercial load profiles are considered for 24 hrs Time period. The Load Profile is represented in Fig. 3 and 4.

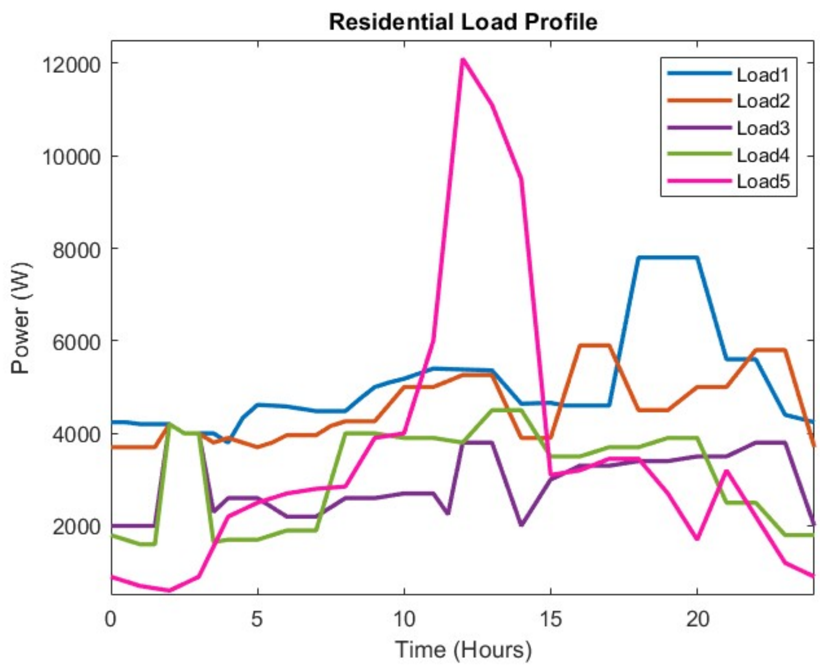

Fig. 3: Residential Load Profile

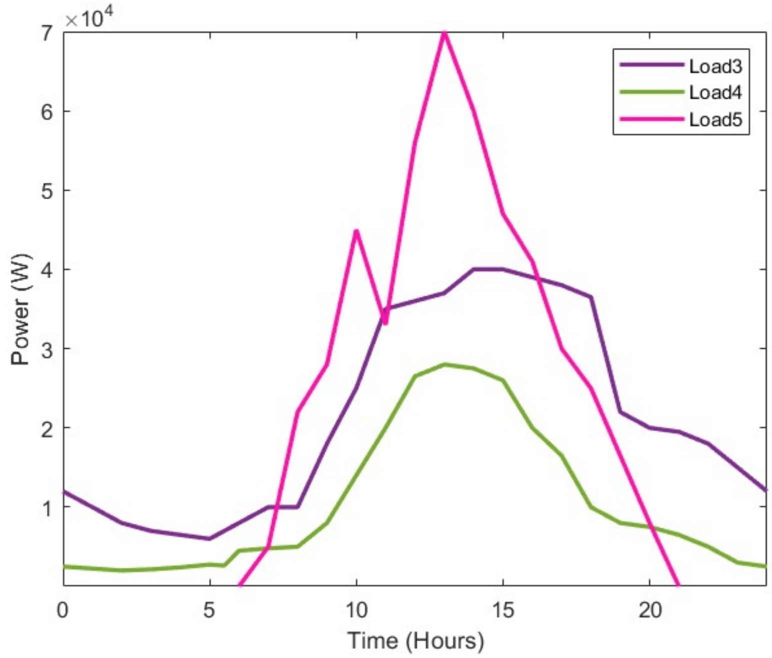

Fig. 4: Commercial Load Profile

The maximum grid power obtained without battery and DNN control is 166.5 kW, The power is represented in Fig. 5.

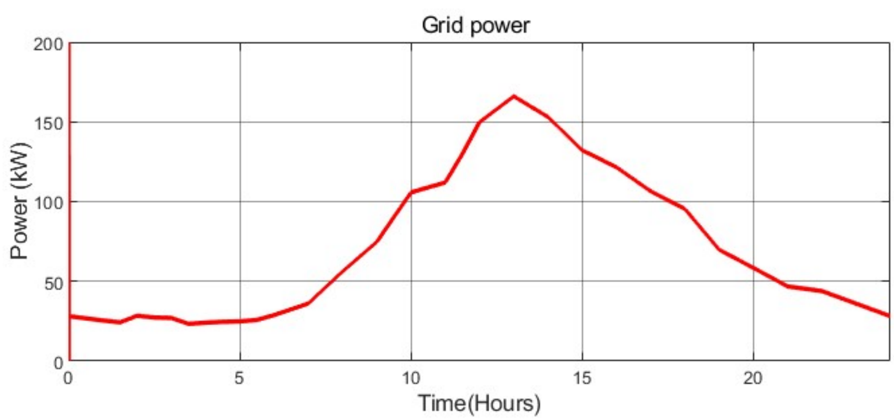

Fig. 5: Grid Power without Peak shaving

When the battery is connected with DNN control, peak shaving is employed in the grid power for effective EM using the DNN control employed in the battery, considering the SOC & time of the loads. The power gained with peak shaving is represented in Fig. 6. Due to peak shaving, the power is distributed uniformly & the maximum peak power is 100 kW. This control helps in reducing the cost of the system and effective operation of the grid. The battery power during peak shaving is represented in Fig. 7. Here the battery is operated in V2G mode from 7 to 20 hours.

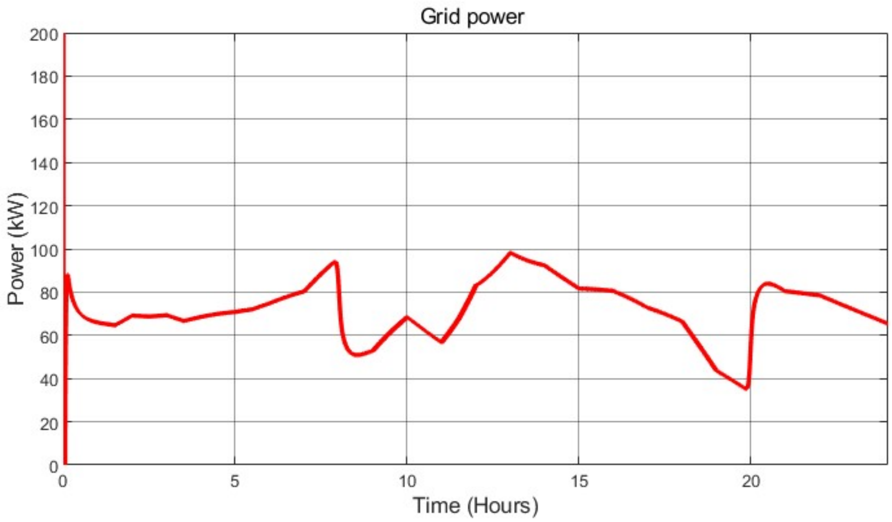

Fig. 6: Grid Power with Peak shaving

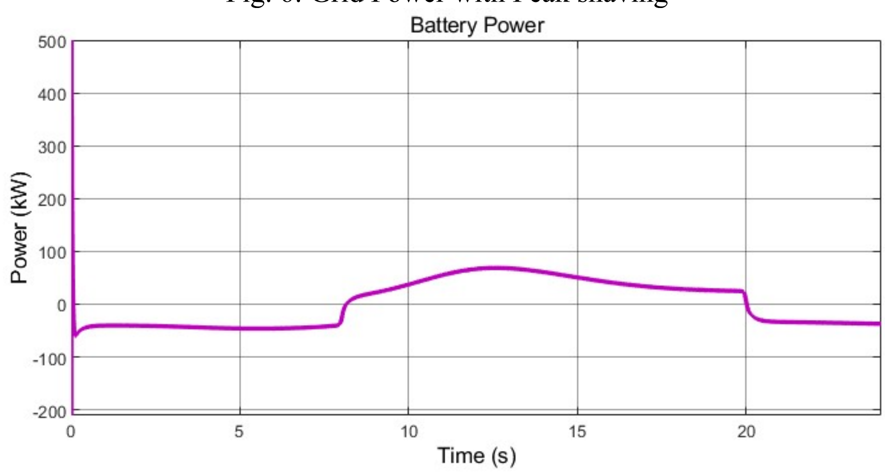

Fig. 7: Battery Power with Peak shaving

The load power obtained for the 5 loads connected during peak shaving is given as follows: based on the load profiles, the power is shared from the grid and battery based on the SOC of the battery.

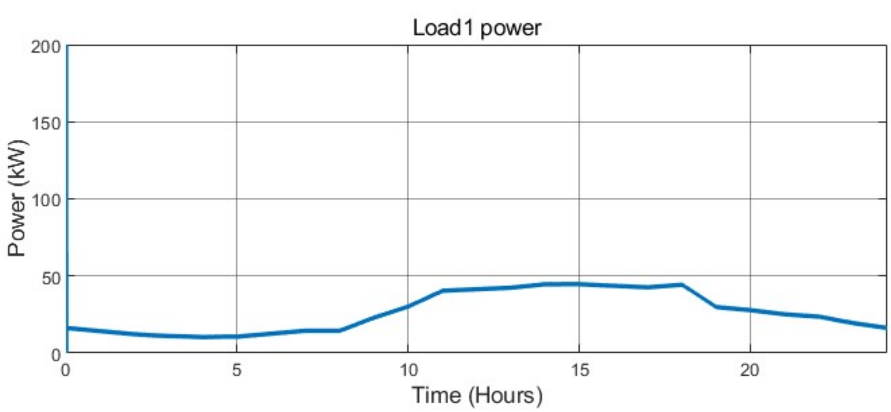

Fig. 8: Load Power-1 during Peak shaving

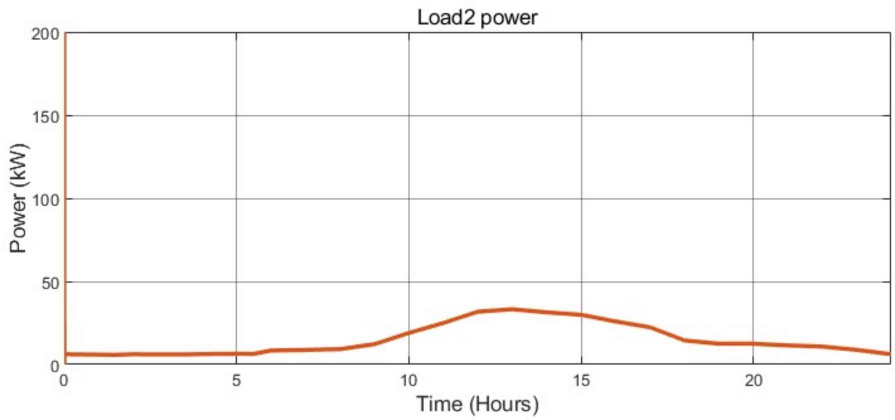

Fig. 9: Load Power-2 during Peak shaving

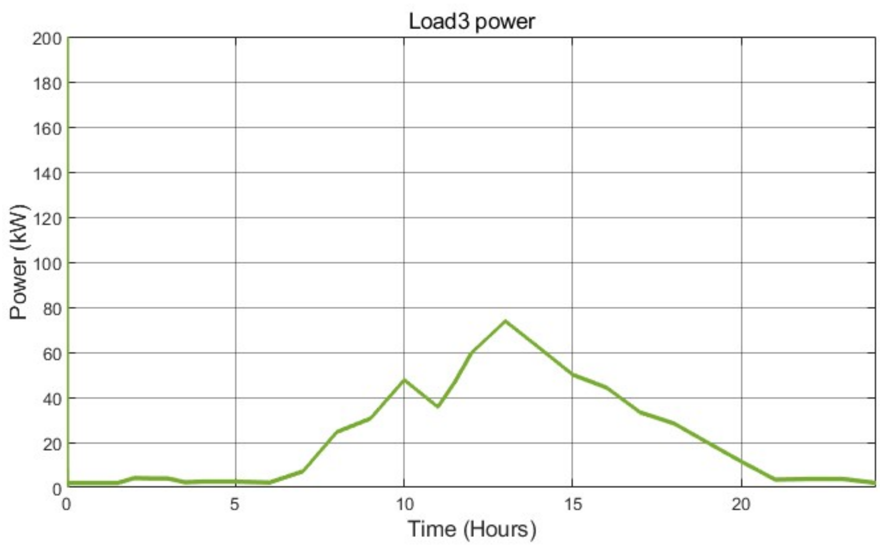

Fig. 10: Load Power-3 during Peak shaving

Fig. 11: Load Power-4 during Peak shaving

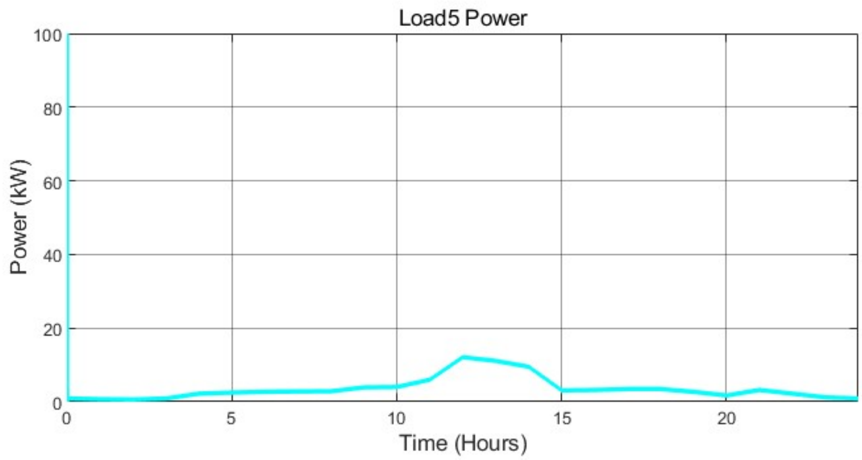

Fig. 12: Load Power-5 during Peak shaving

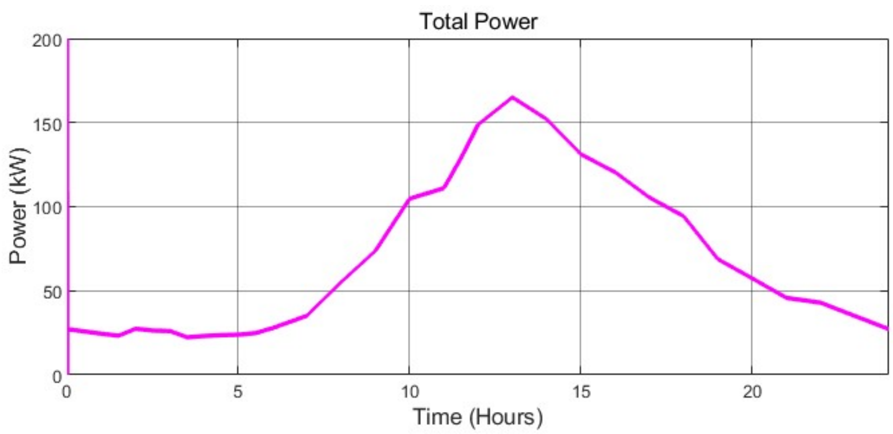

Fig. 13: Total Power-2 during Peak shaving

During peak time, especially from 7 hr to 20 hrs , the peak load is operated from 1 to 6 hr. This shifting will provide smooth operation of the system by making the peak grid power even less. The comparison of the impact of peak shaving and load shifting is represented in Fig. 13.

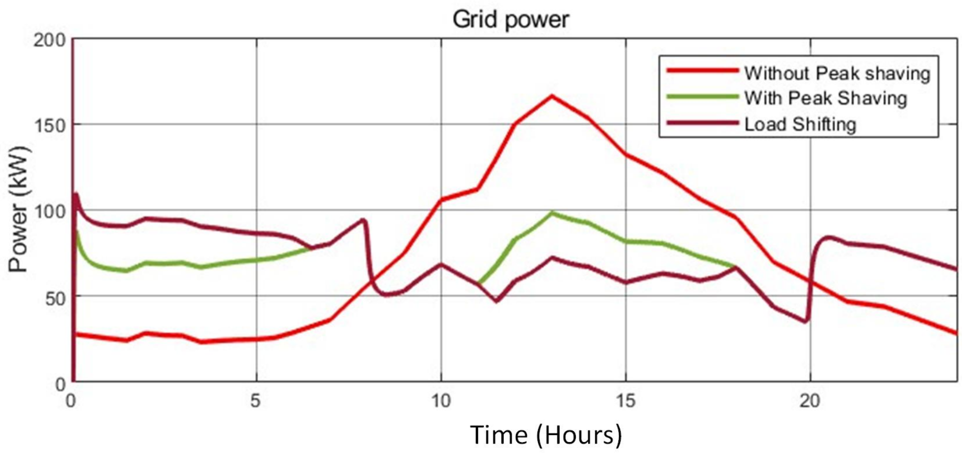

Fig. 13: Impact of Peak shaving and Load Shifting

Fig. 13 illustrates the impact of DNN-based control strategies on grid power consumption during V2G operations. The plot compares three scenarios over a 24-hour time frame: "Without Peak Shaving," "With Peak Shaving," and "Load Shifting." The red curve represents the grid power profile without any control intervention, which clearly shows high power spikes, particularly between 10 and 17 hours, where power demand reaches nearly 170 kW. This uncontrolled demand leads to peak load conditions that stress the grid. In contrast, peak shaving and load shifting illustrate the effectiveness of the DNN-based control approach. Peak shaving smooths out the extreme power peaks by intelligently redistributing the load, particularly noticeable during the high-demand window (10–17 hrs), bringing the demand closer to 90–100 kW. Similarly, the load-shifting strategy redistributes power demand from peak to off-peak periods, achieving a more consistent load profile over time.

5. Conclusion

The additions of EVs and non-conventional resources into the power grid demand intelligent strategies to manage energy distribution effectively and maintain grid stability. This study presents a DSM approach using DNN-based control for a V2G-enabled energy storage system. The proposed system forecasts short-term power demand and user behaviour to optimize EV charging and discharging cycles. By incorporating variables such as battery SOC, grid load profiles, electricity pricing, and EV availability, the DNN ensures smart and timely decisions that reduce stress on the grid. Simulation results, conducted in MATLAB/Simulink using residential and commercial load profiles over a 24-hour period, reveal the significant benefits of implementing peak shaving and load shifting strategies through V2G operations. Without DNN control, grid power peaked at 166.5 kW, creating high stress and operational costs. With DNN-based peak shaving, the maximum grid power was reduced to 100 kW, highlighting an efficient flattening of the load curve. Additionally, load shifting further redistributed energy usage, promoting grid reliability and minimizing demand fluctuations during peak hours. The comparative analysis confirms that both peak shaving and load shifting, enabled by the DNN model, lead to smoother power profiles and more efficient energy utilization. This not only reduces energy costs but also supports large-scale renewable energy integration. Therefore, the DNN-based DSM approach proves to be a robust and scalable solution for future smart grid applications, enhancing both economic and operational efficiency.

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