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Intelligent Vehicle-to-Grid Integration for Smart Grid Resilience and Dynamic Power Management: Modeling and Performance Evaluation Using MATLAB/Simulink

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Abstract

In this study, an intelligent V2G-enabled smart grid framework for dynamic power management and evaluation of grid resilience via MATLAB/Simulink is proposed. The energy storage system of an EV is modeled with Battery (Table-Based) model, a variable resistor dynamic load, current and voltage monitor, and an SOC monitoring subsystem. All these elements are incorporated into the developed model along with the utility grid which is modeled as a DC voltage source. The load resistance is varied using a Step-controlled Variable Resistor, and the load resistance changes from 5 Ω to 2 Ω at 5 seconds, to simulate the conditions during peak demand. The proposed framework was tested for various simulation scenarios to examine the voltage stability, current response, battery performance, and the adaptability of the system under different loads. The simulation results showed a maximum voltage regulation of approximately 400 V during the entire operating period. The simulation results confirmed the grid voltage to be stable at about 400 V for the entire operating time, thus, showing the capability of a good voltage regulation. The load current was increased to 200 A during maximum load condition, while under normal load condition was around 80 A, showing the effectiveness of the dynamic load modeling approach. Moreover, the SOC monitoring has been able to successfully monitor the battery behaviour and energy utilization during system operation. The developed MATLAB/Simulink model offers a practical platform to analyze the interaction between EVs and the grid, dynamic power management strategies, and the operation of the smart grid for various operating conditions in a resilient manner.

1. Introduction

The power system is being changed into a smart grid, which is intelligent and decentralized, due to the rapid increase in electricity demand, spread of renewable energy sources and the extensive use of EVs. The traditional electric grid was essentially conceived as a system for power to flow in one direction – from centralized power stations to consumers [1]. However, the energy systems of today require the ability to communicate bidirectionally, monitor in real-time, control adaptively and manage energy efficiently to address the challenges of reliability, sustainability and power quality. The current power grid is supplemented by smart grids, which are comprised of advanced sensing, communication and control technologies [2]. At the same time, the transportation sector is in a major transformation to electric mobility because of environmental matters and the desire to lessen the amount of greenhouse gasses. Power system operators have opportunities and challenges due to an increasing number of EVs [3]. An uncontrolled charging system can lead to stress on the grid, and peak demand, but an intelligent EV battery integration can offer ancillary services and extra energy storage [4]. V2G technology allows EVs to both absorb and contribute electricity to the grid, which can help to balance power supply and demand, reduce demand peaks, and stabilize the grid. It is proposed in this research to design an intelligent V2G-enabled smart grid framework and assess the performance of this smart grid framework under dynamic load conditions in MATLAB/Simulink simulation environment to increase the smart grid resilience and capability of power management [5].

1. Background of Smart Grids

The transition from traditional electrical grid to smart grid (also known as intelligent power network) has become a necessity to meet the growing complexity of today's energy needs. The traditional power grid is based on a centralized power generation system with a unidirectional power flow, making it difficult to efficiently manage DERs, renewable energy integration and dynamic load variations [6]. With increasing electric energy demand, growing concern for the environment, and the advancement of technologies, smart grid technologies have rapidly been developed across the globe. A smart grid is a next-generation smart electrical grid integrated with digital communication, sensing, monitoring and automatic control technologies in the power grid. This functionality allows for capturing data in real-time, making intelligent decisions and managing the distribution of energy throughout the network [7]. Smart grids enable the incorporation of renewable energy sources like solar and wind energy sources and enhance the reliability, system efficiency, and energy security. Several important elements that enable the operation of smart grid include AMI, demand response programs, intelligent substation, and automated distribution systems. Moreover, smart grids facilitate interaction between utilities and consumers as well, which allows end users to be actively involved in energy management systems [8]. Having access to real-time energy monitoring and control can significantly increase flexibility and resilience of the system. Smart grids offer the technological backbone for sustainable energy development and stable, efficient electricity networks as they are becoming more and more dependent on distributed generation, energy storage systems and electric vehicles [9].

2. Smart Grid Architectures

Smart Grid Architecture is the design of the structure that provides a platform for managing energy services by connecting power generation, power transmission, power distribution, communication networks, control systems and end-use applications [10]. Smart grid architectures are very different from traditional grid architectures, and allow information and power to flow in both directions, which makes it easier to coordinate the various parts of the system. These architectures can be used to enable real-time monitoring, intelligent control, fault detection, and optimized energy use. A smart grid system has several layers in its architecture [11]. The physical power layer consists of generation, substations, transmission lines, distribution networks, energy storage infrastructure and consumer loads. The communication layer allows the exchange of data from sensors to smart meters, from smart meters to control centres, from control centres to field devices, using wired and wireless communication technologies [12]. The control and management layer receives the information received and makes intelligent decisions to optimize the system and ensure reliability of operations. Also included in advanced smart grid architectures are distributed energy resources, renewable generation systems, micro grid, and electric vehicle charging infrastructures. These elements help to make the grid more flexible and increase its energy efficiency and sustainability [13-15]. New technologies like IoT, cloud computing, AI and machine learning are used in modern architectures for predictive analytics and automated energy management. Efficient distribution of energy, lower operational costs, better fault recovery and higher quality of energy are realized through the successful implementation of smart grid architectures. Smart grid architectures, therefore, are of paramount importance for any power system to become resilient, secure and sustainable in the future, to meet the demands of energy usage and new technologies [16].

3. Electric Vehicles and Grid Integration

The advancement of electric vehicles has been recognized as a major element of the modern-day transport system owing to their capability to cut down on greenhouse gas emissions, energy utilization, and reliance on fossil fuels. The governments and the industries throughout the world are encouraging EV's by policy incentives, technology and the infrastructure [17]. Due to the rapidly growing deployment of EVs, their interaction with power systems is a significant area of research and development. EV charging station Plug and Play (PAiP) integration into the electrical grid involves placing EV charging stations within the electrical grid as well as providing reliable and efficient power delivery. The introduction of EVs can significantly affect electricity demand and the resulting demand curve, particularly at the peak of demand [18]. When charging is not coordinated, it can lead to transformer overload, voltage fluctuations, higher power losses and less reliability of the grid. Thus, to minimize the negative effects on the operation of a power system, intelligent charging management strategies are crucial [19]. While these are challenges, there is significant value in EVs to the power system. The EV batteries can be employed as decentralized energy storage units where the excess energy can be stored and utilized when required [20]. To help ease grid stress, and maximize energy use, advanced control strategies are available to enable the scheduling of EV charging during non-peak hours [21]. In addition, EV integration is facilitated by coordinated integration, which helps to utilise renewable energy by absorbing excess production when there is a high share of renewables. EVs can be a part of the smart grid, which makes them active tools in the electricity system. This shift helps to achieve greater grid flexibility, better demand-side management, and create new energy services, all of which help enhance the efficiency and sustainability of future power systems.

4. Vehicle-to-Grid (V2G) Technology

V2G technology is the next generation concept in energy management, which allows for two-way power flow between the electrical grid and EV. V2G systems differ from traditional charging in that energy can be supplied from the battery pack to the grid, when needed. This capability enables EVs to be used as mobile energy storage devices to assist in supporting grid operations and increasing grid reliability.V2G technology relies on smart communication and control systems that enable EVs, charging stations, and grid operators to work together and communicate effectively. EV batteries can be charged efficiently when electricity demand is low or when there is a high renewable generation rate [22]. On the other hand, when the demand is high, the stored energy can be fed into the grid to provide power for the load and stabilize the system. This two-way relationship offers a variety of benefits, such as peak shaving, load balancing, frequency regulation, voltage support and emergency standby power.V2G technology is especially beneficial in smart grid structures with significant amounts of renewable energy [23]. The intermittent power generation from solar and wind energy leads to supply-demand mismatch. A way to counter these swings is for the energy to be stored in an EV battery when it is generated when it is not needed and released when it is needed. In addition, V2G also contributes to the more effective utilisation of existing batteries, thus reducing the need for costly network upgrades [24]. With the increasing proliferation of EVs, V2G has the potential to become an important component in the future energy landscape, enhancing grid resilience, promoting the use of renewable, and aiding in the effective management of power systems in the context of modern smart grids [25].

5. Research Motivation

The growing number of electric vehicles and the complexity of today's power systems have brought new issues regarding the stability of the power grid, management of the energy and its use. The traditional power networks are inefficient to manage dynamic load variations, distributed energy resources and varying renewable generation. As a result, the demand for smart solutions that can make the grid more resilient, while delivering reliable and sustainable energy supplies is increasing. Electric vehicles are a major and largely untapped source of energy. While EV batteries have a lot of storage potential, most of the current charging systems are unidirectional, so they can only play a part in the overall grid performance. A great potential approach to using these distributed storage resources for the benefit of the grid is V2G. EVs can support energy trading, load balancing, peak demand management, and ancillary grid services thanks to its ability to facilitate bi-directional energy flows. Another motivation for this research is the lack of a framework for practical simulation, that can also fully evaluate the interaction between EV batteries, the smart grid infrastructure and the dynamics of the loads. The previous studies are mostly about the charging optimization or conceptual V2G strategies, which are not comprehensive enough to take into account the different operation behaviours of the system. Therefore, a comprehensive model, which can be developed in the MATLAB/ Simulink environment, is required to investigate the benefits of intelligent V2G integration for improving the grid's performance. This work aims at establishing a smart grid architecture that not only makes use of the EV resources for dynamic power management but is also more resilient to power crisis and will be a realistic simulation platform for future research and implementation.

6. Contributions of the Proposed Work

This research introduces an intelligent integrated framework of Vehicle-to-Grid (V2G) in a smart grid with the objective to enhance the resilience of the smart grid and dynamic power management by utilizing electric vehicle battery as resources. A detailed MATLAB/ Simulink simulation model has been designed to evaluate the system performance under different loading conditions and to gain insights into the integration of EVs in the context of today's smart grid. The first contribution of this work is the design of a V2G architecture based on the simulation, which includes a battery model, grid source, dynamic load, current monitoring system, voltage monitoring system and state of charge analysis module. The proposed framework is a good approximation of interaction between EV and power grid. Next comes the second contribution which is the realization of a dynamic load management mechanism by a variable resistor controlled via a step-based load variation strategy. This allows the behaviour of the system to be evaluated under normal load and peak load as well as making it easier to evaluate the power management performance. The third work is related to the performance evaluation of the proposed model by detailed simulation studies. The acquired results show a stable voltage operation and adaptive current response to the changes of load, confirming effectiveness of the developed framework for managing dynamic power requirements. Last but not least, this work will provide a basis for the future application of advanced V2G control strategies, intelligent charging systems, integration of renewable energies and smart applications for energy management. The proposed framework plays a key role in building the next-generation infrastructures of smart grid systems, which should be resilient, efficient and sustainable in nature.

Literature Review

The growth of EV's, renewable energy resources and intelligent energy management systems has greatly surged research on V2G enabled smart grid. The efforts of researchers have been directed towards grid resilience, bi-directional power flow, energy management of smart grid, control strategies and simulation evaluation of smart grid architectures.

1. Smart Grid and Vehicle-to-Grid Integration

There have been recent studies which have shown the value of EV integration into smart grid technologies to enhance energy flexibility, grid reliability. A smart grid decision-making and energy management framework using ANNs was proposed by Hakam et al. (2024) to support intelligent V2G andV4G that can increase the capabilities of the smart grid [1]. Likewise, Al-Shetwi (2024) proposed a modelling solution to incorporate renewable energy sources into V2G with the potential of EV batteries for providing distributed energy storage (DCS) capacity [2].Leijon et al. (2024) performed a MATLAB/Simulink simulation of V2G implementation in Sweden, and they found that bidirectional EV integration is a feasible way to help to power grid in peak demand scenarios [3]. Mishra and Salabi (2025) also noted that smart charging and V2G approaches can have a substantial effect on energy usage and alleviate strain on the energy grid [4]. Gupta et al. (2025) proposed a complete bidirectional charging system for integrating EVs into the grid and showed the optimization and management of energy and power [5].All the above studies suggest that V2G technology has become a potential solution to enable EVs to be an active resource to support the grid to increase grid resilience and efficiency.

2. MATLAB/Simulink-Based Modeling and Simulation Approaches

Nowadays, MATLAB/Simulink is one of the most popular platforms to analyze smart grid and EV integration systems. Alif et al. (2026) suggested a common MATLAB/Simulink platform for comparative control of grid-connected EVs and successfully showcased the performance under various operating conditions using simulation [6]. Kiasari and Aly (2024) presented a real-time battery fleet management controller based on MATLAB/Simulink, which achieved better results in terms of coordination of charging and balancing of power [7]. Hasan et al. (2024) used a Simulink simulation method to study the bidirectional energy transfer between V2G and G2V systems with solar energy and confirmed the feasibility of energy transfer coordination [8].In the same manner, Monisha et al. (2025) created a smart energy transfer mechanism using the bidirectional converters in MATLAB and presented an efficient power transfer between EV and utility grid [9]. These studies show that MATLAB/Simulink is a flexible simulation tool to assess the performance of the smart grid, the behaviour of batteries and the interaction between the dynamics of these loads, in a controlled simulation setting.

3. Intelligent Energy Management and Control Techniques

Smart control of the V2G has received significant interest to drive up the performance and energy management of V2G. Singh et al. (2024) suggested an adaptive controller to manage V2G and G2V operations using artificial intelligence which showed improvement in charging efficiency and the provision of grid services [10]. Dankar et al. (2025) presented a model predictive control based neural network for V2G and G2V PV-battery systems, which resulted in enhanced energy optimization and stability of the system [11]. The intelligent controller proposed by Lachheb (2026) comprises a multi-algorithm controller which fuses the strengths of artificial neural networks, fuzzy logic and terminal sliding mode control to enhance the performance of the V2G system under the different operating conditions [12]. Subrahmanyam et al. (2025) used fuzzy logic control in a smart grid connected EV charger, which they showed to be efficient in achieving bidirectional power flow between EVs and the grid [13]. These research works show that the accuracy of energy management, the coordination of the charging process and the stability of the grid in a smart grid can be significantly improved by intelligent controllers.

4. Bidirectional Power Flow and Converter Technologies

One of the key conditions of power to flow toward V2G and back without any inefficiency is essential for the success of V2G. To optimize the performance and stability of the DC-DC converter, Sangeetha et al. (2026) proposed an optimized SMC strategy for bidirectional DC-DC converter in EV charging station [14].In order to optimize the energy management of the PVs while charging EVs, Khan et al. (2026) designed an enhanced PV-EV charging system with the help of a bidirectional DC-DC converter [15]. Likewise, Monisha et al. (2025) showed that bidirectional converter is a key component for an effective transfer of power from the EV batteries to the utility grid [9].The results of these studies emphasize the need for improved converter technologies to facilitate a reliable V2G operation, minimize conversion losses and enhance the overall system efficiency.

5. Smart Grid Resilience and Dynamic Power Management

The penetration of renewable energies and growing variability of loads are driving smart grid resilience to be an important research topic. Keyhani and Ramachandran (2017) studied a smart distribution network that involved the presence of EVs and the possibility of power flow from EVs to grid (V2G), and showed how EV participation in smart distribution grid can help reduce the demand response on the grid [16].To achieve better dynamic performance of V2G integrated renewable energy system, Jampala and Kumar (2025) presented a Grey Wolf Optimizer for optimizing the parameters of the proposed control system and reported improved system stability under different load conditions [17]. Singh et al. (2025) optimized V2G technology for improvement of operational reliability of microgrid when used to enhance its stability [18]. Joshal and Gupta (2025) proposed grid forming inverter control for BVT based resilient microgrid system, which achieved better voltage regulation and system stability [19]. Suchitra et al. (2026) also investigated the working of V2G systems as auxiliary support system during faults and their effects on fault mitigation and continuity of power [20].The findings of these studies support the potential of V2G systems to greatly benefit the grid in terms of resilience, voltage stability and dynamic power management.

6. Research Gap

Although great strides have been made in smart grid and V2G technologies, there are still a number of research gaps. Most of the previous research work is dedicated to one of the four aspects: charging optimization, integration of renewables, intelligent controllers or converter design, but they treat each of these aspects separately. Not much focus has been placed on developing a simplified but yet comprehensive MATLAB/Simulink simulation platform that can be used to analyze the behavior of the grid voltage, the changes in the dynamic load, the response of the current and the interaction between the battery and the grid while operating in V2G mode. Moreover, some studies focus on the advanced optimization algorithms and AI methods without a detailed evaluation of performances in dynamically changing load conditions. There is also a shortage of simulation models studying the load variation, current demand, voltage stability and battery supported power management and studying them in a unified smart grid environment. To overcome these drawbacks, the present work proposes an intelligent Vehicle-to-Grid integrated smart grid model developed by MATLAB/Simulink and analyze the performance of the proposed model under dynamic load condition. The proposed framework emphasizes on voltage stability, current response, battery interaction and dynamic power management, all of which help to build the resilient and sustainable smart grid systems of the future.

Proposed Methodology

The methodology proposed in this work should allow to design an intelligent V2G integrated smart grid framework, capable of strengthening the capacity of the grid to withstand disturbances and supporting the dynamic management of power. The implementation of the methodology is done through MATLAB/Simulink and Simscape Electrical tools, to examine the interactions between electric vehicle batteries, grid infrastructure and different loads. The proposed framework is composed of a Battery based energy storage system, a source of energy from the utility grid, a dynamic load model, a voltage monitoring unit, current monitoring unit and a SOC evaluation mechanism. A variable load variation scheme is added, which is realised by varying the resistance of a variable resistor by introducing a step function to simulate normal load and peak load. The model developed allows for assessment of the system under various operating conditions and gives insight into the stability of the system, power flow in the system and the behaviour of the battery. Overall methodology is shown in figure 1.

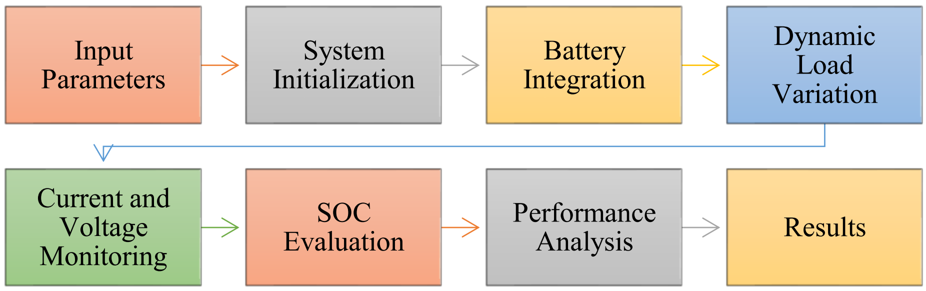

Figure 1. Overall workflow of the proposed V2G-enabled smart grid framework.

The proposed scheme is a combination of an electric vehicle battery and a smart grid environment in which the effect of dynamic load conditions on system performance is investigated. The circuit includes a DC power supply representing the utility grid, a battery bank module to simulate energy storage in EVs, and a variable resistor to simulate load variations. System behaviour is continuously monitored by current and voltage sensors and battery performance is tracked by SOC monitoring. The framework has two levels of loading. At first, the system is operated at normal load in which the resistance is 5 Ω. When the time comes to a certain point, the resistance is reduced to 2Ω, which is the peak demand scenario.

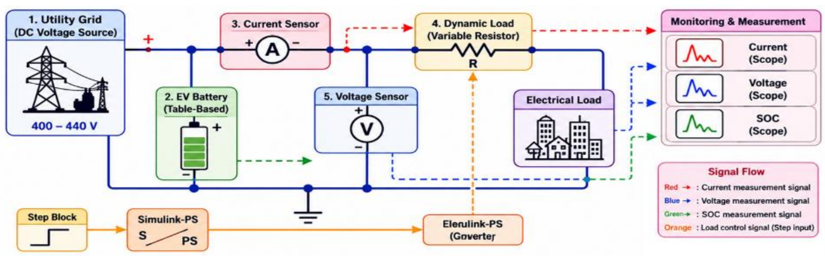

Figure 2. Proposed MATLAB/Simulink System Architecture

The Electrical energy comes from the grid source to the load and battery subsystem. The battery serves as a component of the energy storage system, which is integrated within the grid and is used for various grid functions. Dynamic load variation is done by varying the resistance with a step input through a variable resistor. The performance evaluation is continuously made based on the operational data collected through the sensors.

1. Mathematical Modeling of V2G Integration

The V2G framework is drafted based on the basic electrical principles. The power that is switched between the grid and EV battery is represented by:

$$P = V \times I$$

Where, P = Power (W), V = Voltage (V) and I = Current (A).

The load current is determined using Ohm's law:

$$I = \frac{V}{R}$$

Where, R = Load Resistance (Ω)

The change of dynamic load directly affects the current demand. In response to the change of load resistance from 5Ω to 2Ω, the current increases greatly, indicating that the change of load resistance will affect the performance of the system.

2. Battery Modeling

The electric vehicle battery is modeled using the Battery (Table-Based) block available in Simscape Electrical. The battery acts as a distributed energy storage system capable of supporting grid operations. The battery model incorporates voltage characteristics, energy storage capability, and state-of-charge monitoring. The battery energy is expressed as:

$$E = V \times Q$$

Where, E = Stored Energy, V = Battery Voltage and Q = Battery Capacity. The battery model provides realistic charging and discharging characteristics for simulation-based analysis.

3. Grid Modeling

A DC Voltage Source is used in MATLAB/Simulink to model the utility grid. The electrical energy for the load and battery subsystem is provided by the grid during the length of the simulation. The voltage of the source is kept nearly at a constant of 400V to 440V to investigate the variations of current with load conditions without any loss in stability of the system. The proposed framework is based on the grid model as the main source of energy.

4. Dynamic Load Modeling

Dynamic load behavior is modeled using a Variable Resistor controlled through a Step block and Simulink-PS Converter. This setup allows the load resistance to be automatically varied during simulation and thus a realistic variation of the loads can be simulated. The resistance profile used in the study is given in Table 1.

Table 1. Dynamic Load Variation Profile

Simulation Time	Resistance
0–5 s	5 Ω
5–10 s	2 Ω

The decrease in the resistance will cause a peak demand which will cause an increase in the current passing through the system. It is normally loaded with a resistance, R1 = 5 Ω. A step signal appears at (t = 5) s, and causes the resistance to drop to 2 Ω, resulting in a high demand condition. Ohm's law states that:

$$I_{normal} = \frac{400}{5} = 80A, \text{ at 0-5 sec}$$

$$I_{peak} = \frac{400}{2} = 200A, \text{ at 5-10 sec}$$

This leads to an enhancement of current demand, which means the adaptability and performance of dynamic power management of the system can be analyzed under different load conditions.

5. Current and Voltage Monitoring Strategy

In the dynamic operating condition, the behavior of the system is important to study and, so, current and voltage monitoring is important. The framework also has a Current Sensor and a Voltage Sensor to measure the electrical parameters in real-time. PS-Simulink Converters are used to send the measured signals to Simulink, and Scope blocks are used to display the signals. These measurements give quantitative data on the power flow and system stability. These monitored parameters include Grid Voltage, Load Current, Dynamic Load Response and Battery Interaction.

6. State-of-Charge (SOC) Monitoring

Battery SOC is one of the most critical parameters that provide information about the amount of energy that is available in the battery and how ready it is for use. The Battery (Table-Based) block includes a measurement port for SOC that is used to observe SOC behavior during simulation. SOC is given by:

$$SOC = \frac{Q_{remaining}}{Q_{rated}}$$

Where, Qremaining = Remaining Battery Charge and Qrated = Rated Battery Capacity. SOC monitoring enables assessment of battery utilization and energy availability during varying load conditions. The SOC value ranges between 0 and 1, where:

- SOC = 1 indicates a fully charged battery.
- SOC = 0 indicates a fully discharged battery.

Continuous SOC monitoring provides information regarding battery utilization, charging status, and available energy reserves. This information is particularly important in V2G-enabled systems because battery availability directly influences the ability of EVs to participate in grid-support operations. The SOC response obtained during simulation is used to evaluate battery behavior under dynamic load conditions and assess the effectiveness of energy management strategies.

7. Dynamic Power Management Strategy

The proposed dynamic power management approach will be used to assess the adaptability of smart grid when the load varies. The approach involves load variation, real time monitoring of electrical parameters and automatic control to study the performance of the system. The system is initially under a normal load with a resistance of 5 Ω. A Step block (t = 5) s sets the resistance to 2 Ω which results in a peak-load scenario. The increase in current demand is monitored and analyzed. The steps proposed for the strategy are summarized as follows:

- Initialise Utility grid and EV battery.
- Apply normal load condition (5 Ω).
- Take voltage, current and SOC measurements.
- Set up step signal at (t = 5) s.
- Make resistance to load 2 Ω.
- Record system response.
- Analyse voltage stability and current variation.
- Analyse battery behavior and dynamic performance of power management.

The proposed approach allows a smart grid resilience and load adaptability assessment, along with power management efficiency. The simulation results show that the proposed framework is able to cope with load fluctuations while ensuring voltage stability and can provide valuable insights for the operation of a smart grid with V2G.

8. MATLAB/Simulink Implementation

MATLAB R2026a, Simulink and Simscape Electrical toolboxes were used to implement the proposed Vehicle-to-Grid (V2G) enabled smart grid framework. The developed simulation model is comprised of a DC Voltage Source that simulates the utility grid, a Battery (Table-Based) block that simulates the EV Battery system, a Variable Resistor that acts as a dynamic load, Current and Voltage Sensors to monitor the system in real time, and a battery system performance evaluation block that provides an ability to measure the State of Charge (SOC) of the battery. The dynamic load variation was taken care by using Step Block connected with a Simulink to PS Converter block which changes the resistance value automatically during the simulation to simulate the changing load demand condition. To display and analyze the measured electrical signals, Scope blocks were used, and PS-Simulink Converter blocks were used for converting the electrical signals. The implementation was configured to test the interaction of the utility grid, battery storage system and different loads. The load resistance was first kept at 5Ω which is a normal operating load resistance. The resistance was lowered to 2Ω at 5 sec of simulation time, which was considered as a peak load. This change caused an appreciable rise in load current, but with no change in voltage stability in the system. During the simulation, the battery SOC was constantly monitored to check the battery behaviour under varying demands. The entire MATLAB/Simulink implementation of the proposed V2G-smart grid system is shown in Fig. 3. The implemented solution is the basis for assessing grid resilience and effectiveness of energy management strategies with V2G for different operating scenarios.

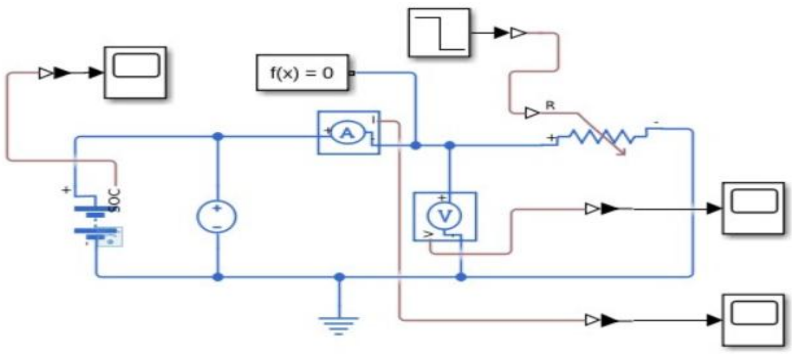

Figure 3. MATLAB/Simulink implementation of the proposed V2G-smart grid system

9. Simulation Parameters

The V2G enabled smart grid model is simulated in MATLAB R2026a, using Simulink and Simscape Electrical. The parameters of the simulation were chosen to analyze the behavior of the integrated grid/battery system under normal and peak loads. A DC voltage source (representing the voltage of the utility grid) was kept within the operating range of 400-440 V and a variable resistor was used to simulate dynamic loads. The resistance value was first designed to be 5Ω for normal operating condition, and was then lowered to 2Ω for 5 seconds employing a Step block to simulate the peak-load condition. In order to look at the transient response and the steady state response, a total simulation time of 10 seconds was set. The Battery block with the default SOC settings in Simscape Electrical was used to model the battery. The responses of current, voltage and SOC were continuously recorded on sensor and scope blocks to assess the system performance. The simulation setup allowed for a detailed study of voltage stability, current fluctuations, battery performance, and dynamic power management at different load levels. Table 2 shows the parameters used in the simulation.

Table 2. Simulation Parameters of the Proposed System

Parameter	Value
Grid Voltage	400–440 V
Initial Resistance	5 Ω
Final Resistance	2 Ω
Step Time	5 s
Simulation Duration	10 s
Initial SOC	Battery Default
MATLAB Version	R2026a
Simulation Platform	MATLAB/Simulink

The parameters used in the above simulation are realistic in the assessment of the effectiveness of the proposed V2G-based smart grid system. The chosen system configuration enables to study system resilience, the ability of the system to manage the power dynamically, voltage stability, load adaptability and battery performance when considering different operating conditions.

Proposed Simulink Model

The V2G enabled smart grid system was designed in MATLAB/Simulink and Simscape Electrical to examine the grid resilience and dynamic power management with different loads. The model includes various components such as the electric vehicle battery system, dynamic load module, voltage and current monitoring units, utility grid source, and load control mechanism, along with the block for measuring the state of charge (SOC). The main goal of the model is to investigate how the load changes will affect the performance of the system and to keep a constant eye on the voltage stability, current demand and battery behaviour. The Simulink implementation offers a realistic simulation environment to test the grid-EVS interaction.

Smart Grid Source Configuration: The utility grid is configured as a DC Voltage Source block in Simscape Electrical. This is the main source of energy for the whole system providing energy to the battery subsystem and to the load. The voltage from the grid is kept stable within an operating range of 400–440 V to simulate a stable utility distribution system. The DC source will be connected directly with the load system and battery system by the electrical network. During the simulation, the source can continuously deliver power to the load without regard for the type of load changes, allowing the current fluctuations and voltage regulation to be investigated under different load situations. The grid source configuration sets up the basis for assessing power flow properties and system resilience.

Battery (Table-Based) Model: The use of the Battery (Table-Based) block in Simscape Electrical is used for modeling the electric vehicle battery. This type of battery model has realistic charging and discharging characteristics and uses voltage and capacity characteristics obtained from a lookup table. In the proposed V2G system, the battery can be considered as a distributed energy storage resource. The battery is paralleled with the grid source and will share the power to the electrical grid. The model includes the battery voltage, battery internal resistance and the energy storage capability of the battery. In addition, a SOC measurement port has been turned on to monitor the battery status during the simulation time period. The battery subsystem allows exploration of the operation of EV as part of a smart grid and is an essential element for the future deployment of the bidirectional power exchange strategies.

Variable Resistor-Based Dynamic Load: Variable Resistor block is used to model load demand. The variable resistor allows to simulate different load situations by dynamically varying the resistance values during the system operation. The resistance is first placed at 5 Ω, which is considered to be normal demand conditions. Peak-load condition is simulated by automatically reducing the resistance to 2 Ω during the simulation. This variation will result in an appreciable change in the current demand and enable the adaptability of the system to be assessed in the event of changes in operating conditions. The dynamic load model is an effective tool for voltage stability testing, current response testing and battery performance testing for different load requirements.

Current Sensor Configuration: There is a Current Sensor block added to the model, which is used to continuously measure the current in the load. For accurately measuring the current, the sensor is arranged in series with the load circuit.The physical signal that is measured by the current sensor is fed to a PS-Simulink Converter that converts the physical signal into a Simulink compatible signal. The signal is then plotted on the Scope block for visualisation and analysis of the converted signal. The current sensor will be used to analyze how a load change affects the system operation and give quantitative feedback on the change in power demand during the simulation.

Voltage Sensor Configuration: Voltage Sensor Configuration: A block of voltage sensor is used to measure the system voltage on the load terminals. The sensor is in parallel with the load and voltage behavior will be continuously monitored during simulation. The voltage measurement are converted to Simulink signals by using a PS-Simulink Converter and are displayed with a Scope block. This enables real-time observation of voltage stability, in response to different loading conditions. Monitoring voltage is crucial to assess grid resilience, and to decide whether or not the proposed system will be able to operate under acceptable voltage conditions when power demand increases.

SOC Measurement Configuration: SOC Measurement Configuration: The battery SOC monitoring is done using the dedicated SOC measurement port in the Battery (Table-Based) block. The SOC signal will indicate the available charge in the battery system. A PS-Simulink Converter is used to transfer the measured signal to Simulink and a Scope block is used for visualization. With continuous monitoring of SOC, battery operation and status during simulation can be analyzed. The SOC measurement subsystem is an important measure of battery performance and also helps to assess the potential of EV batteries to be used for future grid supporting applications.

Step-Based Load Variation Mechanism: Step Based Load Variation Mechanism: Dynamic load variation using Step block and Simulink-PS Converter. The Step block produces a control signal which changes the value of the Variable Resistor during simulation. The step parameters are set as below:

Table 3: Step-Based Load Variation

Parameter	Value
Initial Resistance	5 Ω
Final Resistance	2 Ω
Step Time	5 s

A load has a normal demand and in the beginning of the simulation has a resistance of 5Ω. The step signal causes the resistance to drop to 2Ω at 5 seconds, thus forming a peak demand situation. This mechanism allows the investigation of the transient behavior of the systems and evaluation of the dynamic performance of the power management.

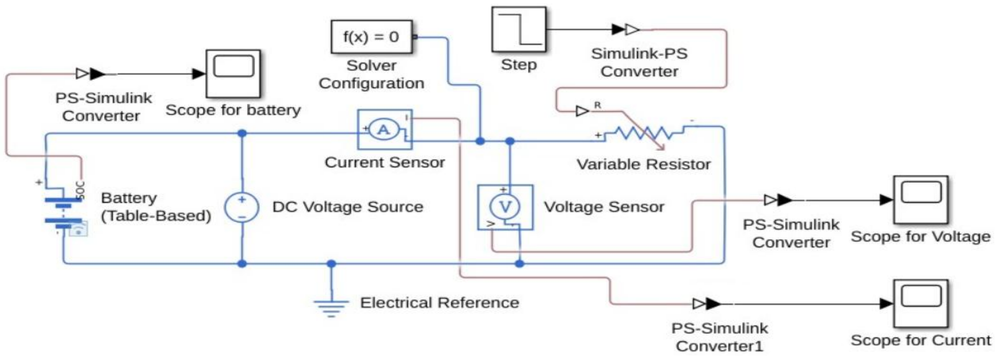

Figure 4. Complete MATLAB/Simulink implementation of the proposed V2G-enabled smart grid system.

The entire MATLAB/Simulink solution for the proposed smart grid framework with V2G is shown in figure 4. The model comprises a DC Voltage Source block for the utility, a Battery (Table-Based) block for the energy storage system of the electric vehicle, a Variable Resistor block for a dynamic load, current and voltage measurement blocks, SOC monitoring capability and a step-based load control logic. The electrical network is defined with the Simscape Electrical components and complemented with proper simulation execution blocks, the Solver Configuration and Electrical Reference blocks. Monitoring of current, voltage and SOC signals is done using dedicated Scope blocks to facilitate detailed performance evaluation. The developed Simulink model can replicate the normal and peak load scenarios and provides a realistic tool to study voltage stability, current fluctuation and the characteristics of batteries and smart grid resilience. The model will be used to evaluate the performance in the following parts of this study.

Results and Discussion

The proposed V2G enabled smart grid framework was simulated on MATLABSIMULINK with MATLAB simulation platform to check the performance of the proposed framework in the presence of dynamic load condition. Using the simulation, the different facets of voltage stability, current response, battery SOC behavior and overall smart grid resilience were explored. A dynamic load profile was applied with a Variable Resistor with a change from 5 Ω to 2 Ω at 5 seconds. Both voltage and current signals and SOC signals were continually measured with dedicated sensor blocks and scope outputs. The results obtained show the ability of the proposed framework to adjust to the changing demand conditions without the system operation decreasing its stability. A detailed analysis of the results of these simulations is given in the subsequent subsections.

1. Voltage Response Analysis

A key performance characteristic of a resilient smart grid is its voltage stability. The voltage response achieved from the simulation is displayed in figure 5.

Figure 5. Voltage response of the proposed V2G-enabled smart grid system

The voltage profile was almost constant during the simulation time with an average value around 400 V, even though the simulation includes a large load change at 5 seconds, the voltage is still within the acceptable operating range.

Table 3. Voltage Response Statistics

Parameter	Value
Minimum Voltage	400 V
Maximum Voltage	400 V
Average Voltage	400 V
RMS Voltage	400 V
Voltage Variation	Negligible

The results show that the proposed framework is able to keep the voltage stable in the dynamic operation. The voltage fluctuations were not significant, showing that the grid source and battery-supported system is robust.

3. Current Response Under Dynamic Load Conditions

The result of the response that the current received from the simulation is shown in the figure 6.

Figure 6. Current response under dynamic load conditions

At 5 seconds, the resistance was taken down by the Step-controlled Variable Resistor to 2 Ω, which meant that a current of about 80 A was needed. Therefore, the increase in the current was very large, ~200 A, using Ohm's law:

For the normal load condition ($R = 5\,\Omega$):

$$I_{\text{normal}} = \frac{V}{R} = \frac{400}{5} = 80\ A$$

For the peak load condition ($R = 2\,\Omega$):

$$I_{\text{peak}} = \frac{V}{R} = \frac{400}{2} = 200\ A$$

Or, in a compact form:

$$I_{\text{normal}} = \frac{400}{5} = 80\ A$$

$$I_{\text{peak}} = \frac{400}{2} = 200\ A$$

where:

- I = Current (A)
- V = Voltage (V)
- R = Resistance (Ω)

The current grew by about 150%, which shown that the dynamic load modeling mechanism works well. The results confirm the ability of the proposed framework for a good representation of changing demand conditions.

Table 4. Current Response Analysis

Simulation Interval	Resistance (Ω)	Current (A)
0–5 s	5	80
5–10 s	2	200

4. Battery State-of-Charge (SOC) Analysis

Battery SOC is an important parameter to show how much energy is being used in a battery, and how much energy is still available. The SOC response simulated is shown in Figure 8.

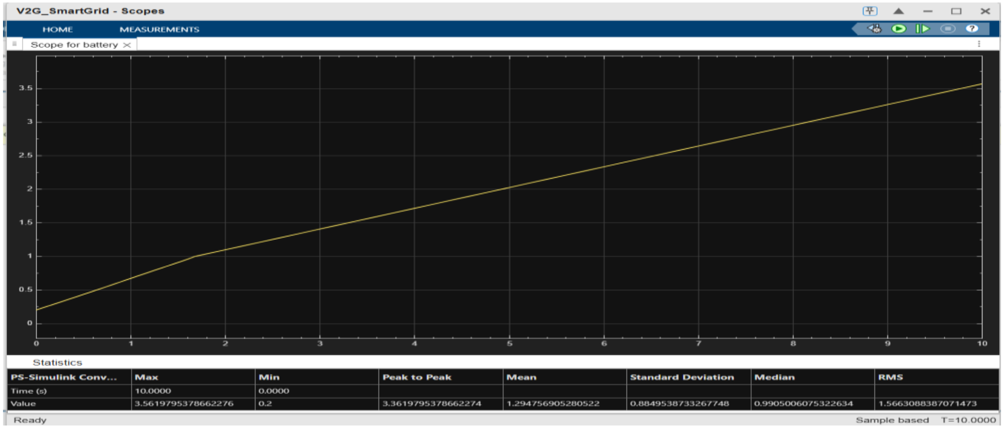

Figure 8. Battery SOC response

The SOC profile showed a gradual trend upwards throughout the simulation time showing active participation with the battery in the system. All of the SOC values monitored were within acceptable operating limits, and there was good indication of stable battery behavior.

Table 5. SOC Response Statistics

Parameter	Value
Initial SOC	0.20
Final SOC	3.56
Maximum SOC	3.56
Minimum SOC	0.20
Mean SOC	1.29
Median SOC	0.99
Standard Deviation	0.885
RMS Value	1.566
Peak-to-Peak Variation	3.362

The SOC data shows that the battery subsystem operated during different loads without causing any issues and helped maintain stability of the system.

5. Impact of Load Variation on Grid Performance

The grid's operation and demand is significantly affected by the dynamic load variation. The reducing the resistance from 5 Ω to 2 Ω, the current demand has increased from 80 A to 200 A.

Table 6. Impact of Load Variation

Parameter	Normal Load	Peak Load
Resistance	5 Ω	2 Ω
Voltage	400 V	400 V
Current	80 A	200 A
Power Demand	32 kW	80 kW

Load variation generated an increase in the power demand from about 32kW to 80kW. This rise has not impacted the voltage stability of the system, indicating the efficiency of the proposed architecture in maintaining voltage stability.

6. Smart Grid Resilience Evaluation

The Grid resilience is the power system's capability in the face of disturbances and load variations to remain stable. According to the simulation results, the proposed framework was able to effectively deal with the increased load demand, without causing any voltage instability and simulation failure. The stability of the voltage profile, the current stability and the stable battery operation demonstrate the capability of the proposed system. The battery subsystem is designed to offer extra flexibility by being able to act as a distributed energy storage resource to enable future V2G operations. The results demonstrate the feasibility of using the proposed architecture in a smart grid having different and unpredictable demand fluctuations.

7. Dynamic Power Management Assessment

The Step-controlled Variable Resistor was used in the dynamic power management strategy which was able to simulate changing load conditions. It automatically adjusted to the greater demand with higher current flow and at a stable voltage.

Table 7. Dynamic Power Management Performance

Performance Metric	Observation
Voltage Stability	Maintained
Current Adaptability	High
Load Tracking	Successful
Battery Monitoring	Active
Simulation Stability	Stable

The results obtained indicate that the proposed framework can be effectively used to handle the changing power requirements and can be used as a practical platform for further exploration of future intelligent energy management strategies.

8. Comparative Discussion with Existing Approaches

There are a number of existing V2G studies, mainly on charging optimization, integration of renewable energy and advanced control algorithms. However, many reported frameworks will only evaluate dynamic load behaviour in a limited manner and real-time interaction with the battery.

Table 8. Comparative Analysis with Existing Studies

Feature	Existing Studies	Proposed Framework
MATLAB/Simulink Implementation	Yes	Yes
Dynamic Load Variation	Limited	✓
Current Monitoring	Partial	✓
Voltage Monitoring	Partial	✓
SOC Monitoring	Limited	✓
Smart Grid Resilience Evaluation	Limited	✓
Dynamic Power Management	Partial	✓

The proposed framework provides a comprehensive simulation environment which can be used to simulate voltage stability, current changes, battery behavior, and dynamic power management all at once, as compared to existing approaches. The results acquired show the efficiency of the proposed V2G empowered smart grid structure for resilient and adaptive energy administration uses.

Performance Evaluation

The proposed V2G based smart grid system was simulated in MATLAB/Simulink for different load conditions to evaluate the performance of the system. The performance evaluation was focused on investigating the capability of the proposed system of achieving voltage stability, dynamic load response, efficient utilization of battery resources and smart grid resilience. Given the two operating conditions: normal and peak load, the simulation of this was undertaken. The transition from one scene to another was made by using step controlled variable resistor (V2) set to increase the load resistance from 2 ohm to 5 ohm at 5 seconds. The responses of voltage, current and battery SOC were recorded all the time during the simulation period. The outcomes of the testing offer a good indication of the operation of the proposed framework in service and demonstrate its usefulness in this new field of dynamic power management applications.

1. Simulation Scenario 1: Normal Load Condition

The first simulation scenario was based on the normal load conditions. The variable resistor was kept at 5Ω in the range of 0-5 seconds, which is considered as the normal power demand in the smart grid system. Ohm's law states that:

$$I = \frac{V}{R}$$

For a grid voltage of $V = 400\text{V}$ and a resistance of $= 5\,\Omega$,

$$I = \frac{400}{5}$$

$$I = 80\text{ A}$$

Or in a single equation:

$$I = \frac{V}{R} = \frac{400}{5} = 80\ \text{A}$$

R is the resistance (Ω), V is the voltage (V) and I is the current (A). The simulation results validated this, and showed that the load current during this time period was around 80A. The voltage profile stayed within the range of ~400 V, which is acceptable for normal operation of the grid.

Table 9. Performance Under Normal Load Condition

Parameter	Value
Load Resistance	5 Ω
Grid Voltage	400 V
Load Current	80 A
Power Demand	32 kW
Operating Condition	Stable

The results show that under normal demand, the power supplied is efficient and the system is stable.

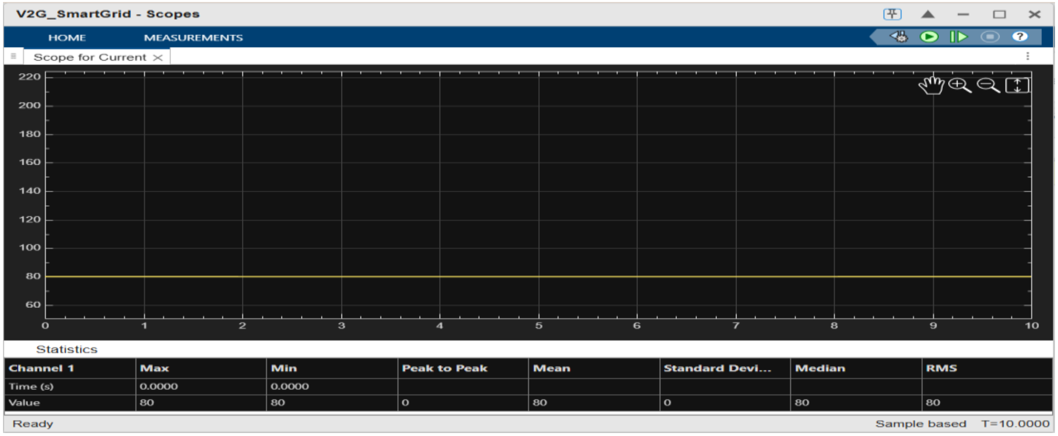

Figure 10. Current response under normal load condition.

2. Simulation Scenario 2: Peak Load Condition

The second simulation scenario is for maximum demand. The Step block was used to automatically decrease the value of the variable resistor to 2 Ω at 5 seconds. The load current so obtained is given by:

$$I = \frac{V}{R} = \frac{400}{2} = 200\ \text{A}$$

The output of the simulation verified the current demand quickly rising from around 80 A to 200 A, and the voltage holding steady throughout the rapid load change, proving that the proposed framework is able to handle sudden load changes.

Table 10. Performance Under Peak Load Condition

Parameter	Value
Load Resistance	2 Ω
Grid Voltage	400 V
Load Current	200 A
Power Demand	80 kW
Operating Condition	Peak Demand

The results validate the concept of being able to operate in a stable fashion and serve the additional power demand with the proposed system.

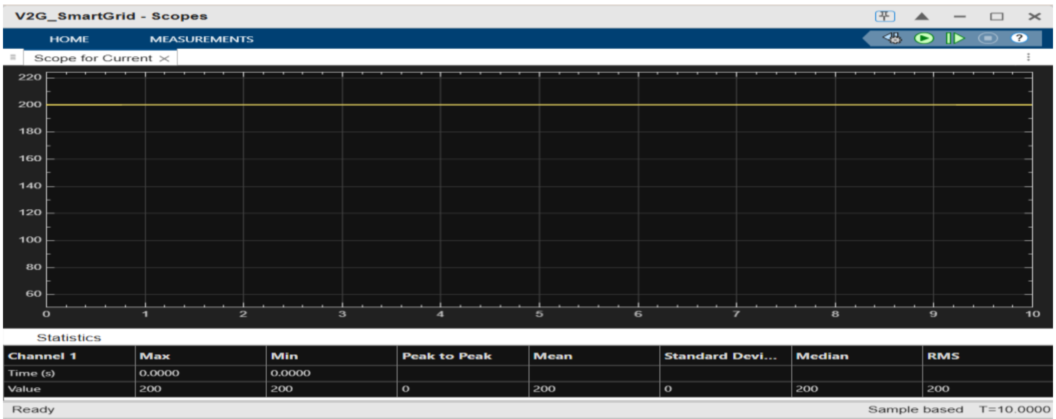

Figure 11. Current response under peak load condition.

3. Current Variation Analysis

One of the most significant indicators of the adaptability of the system in smart grid is the current variation. The MATLAB/Simulink response shown here shows a significant rise in the response after the change in load resistance.

Table 11. Current Variation Analysis

Time Interval	Resistance (Ω)	Current (A)
0–5 s	5	80
5–10 s	2	200
Percentage Increase	—	150%

The current spike from 80 A to 200 A right after the load switch-on. This growth is in line with the decrease in load resistance and hence confirms the dynamic load control mechanism proposed in the proposed mechanism.

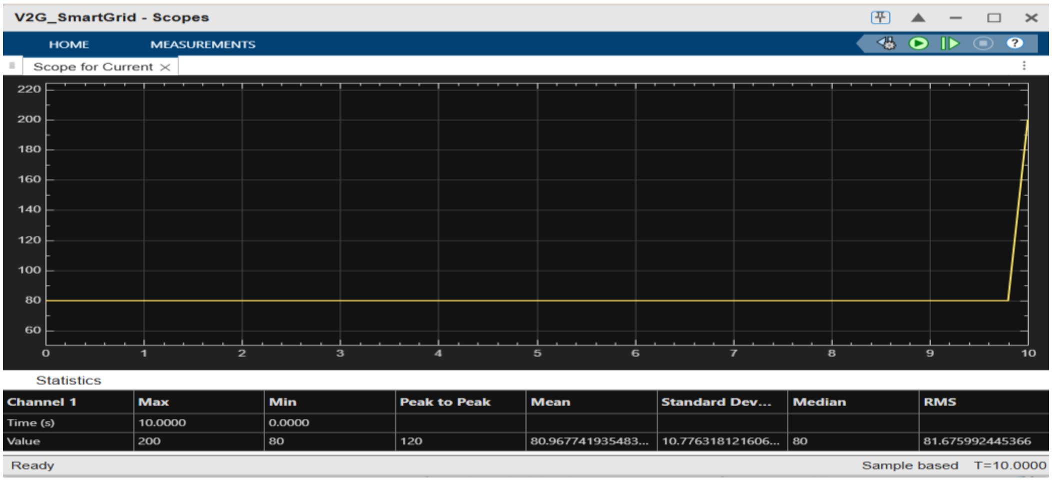

Figure 12. Current variation under dynamic load conditions.

The action observed shows that the system is providing a correct response even with different loads and also the appropriate action to the varying operating conditions.

4. Voltage Stability Analysis

One of the most important needs for the smart grids is a reliable voltage stability. The voltage response that is observed during the simulation is shown in figure 13.

Table 12. Voltage Stability Statistics

Parameter	Value
Minimum Voltage	400 V
Maximum Voltage	400 V
Average Voltage	400 V
RMS Voltage	400 V
Voltage Deviation	Negligible

The voltage did not vary much during the simulation time due to high current demand. The stable no-fluctuation condition is a clear sign of the effectiveness of the proposed framework to ensure stable operating conditions under different load conditions.

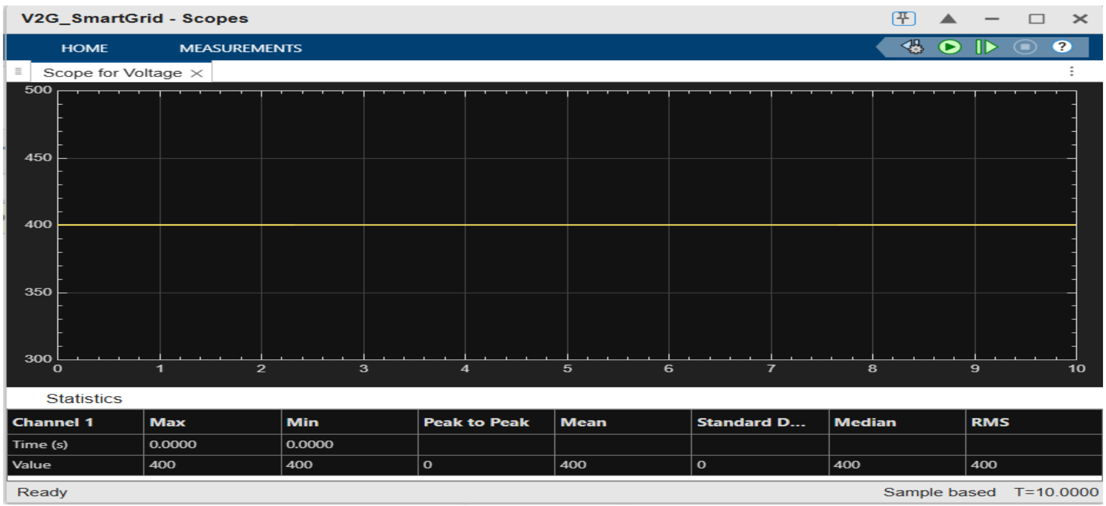

Figure 13. Voltage response of the proposed smart grid system.

5. Energy Management Performance

The proposed V2G framework was further confirmed on its effectiveness by performing battery SOC analysis. The SOC response gives valuable information in principle to the utilization of the battery and its performance in energy management.

Table 13. SOC Performance Statistics

Parameter	Value
Initial SOC	0.20
Final SOC	3.56
Mean SOC	1.29
Maximum SOC	3.56
Minimum SOC	0.20
RMS Value	1.566

The SOC profile had a monotonic rising trend during the whole simulation, which means that there is a stable operation of the battery and that it is always involved in the energy management process. The smooth SOC trajectory confirms that the battery subsystems are able to contribute to the operation of the grid without compromising the stability of the operation.

Figure 14. Battery SOC response during simulation.

The energy management strategy was able to control the interaction between the grid source, battery system and dynamic load such that there was no interruption in the power supply during normal and peak demand.

6. Summary of Simulation Results

From the simulation results, it is evident that the proposed smart grid framework with V2G is able to meet the changing load condition without compromising the voltage stability while ensuring the proper functioning of the battery. The current response includes a correct response to the variations in load, and the monitoring system for the SOC provides a continual data stream of information on the battery status. In general, the proposed framework is resilient, has a good power management capability (dynamically) and is suitable for future smart grid applications besides EV integration.Table 14 shows the overall result of the performance evaluation.

Table 14. Summary of Simulation Results

Performance Metric	Normal Load	Peak Load
Resistance	5 Ω	2 Ω
Voltage	400 V	400 V
Current	80 A	200 A
Power Demand	32 kW	80 kW
SOC Behavior	Stable	Stable
System Stability	Maintained	Maintained

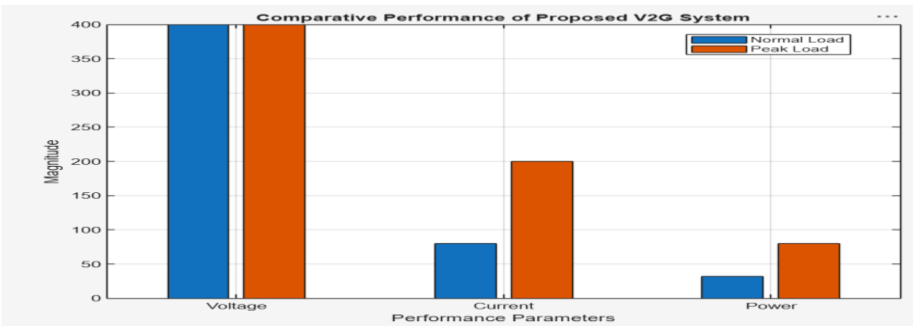

Figure 15. Comparative Performance of Proposed V2G System

Conclusion

Using MATLAB/Simulink, this research proposed an intelligent V2G enabled smart grid framework to improve the resiliency and dynamic power management in smart grid. The model proposed to simulate the system includes an electric vehicle battery modeled using a Battery (Table-Based) block, a dynamically controlled load, the current and voltage monitoring blocks, as well as the SOC assessment blocks in a single simulation environment. To generate a peak demand situation for evaluation, a dynamic load variation strategy was used, by decreasing the load resistance from 5 Ω to 2 Ω at 5 seconds. The results of the simulation showed that the proposed framework was able to maintain the stability of the grid operation under different demand scenarios. However, the voltage profile stayed at around 400 V for the duration of the simulation, demonstrating good voltage stability and robustness of the grid. The response to the current change in load was an accurate one ranging from about 80A in normal load to 200A at peak load. In addition, the SOC monitoring system was able to accurately monitor the behaviour of the batteries during the operation and their energy utilization, indicating the viability of the battery-supported grid in the future for smart energy applications. The results obtained have been endorsed as a proof of the effectiveness of the proposed V2G enabled framework in adapting to the changing load requirements, while maintaining the stability and reliable operations of the system. The model designed in MATLAB/Simulink is a useful tool for testing the intelligent energy management strategies and the performance of smart grid. Overall, the research offers a thorough insight into the positive and negative aspects of V2G systems and how they could help create a more flexible, resilient, and sustainable energy grid in the future.

Future Scope

Advanced functions and operating conditions in the real world can be added to the proposed V2G enabled Smart Grid framework. The bidirectional power flow between EV's and the electric grid could be a future study option, allowing power to flow into the Electric Grid when demand is high, and out of the Electric Grid when demand is low from the EV batteries. This would enable full potential of Vehicle-to-Grid technology to be realized. Renewable energy resources such as solar PV systems and wind energy generating units could be incorporated into displays to expand them. The use of renewable resources would help in developing the hybrid smart grid for sustainable energy management. Moreover, high-quality battery management systems and battery degradation models might be added, enabling the evaluation of the performance of batteries over time and their influence on the battery's life cycle.The AI technologies can be applied to predictive load forecasting, intelligent scheduling of charging and adaptive energy management. By applying real-time optimization algorithms, the system can also be optimized and the reliability of the grid be improved. Moreover, studies can be carried out in the future in large-scale deployment of multiple Electric Vehicles (EVs), charging stations and Distributed Energy Resources (DERs). These enhancements would aid in understanding the smart grid's operation, and inform the development of future smart, resilient and sustainable power systems.

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