



# Dynamic Modelling for Hybrid Electric Vehicles with Its Performance Optimization Using Different Control, Energy Management Strategies

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**Abstract.** Fuel cell vehicles have emerged as a promising alternative to traditional internal combustion engine vehicles, mainly as advancements in technology make them more practical for commercial use. This study focus focuses on developing and analysing energy management strategies for fuel cell-based hybrid electric vehicles using a dynamic model. This model integrates key components such as fuel cell stack, battery system, induction motor, and vehicle drivetrain to evaluate and compare performance with that of conventional ICE vehicles. A PI controller is used to simulate the behaviour of driver, induction motor operates under a slip mode algorithm. The overall power distribution between the fuel cell and battery is managed within defined limits. Simulation results reveal that the fuel cell hybrid system achieves energy consumption levels similar to conventional light vehicles but with significantly reduced fuel usage. Moreover, the hybrid configuration offers superior performance and efficiency compared to standard combustion-based systems. The developed model also proves effective for testing and optimizing different control strategies aimed at enhancing the performance of hybrid electric vehicles.

**Keywords:** Hybrid electric vehicles, fuel cell stack, power management, energy management strategy, battery bank.

## 1 Introduction

The number of vehicles on roads today has reached its highest level in history and most of them still use fossil fuels. These vehicles play a major role in releasing over 36 billion tons of carbon dioxide into the environment each year [1]. As a result, finding sustainable solutions to reduce air pollution and protect the planet for future generations has become global priority. It focuses on designing vehicles that help to reduce the air pollution. In this regard, vehicles powered by renewable energy sources have become a key area of interest. Major automakers around the world are actively developing and testing alternatives to fossil fuels, while several countries have already set clear targets to cut emissions. Germany aims to phase out fossil-fuel vehicles by 2030, the UK plans to end sales of new petrol and diesel cars by 2040, and Norway and India intend to promote only fully electric vehicles by 2025 and 2030, respectively. The development of clean energy technologies for land transportation has encouraged researchers to explore a wide range of options from solar energy and high pressure. Among the most promising technologies of electric vehicles [2] and hydrogen powered. The main automobile industries have already introduced business models of these types, but their establishment as a real successor for conventional vehicles still demands significant research, development, and technological advancement.

Besides vehicles that runs on a single alternative energy source and another approach is to combine multiple sources in one vehicle. These are known as hybrid electric vehicle, and they are divided into three types based on their design [3]. In a series configuration, the traction power delivers to the wheels come entirely from one or more electric motors. In a parallel configuration, both the internal combustion engine and the electric motor can drive the vehicle directly through a shared gear system. Finally, in a mixed or combined configuration, each axle of the vehicle is powered by a different energy source, allowing better performance and flexibility. Another way to classify the hybrid electric vehicle is based on the management of battery charging. Load maintainer can keep the battery charge within a specific range during all deriving condition, while load depleters cannot sustain the charge on their own and must be plugged into an external power source to recharge the

battery. Using multiple energy sources in a single vehicle requires an efficient power management strategy to properly distribute power demand and ensure good vehicle performance [6]. A dynamic optimization method to consider the dynamics of the system and the optimization starts to be considered according to a time dependent behaviour of the system. Instead of optimizing at each instant, they optimize performance over a defined time horizon. Although these methods offer global optimization and more accurate results, they are highly dependent on the driving cycle and are difficult to implement in real time. Examples of such applications include hybrid trucks with parallel configurations, as discussed in [5] and [9]. From the literature review it is possible to understand the current research and identify the most efficient energy management system suits for a city household environment. The goal is to develop a model that can efficiently control the power flow between the house and the electrical grid, ensuring that the adding of new components, such as electric vehicles, from overloading the network. At the same time the system the system should help to reduce cost of electricity without disrupting normal household energy usage[4]. This study provides an overview of the current Electric Power System (EPS) and explores its evolution toward a futures mart grid integrated with intelligent energy management systems. It highlights the potential benefits, challenges, and limitations of this transition, emphasizing how such systems can lead to a more sustainable and efficient energy future.

## **2 Literature Review**

By using multiple energy sources within the same vehicle needs an efficient control to provide optimal system performance. A power management strategy (PMS) is preceded through an algorithm that calculates the quantity of power needed for a driver request and distributes it appropriately among the energy resources. There are various approaches are available to design a PMS and they are generally classified into three main categories such as heuristic techniques, static optimization methods and dynamic optimization methods. Heuristic methods like fuzzy control logic and rule-based control are mostly used for power management in hybrid vehicles which are discussed in literature [8]. These methods are

simple and low cost which makes them famous but they have some limitation like they can't make full use of vehicle's complex system. The rules in these methods are mostly set based on the experience of the designer or institution and they don't need to the driving pattern in advance which makes them suitable for real-time use while driving [2].

In static optimization, the power is converted into an equal amount of steady state fuel use to find the entire amount. An optimal control strategy then decides how to share the power demand between different energy sources using efficiency maps [6]. These are the methods that can be used in real time based on the system's conditions to achieve maximum optimization. The frequent common method of this group is the energy efficient control strategy [5]. It was used for hybrid vehicle powered by a diesel engine and battery. Later, other researchers improved an algorithm which is adaptable to estimate the equal fuel use for part of the current driving cycle in real time. Dynamic optimization method is used to analyse the changes in system over time. They optimize the system's performance over a period time called time horizon instead of focusing on the single moments. Even though these methods can provide overall solutions, they still depend on the conduction cycle and cannot be used for real-time operation. Therefore, they are typically used as benchmark references to evaluate the performance and optimality of real time algorithm [9].

### **3 Electrical Power System**

Electric energy plays a main role in social and economic development of every nation. It powers essential system such as healthcare, security, education, telecommunications, lighting, agricultural and industry making it a cornerstone of model life. In large countries like India, the electrical power system is highly complex due to the wide geographical area and the diversity of energy source. According to the 2022 monthly operating report, generation of electricity in India is divided into hydroelectric (about 62.5%), wind (about 11.9%), thermoelectric using gas and liquefied natural gas (about 8.8%), biomass (about 8.3%), solar (about 2.7%) oil and diesel thermoelectric (about 2.5%), coal thermoelectric (about 1.7%), nuclear (about 1.1%) and other sources (about 0.4%). The complexity of such

electric power systems arises from their scale, diversity of generation sources, and the seasonal variations in both power supply and demand. The complexity of such systems arises from their scale, diversity of generation sources, and the seasonal variations in both power supply and demand. Managing the power flow within these systems requires continuous monitoring and the integration of smart technologies capable of responding to real-time changes. This growing need for efficiency and reliability is driving the transition toward Smart Grids intelligent networks designed to optimize energy distribution and enhance system stability.

### **3.1 Energy management systems**

The energy management system is an important part of Smart Grids, responsible for coordinating power generation and reducing energy use through power control of energy for different applications. A review of existing studies highlights the key roles and objectives of EMSs in optimizing modern power system. They are classified in several ways. However, this work focuses on classification based on their operational roles and function. The primary goals of an EMS include reducing operating costs, minimizing pollutant emissions, improving voltage and system stability, reducing recovery time after disturbances, and enhancing overall energy efficiency. To reduce operating costs, the energy management system optimizes power generation based on real time demand, avoiding the use of expensive energy sources, especially during peak hours. It also helps reconfigure distribution system schedule, making the system more effective and cost effective. Global warming is one of the main global challenges, as emission from vehicle and other fossil fuel sources have a serious environment impact. To reduce polluting emissions , the EMS focus on selecting and managing energy sources that are clean and renewable, such as wind, solar, and geothermal power, helping to cut down greenhouse gas emission while meeting energy demands efficiently [8].

To improving efficiency, the energy management system helps to monitor the distributed energy sources, and with the help of IoT technologies, allows consumers to optimize their energy use by scheduling high demand devices at suitable times [10]. Through continuous

monitoring and control, the energy management system can manage different power sourced effectively reducing pressure on the grid, minimizing power losses, and increasing overall system efficiency. For example, in a home equipped with distributed generation, electric vehicles, and other electrical loads, the energy management system can schedule electric vehicle charging during off-peak hours, such as late at night when demand is lower. The main functions used in energy management system include monitoring, improving, predicting and forecasting, control and management. Among these, the functions that contribute the most to energy savings are control (about 30%), optimization (about 25.6%) and management (about 25%). The most effective combination is control and optimization, which together achieve an average saving of about 21.27%, while estimation and prediction functions contribute around 10% saving. In general, the optimization function focuses on developing strategies and systems that create the best energy usage schedule within a building, helping to smart, data-driven decisions. The control function, on the other hand, involves managing and regulating the operation of energy-consuming devices. For example, instead of relying on simple on or off control, a neural network-based predictive control system was implemented which helped reduce energy use by approximately 20% [10].

## **4 Fuel Cell Electric Vehicle Model**

### **4.1 Battery bank**

Batteries are devices which stores chemical energy and convert it into electrical energy when it needed. In the case of rechargeable batteries, this chemical reaction can be reversed by charging the direction electrical current, restoring the state of charge to a desired level. A collection of connected batteries is called a battery bank, which plays a vital role in electric vehicle. Besides supplying power for vehicle operation, the battery bank also enables energy recovery during braking, a process known as regenerative braking. In urban driving conditions, this recovered energy can account for over 25% of the total traction

energy, and in large cities with frequent stops, it can reach up to 70%, significantly improving overall energy efficiency.

The Peukert Capacity was shown in Equation (1)

$$C_p = (I_{bat})^k * t = \left(\frac{C}{t}\right)^k * t \quad (1)$$

When the battery supplies a constant current  $I_{bat}$  for a certain period of time  $\delta t$ , the total charge used by the battery during the particular time can be calculated using Equation (2)

$$Q_{\delta t} = \delta t \times (I_{bat}) \quad (2)$$

If  $\delta t$  is given in seconds, then after repeating this process for  $n$  times, total charge taken from the battery  $Q_n$  can be calculated using Equation (3).

$$Q_n = Q_{n-1} + \frac{\delta t \times (I_{bat})^k}{3600} \quad (3)$$

$$Q(t) = \frac{1}{3600} \int_{t_1}^{t_2} (I_{bat})^k dt \quad (4)$$

By taking ratio the equation is shown in (5)

$$SOC = 1 - \frac{1}{3600} \int_{t_1}^{t_2} \frac{(I_{bat})^k dt}{C_p} \quad (5)$$

To calculate the open-circuit voltage ( $E$ ), we need to know the number of cells used to form the battery, as the open circuit voltage depends on the state of charge. It can be calculated using the Equation(6).

$$E = n \times [2 + 0.15(SOC)] \quad (6)$$

The battery terminal voltage is calculated using Ohm's law, where the internal resistant  $R_{int}$  is assumed constant and determined from the current  $I_{10}$  that would fully discharge the battery in 10 hours, which represented in equation 7

$$V = E - n \times \frac{0.022}{110} I \quad (7)$$

## 4.2 Fuel cell stack

Fuel cells work like batteries by converting chemical energy into electrical energy, but unlike batteries, they can produce power continuously as long as fuel is supplied. Hydrogen

and oxygen react inside the cell to generate electricity, water, and heat. The output voltage is given by:

$$V_{FC} = E_{ocv} - V_{act} - V_{ohmic} - V_{con} \tag{8}$$

Where  $E_o$  is the voltage of open circuit of the cell, while  $V_{act}$ ,  $V_{ohmic}$ , and  $V_{con}$  represent activation, resistance, and mass transport losses. In Equation (8),  $v_{ct}$  refers to the voltage loss caused by the slow chemical reactions on the electrode surfaces. Part of the generated voltage is used to drive these reactions, and this loss is calculated by Equation (9).

$$V_{act} = - \frac{RT}{nF} \ln \left( \frac{i_{FC}}{i_0} \right) \tag{9}$$

### 4.3 Dynamics of the CaC

The response at the fuel cell electrode and electrolyte depend on the charge concentration of electrons and hydrogen ions. Higher charge denotes high amount of current. This charge acts like a capacitor, causing a small delay in voltage response when the current changes, which can be described by an equation.

$$\frac{dV_d}{dt} = \frac{i_{FC}}{C} - \frac{V_d}{\tau} \tag{10}$$

Equations (8)–(10), a simple computational model can simulate the fuel cell’s output voltage, power, and gas pressures based on the required current. Table 1 shows the equivalent electrical circuit of a fuel cell. Fig.1 shows the Equivalent electrical circuit of a fuel cell.

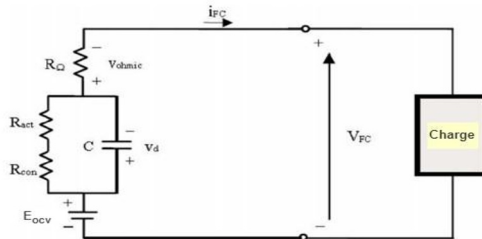
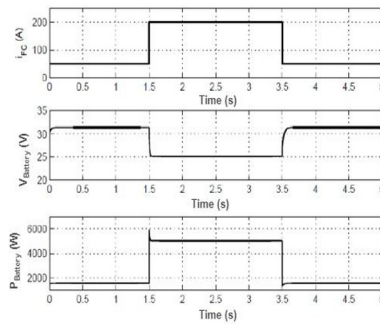


Fig.1. Equivalent electrical circuit of a fuel cell.



**Fig.2.** CaCs voltage and power as a function of load insertion and removal.

Fig.2 shows the simulation results for a polymer membrane fuel cell stack. Although the voltage of the stack changes quickly, it varies more smoothly compared to the fluctuations in current.

## 5 Power Management Strategies

VECaCs are divided into three types non-hybrid, non-regenerative hybrid, and regenerative hybrid. In regenerative hybrids, the battery stores energy usually lost during braking, in nonhybrids waste it as heat. Hybrid systems without regeneration use the battery only to assist the fuel cell during low efficiency operation, offering a simpler and more cost-effective setup.

### 5.1 Driving cycles

The driving behaviour expected by the driver can be simulated using standard driving cycles, which is represented by different real world conditions. In this study from Table 1, there are three cycles named, federal urban driving schedule, the highway fuel economy driving schedule, and the US06 supplemental federal test procedure, all are defined by the U.S. environmental protection agency. The SFTP cycle, simulates hard driving with rapid acceleration, high speed, quick gear shifts, and post-start driving conditions The vehicle's control process works as follows, first, the target speed is compared with the vehicle's

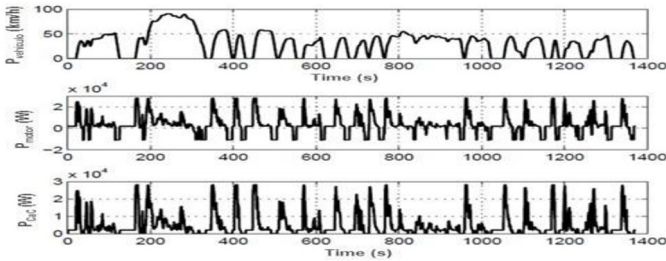
current speed. Based on this, a PI controller generates a reference torque signal required to reach the target speed. The motor controller ensures the desired torque is produced, while the vehicle controller requests the necessary power from available energy sources, dividing it according to the chosen control strategy and system limitations. However, the torque generated by the motor may not always match the driver's demand, depending on the motor's capacity and available power from the sources. Apart from propulsion, the energy system must also support auxiliary loads such as air conditioning, lighting, and other in-vehicle electronics. To account for this, an additional 2 kW of power was included in each simulation step to represent the typical auxiliary energy demand of a light vehicle.

**Table 1.** Main characteristics of conduction cycles.

Cycle	FUDS	HFET	SFTP
Distance (km)	11.8	16.5	12.8
Duration (s)	1372	766	601
Average speed (km/h)	31.4	77.6	77.1
Maximum speed (km/h)	91.2	96.4	129.2
Number of stops	18	1	8

## 5.2 Non-hybrid VECaC

In non-hybrid fuel cell vehicles, the control system adjusts the CaCs stacks power to meet the energy demands, as the battery stays disconnected during braking. As shown in Fig.3, the FUDS cycle demonstrates how vehicle speed, motor power, and fuel cell output. Table 2 compares hydrogen use and efficiency for FUDS, HFET, and SFTP cycles, showing that HFET consumes the least hydrogen due to lower power needs. Without any backup energy source, the CaCs stack often operates at lower efficiency.



**Fig.3.** Non-hybrid VECaC with FUDS cycle.

**Table 2.** Consumption and  $\eta_{FC}$  for the non-hybrid VECaC.

Cycle	$\eta_{FC}$	SOC average
FUDS	$12.90 \times 10^{-2}$	47.83%
HFET	$10.23 \times 10^{-2}$	42.62%
SFTP	$12.33 \times 10^{-2}$	43.19%

### 5.3 Hybrid VECaC without regeneration

For hybrid VECaCs without regeneration, during normal operation, the stack power kept constant, and any extra power required by the driver is drawn from the battery bank. This continues until the battery charge reaches its minimum limit. Once this limit is reached, the battery is no longer used until it is recharged by the CaCs stack when demand is lower, allowing the charge to reach its upper limit. When the driver power demand exceeds the CaCs stack can provide, two options arise: either use the battery to meet the extra demand reducing battery life due to more frequent cycle or limit the output to the stack's maximum capacity, slightly affecting performance. Fig.4 shows the power distribution during the FUDS driving cycle, which shows that the CaCs stack maximum output is restricted to prevent operation in less efficiency zones, with a minimum efficiency threshold of 30%. Additionally, the CaCs stack in this configuration uses half the number of cells compared to the non-hybrid version, and the battery bank consists of twelve 12 volt lead acid batteries, similar to those found in standard light vehicles.

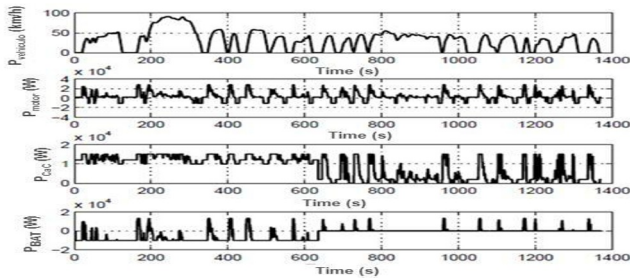


Fig.4. Hybrid VECaCs without regeneration with FUDS cycle.

Fig.5 shows the state of charge of the battery bank during the simulation. It can be seen that the battery stops charging once it reaches about 60% of its capacity. In this simulation, the initial state of charge of the battery was set at 50%, which is the minimum level allowed range. The control strategy was applied for different driving cycles, and the key results are summarized in Table 3.

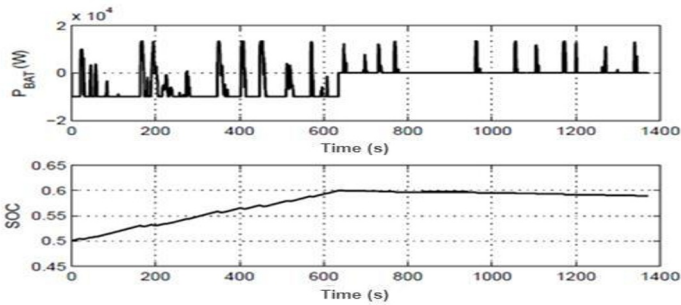


Fig.5. SOC of hybrid VECaC without regeneration with FUDS cycle.

Table 3. Consumption,  $\eta_{FC}$  and SOC for the hybrid vecac without regeneration.

Cyc	Consumption of $H_2(kg)$	$\eta_{FC}$	SOC average
FU	$12.72 \times 10^{-2}$	48.67	56.67%
DS		%	
HF	$10.01 \times 10^{-2}$	44.05	58.58%
ET		%	

SFT	$09.84 \times 10^{-2}$	44.02	54.66%
P		%	

### 5.4 VECaC regenerative hybrid

In this setup, the control system is designed to recover energy during braking and keep the battery’s charge close to an ideal level. It avoids running the CaCs stack in low efficiency zones and maintains the battery within safe charge limits. The system adjusts power flow based on how far the charge deviates from the ideal value, reducing battery wear. The algorithm works in two modes fast charging, where the CaCs stack delivers high power until the charge reaches 55%, and normal charging, where power is balanced between the stack and the battery across four stages regeneration, low power, high power, and moderate power.

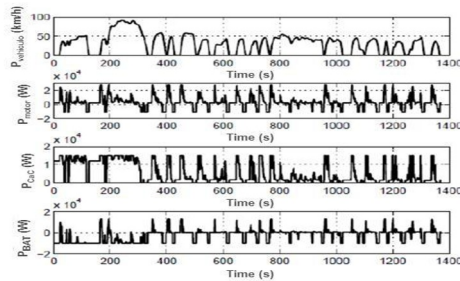
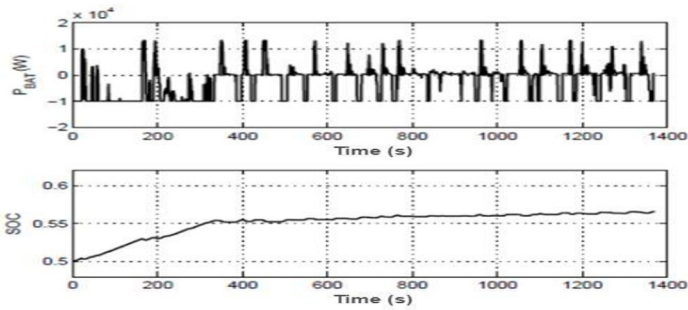


Fig.6. Regenerative hybrid VECaC for the FUDS cycle.

Fig.6 shows the speed of the vehicle and the power from each of the sources while performing the FUDS driving cycle, based on the control strategy explained in this section. The battery bank starts with an initial state of charge of 50%. Fig.7 illustrate how the battery charge level changes under the same driving conditions.



**Fig.7.** SOC of regenerative hybrid VECaC for FUDS cycle.

The system begins to operating in fast recharge mode because the battery initial state of charge is at the low allowed level. It stays in this mode for about 340 seconds, which is the time needed for the battery to reach around 55% charge. After that, the system switches to usual charging mode, where the CaCs stack to longer provide power for charging. Instead, the battery is recharged whenever the induction motor works as a generator, using the energy recovered from mechanical braking. Table 4 presents the results for the FUDS, HFET and SFTP conduction cycles.

**Table 4.** Consumption,  $\eta_{FC}$  and SOC for the hybrid regenerative VECaC

Cycle	Consumption of $H_2(kg)$	$\eta_{FC}$	SOC average
FUDS	$07.94 \times 10^{-2}$	55.89%	55.29%
HFET	$04.79 \times 10^{-2}$	55.37%	53.86%
SFTP	$08.35 \times 10^{-2}$	47.08%	54.55%

## 6 Conclusion

A literature review shows key studies related to electric energy management systems, which cover both broad and specific approaches. These studies show that the energy management system has some advantages like network efficiency, reducing peak demand and reduce the

cost of energy. The better result was obtained by control and optimization management systems, with an average energy savings of about 21.27%. Therefore, research using this method usually provides better results in the energy management of applications. on this approach tends to provide better outcomes in energy management applications. This research introduces a dynamic model for fuel cell hybrid electric vehicles designed to manage between different energy sources. The proposed simulation model helps to analyze the performance of the vehicle under various power demands. It includes battery bank, a fuel cell stack and an electric motor, a PI controller, a sliding mode controller for motor control and a controller for power management. The model is developed using the components of compact passenger vehicle which allows comparison of energy consumption between hybrid vehicle and internal combustion vehicle. Three configurations are evaluated with non-hybrid VECaC, hybrid non-regenerating VECaC, regenerative hybrid VECaC. The results show that hybrid configurations offer better fuel efficiency and lower energy consumption compared to conventional ICE vehicles. The developed model is flexible and adaptable to make them suitable for different types of vehicles. It can also be expanded to include other subsystems new energy storage or generation sources and advanced control strategies for future improvements.

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