Simulation of BLDC Motor Run Electric Vehicle Using PEM Fuel Cell

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Abstract—**The global market is currently focused on the imperative task of reducing carbon emissions and shifting towards the generation of green electrical energy. A key strategy in achieving this goal involves harnessing power from clean sources, with fuel cell emerging as a prominent solution. Proton Exchange Membrane Fuel Cells (PEMFC), especially those utilizing hydrogen and oxygen, holds tremendous promise as a reliable source of power. In fuel cell-powered vehicles, the fuel cell serves a pivoted role by providing primary propulsion power and functioning as a range extender for battery operated cars. The demand for fuel cell vehicles is expected to expand significantly over the projected time frame. This paper aims to provide an overview of the current landscape and future prospects of PEM Fuel Cells, particularly in the context of fuel cell vehicles and their contribution to reducing carbon emissions in the transportation sector. This paper presents a comprehensive study on the integration of Brushless Direct Current (BLDC) motors with Proton Exchange Membrane Fuel Cells (PEMFC) for Electric Vehicle (EV) applications. As the demand for sustainable and efficient transportation solutions grows, the combination of PEMFCs and BLDC motors offers a promising alternative to traditional battery-powered systems. Ultimately, this research aims to contribute to the development of cleaner, more efficient EV technologies, paving the way for a sustainable future in transportation.**

Keywords—*Fuel Cell, PEMFC, Power Converter, BLDC Motor, Electric Vehicles.*

I. Introduction

The recent upsurge in power demand, combined with the unpredicted nature of rising oil costs and escalating environmental concerns, has elevated the importance of renewable energy [1-2]. Among the various renewable energy sources, fuel cell (FC) technology has garnered significant attention due to its superior efficiency, clean operation, and cost-effective power supply, as demanded by consumers. In the realm of fuel cells, proton exchange membrane (PEM) FC technology holds a leading position among competitive forms, making it a preferred choice for numerous applications [3, 15].

Advanced propulsion technologies, such as fuel cell electric vehicles, have the potential to profoundly influence future mobility. In the past two decades, alternative automotive powertrain concepts have been gaining increasing attention. PEM fuel cell systems, in particular, demonstrate high efficiency in generating electric power; operate with low noise, and produce minimal or no emissions when utilizing hydrogen and oxygen. Despite the advancements in battery electric vehicles, they have faced challenges in gaining widespread acceptance as a low-noise, emission-free alternative due to limited operating ranges, long recharge times, and comparatively lower efficiency [4, 31]. In this context, fuel-cell electric vehicles have recently been introduced to the global market [5, 39]. A fuel cell-based electric vehicle can be a great alternative to internal combustion engine vehicles in the near future [6, 9, 13]. Simulation is a virtual tool for conducting various types of experiments to reduce costs and time and increase the effectiveness of the experiments [7].

II. Working of Fuel Cell Electric Vehicle System

As recommended by NITI AAYOG e-Amrit; compared to petrol or diesel vehicles, an electric vehicle has significantly reduced operating and maintenance costs. Instead of utilizing fossil fuels like petrol or diesel to charge their batteries, electric vehicles use electricity. Due to their greater efficiency and the lower cost of power, charging an electric car is more affordable than purchasing fuel or diesel for your travel needs. The use of electric vehicles can be more environmentally benign when powered by renewable energy sources. If charging is done with the aid of renewable energy sources installed at home, such as solar panels, the cost of electricity can be further decreased.

As one of the most potential EVs (Electric Vehicles), FC-HEV (Fuel Cell-Hybrid Electric Vehicle System) uses fuel cell to generate electricity from hydrogen and air. The electricity is used to drive the vehicle. PEMFC-EVs (Proton Exchange Membrane Fuel Cells-Hybrid Electric Vehicles) use PEMFC as their main energy source [8, 19, 30]. Fig.1 indicates the power flow in a FCEV (Fuel Cell Electric Vehicle System), the power converter connected to Brushless DC motor. The driver power comes from a BLDC motor, the power supply sources available as PEMFC. Because of EV

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controllability, Brushless direct current (dc) motor is a great driving force [9-10].

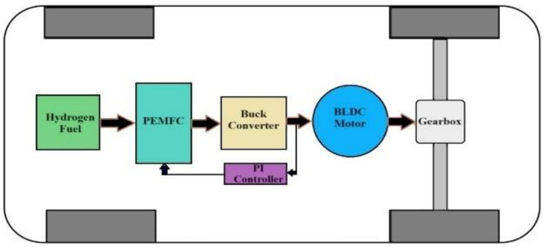

Fig.1. Block diagram of Electric Vehicle

A. *Fuel cell technology in automobile sector*

The fuel cell vehicles are better alternative to the battery driven electric cars as they are light in weight, smaller in size, offer supply of power for a long time, easily replaceable cartridges and no self-discharge with time. Fuel Cell Vehicle (FCV) can be made compact and hence improve the packaging of power trains in vehicles [11]. It is quite simple and contains no moving parts. The fuel cell technology offers low noise and vibration free operation even in high acceleration period when the fuel demand is high [12-13].

B. *Proton exchange membrane fuel cell (PEMFC)*

As the name suggests, the operational part of the proton exchange membrane fuel cell is the proton exchange membrane. PEMFCs are low-temperature fuel cells with operating temperatures between 60 and 100ºC. They are lightweight compact system with quick start-up processes. The sealing of electrodes in PEM fuel cells is easier compared to other types of fuel cells because of the solidity of the electrolyte. PEMFC systems are generally used in portable, transportation and stationary applications. The schematic diagram of PEMFC is shown in Fig. 2. This type of fuel cell requires the least amount of maintenance for the reason that there are no moving parts in the power-generating stacks of the fuel cells. This type of cell technology uses hydrogen and oxygen gases as fuels. As a result, the electrochemical reaction between Hydrogen and Oxygen in the cell, electricity, water, and heat are produced. As Oxygen is found in the air in a large quantity, we only need to produce hydrogen to run the cell. Hydrogen is produced through the electrolysis process. PEMFC uses a solid polymer as an electrolyte and porous carbon electrodes containing a platinum or platinum alloy catalyst. The materials used as anode and cathode electrodes in proton exchange membrane membrane fuel cells are platinum or platinum-ruthenium and platinum and eq. (i) and (ii) describe the reactions at the anode and cathode [14, 15].

$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{(i)}$$

$$0.5O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad \text{(ii)}$$

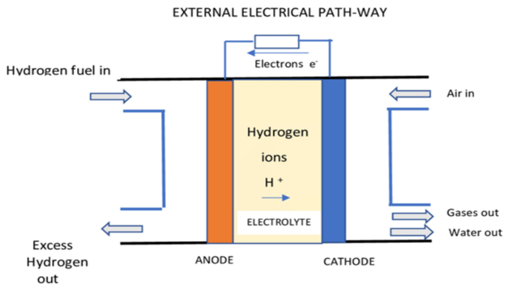

Fig.2. Schematic diagram PEMFC

III. Electrical Topology Used in Fuel Cell Vehicle System

The electrical topology of Fuel Cell Electric Vehicle (FCEV) system comprises several key components that collaborate to generate power and propel the vehicle [16]. These components include fuel cell system, hydrogen storage system, power electronics devices, controller, electrical machine (BLDC motor) and power rating of EV. The Fuel Cell Electric Vehicle system consists of a fuel cell connected to a BLDC motor and DC/DC buck Converter to provide the required input voltage for the BLDC (Brushless Direct Current) motor which, in turn, runs following a required speed [17].

A. *Fuel Cell*

The Matlab fuel cell model developed for power generation is shown in Fig. 3. In a fuel cell, electricity is generated through the electrochemical reaction between hydrogen and oxygen gases, resulting in the formation of water. The process generally involves delivering hydrogen to the anode, where it undergoes a reaction, releasing electrons [18]. This process is typically facilitated by planar electrodes arranged in a stack configuration. An external circuit is then connected to the anode, creating a pathway for the movement of electrons from the anode to the cathode, thus producing electric power [19].

Beyond the fuel cell stack, a Proton Exchange Membrane Fuel Cell (PEMFC) system comprises several other components, included but not limited to air delivery system, hydrogen delivery system, thermal and water management system [20]. These components work together to create a functional and efficient PEMFC system, ensuring a continuous and reliable supply of electricity through the controlled reaction between hydrogen and oxygen [21]. The characteristics of the Proton exchange membrane fuel cell are shown in Fig. 4.

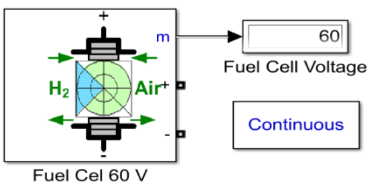

Fig.3. Fuel Cell

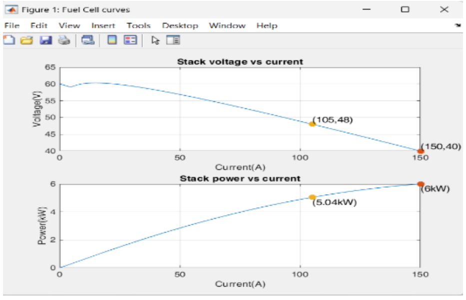

Fig.4. Fuel Cell Characteristics

B. Hydrogen Storage System

The hydrogen required to power Fuel Cell Electric Vehicles (FCEVs) is stored onboard the vehicle itself. Hydrogen storage in carbon materials is considered highly promising because carbon is one of the very few lightweight materials that remain solid at room temperature [22]. This storage method contributes to the practical implementation of FCEVs.

Hydrogen, when created from renewable sources, does not contribute to global warming and is recognized as a non-polluting energy carrier [23-24]. The versatility of hydrogen production from various renewable energy sources is a focal point of discussions. Hydrogen is well suited for various applications, including stationary, portable, and transportation uses [20, 25]. This highlights its potential as a clean and versatile energy carrier that can play a key role in sustainable energy solutions.

C. BLDC Motor

Brushless Direct Current (BLDC) motors are favored for small horsepower control applications due to their notable advantages, including high efficiency, silent operation, compact form, reliability, and low maintenance requirements. Technological advancements over the past two decades, particularly in power semiconductors, adjustable speed driver control schemes and the production of permanent-magnet brushless electric motors, have converged to provide reliable and cost-effective solutions for a wide range of adjustable speed applications [26].

BLDC motors are employed across various market segments such as appliances, automation, industrial control, aviation and more. The absence of brushes in a BLDC motor means that commutation is controlled electronically. To rotate the motor, the stator windings must be energized in a specific sequence and the position of the rotor (North and South poles) must be precisely known to energize a particular set of stator windings. The advantages of BLDC motors include, no mechanical commutator and associated problems, high efficiency due to the use of permanent magnet rotor, high speed operation in both loaded and unloaded conditions, as there are no brushes limiting the speed, smaller motor geometry and lighter weight compared to both brushed-type DC and induction motors, long life with no need for inspection and maintenance of a commutator system [25, 27].

For an electric vehicle with a load of 450 kg, a 3 kW Brushless DC motor with an excitation voltage of 48V is selected as the traction motor. Unlike DC motors, BLDC motors use an electric commutator rather than a mechanical one, making them more reliable. In BLDC motors, rotor magnets generate the rotor's magnetic flux, contributing to higher efficiency [28].

D. Buck Converter

To achieve the required controlled voltage levels for supplying electricity to the electric vehicle system, a converter is an essential component [29]. Power electronic devices play a crucial role in regulating the output voltage of the fuel cell, providing stability to the variations in the fuel cell stack's output. DC/DC converters, as power electronic devices, are responsible for converting an often-unstable electrical voltage at the input into a stable voltage at the output [30-31].

In the automotive field, the voltage needed by the electric motor is met through the output of the converter. For instance, in the case of a Brushless DC (BLDC) motor connected to the Power converter, a Buck converter is commonly used [32-33]. The converter serves as the input source for the electrical machine, driving the vehicle and supplying power to auxiliary loads such as lighting, windshield wipers and other electrical components. Fig. 5 shows the circuit diagram of buck converter. The converter's role is crucial in ensuring a stable and suitable power supply for both the vehicle's propulsion and auxiliary systems [34-35].

Design Calculation: The design equations for a boost converter are given in equations (iii)-(viii); defining various terms as follows:

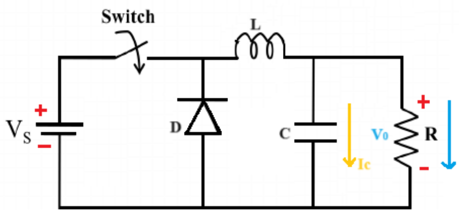

Fig.5. Buck Converter

$$I_{outmax}=\frac{P}{Vout} \quad \text{(iii)}$$

$$\Delta I_L=0.01*I_{outmax} \quad \text{(iv)}$$

$$\Delta V_{out}=0.01*V_{out} \quad \text{(v)}$$

Value of Inductor *L:*

$$L=\frac{\{V_{out}*(V_{in}-V_{out})\}}{(\Delta I_L*f_s*V_{in})} \quad \text{(vi)}$$

Value of Capacitor *C:*

$$C=\frac{\Delta IL}{(8*fs*\Delta Vout)} \quad \text{(vii)}$$

Value of Resistance *R*:

$$R=\frac{Vout}{Ioutmax} \quad \text{(viii)}$$

Where:

Vin is the input voltage,

Vo is the output voltage,

fs is the switching frequency,

ΔI_L is the inductor ripple current,

ΔV is the Capacitor ripple voltage,

I_{outmax} is the maximum output current.

These equations provide the values for the inductor (L), capacitor (C), and load resistance (R) in a boost converter design, considering key parameters such as input and output voltages, switching frequency, and desired current and voltage ripples.

PI controller

A Proportional-Integral (PI) controller is a feedback mechanism commonly used in industrial control systems. In industrial processes, a PI controller aims to correct the error between a measured process variable and desired set point by calculating and then outputting corrective action to adjust the process accordingly. The PI controller's calculation involves two separate modes: the proportional mode, and the integral mode. The proportional mode determines the reaction to the current error, while the integral mode determines the reaction based on recent errors. The weighted sum of the outputs from these two modes serves as the corrective action applied to the control element. The PI controller is widely employed in industries due to its ease of design and simple structure (Fig. 6) [36-37].

PI controller algorithm can be expressed as follows:

$Output\ (t) = K_P\, e(t) + K_I \int_0^t e\,(\tau)\, d\tau$

Where $e(t)$represents the error, calculated as the set reference value minus the actual value,

K_P is the proportional gain,

K_I is the integral gain.

This algorithm allows the controller to adjust the output based on both the current error and the accumulated historical error, providing a robust method for controlling any process.

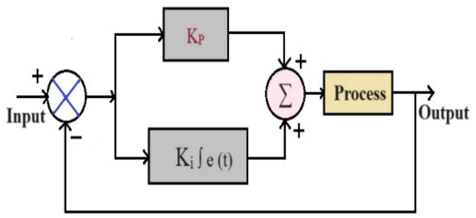

Fig.6. Block diagram of PI controller

F. Power rating based on vehicle dynamics

When determining the power rating of a vehicle, various vehicle dynamics factors such as rolling resistance, gradient resistance, aerodynamic drag, etc. must be taken into consideration. For the selection of the motor rating, an electric car with a gross weight of 450 kg is considered [38].

The force required to drive the vehicle is calculated as follows:

$$F_{total}=F_{rolling} + F_{gradient} + F_{aerodynamic\ drag} \quad \text{(ix)}$$

Where:
F_{total} is the total tractive force
$F_{rolling}$ is the force due to Rolling Resistance
$F_{gradient}$ is the force due to Gradient Resistance
$F_{aerodynamic\ drag}$ is the force due to Aerodynamic Drag.

The vehicle is subjected to different resistances while driving. These resistances create a force that counteracts the movement of the vehicle. In the vehicle, the electric motor ensures acceleration by generating a torque that exceeds the resistance forces acting on the vehicle. As the resistance forces acting on the vehicle increase, the force required to move the vehicle also increases and, as a result, significantly increased energy consumption. Vehicles are influenced while driving by aerodynamic resistance, rolling resistance, acceleration and gradient resistance. These resistances acting on the vehicle are included in the model [39].

This equation accounts for the combined effects of rolling resistance, gradient resistance, and aerodynamic drag, providing a comprehensive understanding of the forces acting on the vehicle that the motor must overcome for effective propulsion.

a. Rolling resistance

Rolling resistance is the resistance a vehicle encounters due to the contact of its tires with the road. The formula for calculating the force due to rolling resistance is given by equation (vii):

$$F_{rolling}=Crr*M*g \quad \text{(x)}$$

Where:

Crr is the coefficient of rolling resistance,
M is the mass in kgs,
g is the acceleration due to gravity (9.81 m/s^2).
For the application considered, Crr is set to 0.01, and M is 450 kg. Therefore:
$F_{rolling}= 0.01*450*9.81=44.145\ N$
Power required to overcome the rolling resistance of 44.145 N is calculated using equation (xi):

$$P_{rolling}= F_{rolling}*V/3600= 156.96*100/3600= 1.226\ kW \quad \text{(xi)}$$

Where V is the velocity in km/h. This provides an estimation of the power required to overcome the rolling resistance at a given velocity.

b. Gradient resistance

The gradient resistance of a vehicle is the resistance it encounters while climbing a hill, traveling on a flyover, or moving downhill. The angle between the ground and the slope of the path is denoted as α.The formula for calculating the gradient resistance is given by equation (xii):

$$F_{gradient\ resistance}=+ M*g*\sin\alpha \quad \text{(xii)}$$

In this illustration, let's assume the electric car is travelling on a flat road. Therefore, the angle α is 0^o. Substituting this value into the formula:

$$F_{gradient}= 450*9.81*\sin 0^o= 0\ N. \quad \text{(xiii)}$$

In this case, the gradient resistance is 0 N, and consequently, the power required to overcome the gradient resistance is also zero. This implies that when the electric car is on the flat road, no additional power is needed to overcome the resistance associated with the gradient.

c. Aerodynamic drag

The resistive force acting on the vehicle due to as aerodynamic drag is determined by the formula given by equation (xiv):

$$F_{aerodynamic\ drag} = 0.5*CA*Af*\rho*(V+Vo)^2 \qquad \text{(xiv)}$$

When a vehicle operates at a constant speed, the three principal forces are the aerodynamic drag, rolling resistance, and gravitational force. In this specific scenario, let's assume the power required to overcome aerodynamic drag and other resistive forces is approximately 1.3 kW. Therefore, the total tractive power required to move the vehicle is given by:

$$P_{total} = 1.226\ kW + 1.3\ kW = 2.526\ kW. \qquad \text{(xv)}$$

However, selecting an electric motor with an output power rating of 2.526 kW is not considered an effective decision. It is important to account for losses that occur during power transfer to the wheel. Thus, the mechanical power output ($M_{tractive}$) required to drive the vehicle is determined by equation (xiii):

$$M_{tractive} = P_{total} / efficiency \qquad \text{(xiii)}$$

Where η represents the efficiency of the transmission gear system. Assuming the efficiency of the transmission system is 0.85, the mechanical power output required is calculated as follows:

$$M_{tractive} = P_{total} / efficiency = 2.526/0.85 = 2.97 \approx 3\ kW$$

Therefore, it is recommended to select a motor with an output power rating of 3 kW when determining the power rating for a 450 kg electric vehicle. This method provides an estimation of the power required for driving an electric car with a specific load, considering losses in the system.

TABLE-1

Power Rating Of The Designed Motor		
Sr. No.	***Parameter***	***Values***
1	Input power	4.6 kW
2	Output power	3.0 kW
3	Maximum Output Power	5.0 kW
4	Losses	1.6

IV. SIMULATION RESULTS

Fig. 7 shows the Simulink model of proposed PEMFC-EV (Proton exchange membrane uel Cell-Electric Vehicle) System. The motor picked is a BLDC (Brushless direct Current) motor with a nominal output of 3 kW, making it the optimal choice for a light weighted electric vehicle. A 48 V DC, 5 kW PEMFC stack is connected to a DC/DC power converter, which is loaded by a 5 kW RL element with a PI controller. The use of a PEM Fuel cell is deemed suitable for electric vehicles, taking into consideration environmental conditions.

The proposed work is implemented using MATLAB/Simulink software, and the results are validated for the parameters outlined in Table.1. The power generated by the fuel cell and consumed by the BLDC motor to propel the electric vehicle and power auxiliary loads are examined. According to calculations [40], a 48-volt, 3-kW supply is deemed sufficient for an electric vehicle weighing 450 kg.

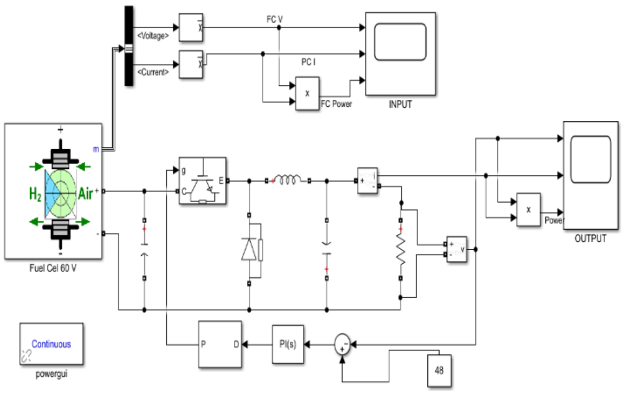

Fig.7. Simulink Model of PEMFC-EV System

RESULT AND DISCUSSION

Based on the simulation of PEMFC, the input and output characteristic curves have been acquired by utilizing MATLAB/Simulink. The input and output curves of the PEMFC model are presented in Fig.8 and Fig.9. For a pure fuel cell-powered electric vehicle designed to have an output power capability of 3.0 kW, it can be observed that the fuel cell meets the required energy source.

Fig.8. and Fig. 9. depict the input and output simulation results for a BLDC-operated electric vehicle. A slide deviation is noticed in Fig. 8, which is unsatisfactory for electric vehicles as the power of electric vehicles is fixed according to the gear mechanism. This issue has been addressed by employing a power converter interface. The vehicle can operate in both forward and reverse modes, as shown in Fig.9, where the threshold is set to a minimum of 0.05 sec and a maximum of 0.09 sec. The Full operating mode will also be engaged during start-up, after 0.1 seconds, this enhances EV stability and provides the capacity to operate under various conditions by adjusting the gear. Fig.10 shows the Comparative Input and Output characteristics of the fuel cell system, which is clearly shows the output voltage is stepped down to the desired output voltage.

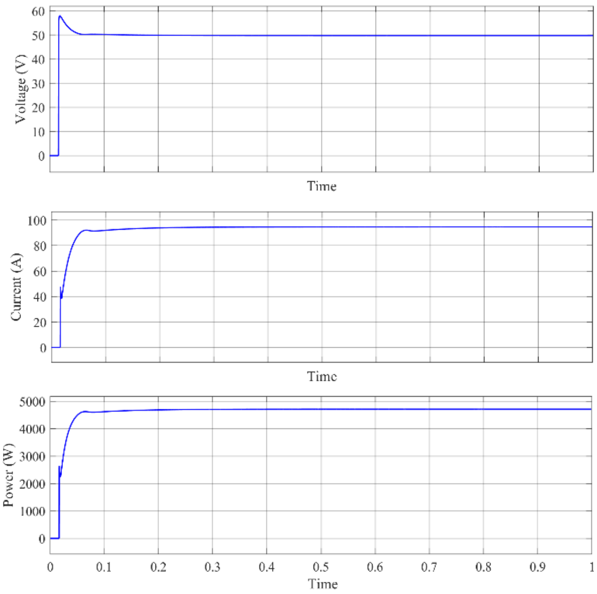

Fig.8. Input characteristics of fuel cell

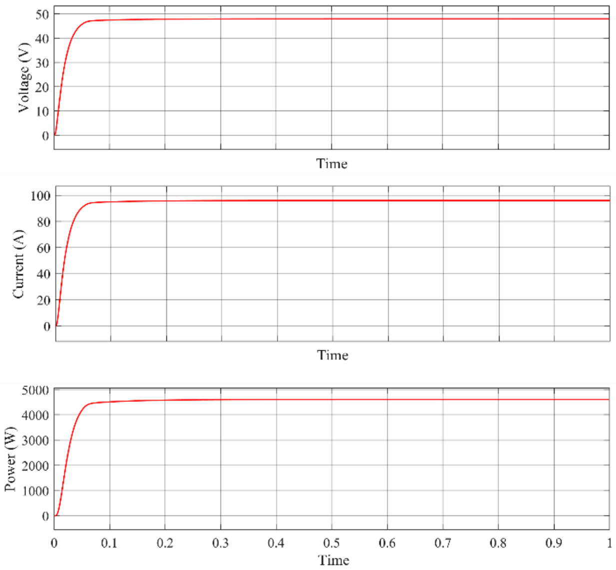

Fig.9 Output characteristics of fuel cell

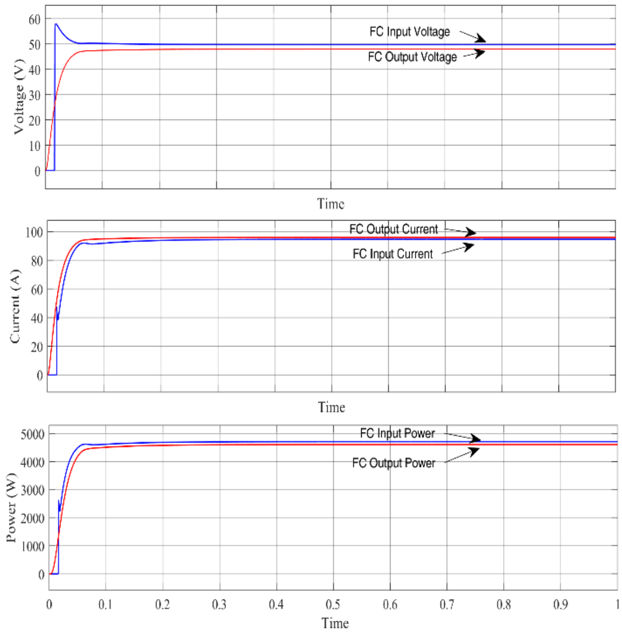

Fig.10 Comparative characteristics of Input / Output

Fuel saving strategies applied to recently proposed power control topologies for hybrid propulsion systems based on fuel cells and other renewable energy. The future of FCEV (Fuel Cell- Electric Vehicle) topologies lies in hybridizing the existing components to create an optimal propulsion system that is competitive with the modern automotive market. For transportation systems, an integrated system should be designed and developed if it is integrated into the microgrid.

V. CONCLUSION AND FUTURE SCOPE

This research paper focuses on the construction of the light four-wheeled electric vehicle powered by a 3 kW nominal power brushless DC motor (BLDC), which is deemed to be the optimal solution for this type of vehicle. The incorporation of a 3 kW BLDC motor contributes to the vehicle's speed and power, aligning it with the performance of other electric cars. Similar to all-electric vehicles, fuel cell electric vehicles (FCEVs) utilize electricity to propel an electric motor. However, in contrast to other electric vehicles, FCEVs generate electricity through a fuel cell powered by hydrogen, rather than relying solely on a battery for power. FCEVs, powered by hydrogen, boast higher efficiency compared to traditional internal combustion engine vehicles and emit only water vapor and warm air, eliminating harmful tailpipe emissions.

The growing interest in fuel cell vehicles is driven by concerns over fossil fuel depletion and environmental issues. Major automobile manufacturers are actively addressing technical challenges to enable mass production, and there is a widespread prediction that fuel cell vehicles will achieve commercial viability by 2025, competing effectively against internal combustion engines by 2030. This paper explores general aspects related to fuel cell technology and introduces the development of a model for a fuel cell electric vehicle operated by BLDC motors. While PEMFCs present a promising alternative for electric vehicles, their current economic feasibility is challenged by high initial costs, limited infrastructure, and competition from rapidly advancing battery technologies. However, targeted investments in hydrogen infrastructure, and technological advancements could enhance their viability in the long term. Considering both economic factors and environmental impacts will be crucial for determining the future landscape of sustainable transportation technologies.

REFERENCES

[1] P. T. Bankupalli, S. Ghosh, L. K. Sahu, and A. Kumar Dwivedi, "Parameter estimation of PEM Fuel Cell Electrical Equivalent Model using Hybrid Optimization," in 8th International Conference on Power Systems (ICPS), 2019.

[2] Mancino AN, Menale C, Vellucci F, Pasquali M, Bubbico R. "PEM Fuel Cell Applications in Road Transport", Energies 2023; vol. 16 no. 17:6129, 2023.

[3] Daniel Akinyele, Olabode Elijah, & Amole Abraham. (2020). "Review of Fuel Cell Technologies and Applications for Sustainable Microgrid Systems" Inventions 2020, vol. 5 no. 42, pp 1-35.

[4] Mehrdad Ehsani, Krishna Veer Singh, Hari Om Bansal, and Ramin Tafazzoli Mehrjardi, "State of the Art and Trends in Electric and Hybrid Electric Vehicles," in Proceedings of the IEEE, vol. 109 no. 6, pp. 967-984, 2021.

[5] A. Schell, H. Peng, D. Tran, E. Stamos, C.-C. Lin, and M. J. Kim, "Modeling and control strategy development for fuel cell electric vehicles," in Annual Reviews in Control, vol. 29, no. 1, pp. 159–168, 2005.

[6] U. Mitra, A. Arya, A. Khan, N. Javara, S. K. Gawre and M. Arya, "Simulation and Performance Analysis of a Fuel Cell Hybrid Electric Vehicle," IEEE International Students' Conference on Electrical, Electronics and Computer Science (SCEECS), Bhopal, India, pp 1-6, 2023.

[7] P. K. Gautam, A. Arya, S. Kumar, U. Mitra, S. Mehroliya and S. Gupta, "Modelling And Simulating Performance Of Hybrid Electric Vehicle Using Advisor 2.0," IEEE 4th International Conference on Computing, Power and Communication Technologies (GUCON), Kuala Lumpur, Malaysia, pp 1-6, 2012.

[8] X. Lü, Y. Qu, Y. Wang, C. Qin, and G. Liu, "A comprehensive review on hybrid power system for PEMFC-HEV: Issues and strategies," in Energy Conversion and Management, vol. 171, pp. 1273–1291, 2018.

[9] Tingke Fang, Coleman Vairin, Annette von Jouanne, E.B. Agamloh, Alexandre Yokochi, "Review of Fuel-Cell Electric Vehicles", Energies, 17. 2160, 2024.

[10] Feyijimi Adegbohun, Annette von Jouanne, Ben Phillips, Emmanuel Agamloh and Alex Yokochi, "High Performance Electric Vehicle Powertrain Modeling, Simulation and Validation" Energies. 14. 1493, 2021.

[11] Mustafa İnci, Mehmet Büyük, Mehmet Hakan Demir, Göktürk İlbey, "A review and research on fuel cell electric vehicles: Topologies, power electronic converters, energy management methods, technical challenges, marketing and future aspects", Renewable and Sustainable Energy Reviews, vol. 137, 110648, 2021.

[12] H. Mishra and S. Ray, "A Review on Fuel Cell based Hybrid Electric Vehicles," in Journal of Harvesting Energy, vol. 1, no. 1, pp. 1-14, 2022.

[13] Alireza Soleimani, Sayed Hamid Hosseini Dolatabadi, Mehrdad Heidari, Anna Pinnarelli, Behrouz Mehdizadeh Khorrami, Yang Luo, Pasquale Vizza & Giovanni Brusco, "Progress in hydrogen fuel cell vehicles and up-and-coming technologies for eco-friendly transportation: an international assessment", Multiscale and Multidisciplinary Modeling, Experiments and Design, 2024.

[14] N. Sazali, W. N. Wan Salleh, A. S. Jamaludin, and M. N. Mhd Razali, "New Perspectives on Fuel Cell Technology: A Brief Review," in Membranes, vol. 10, no. 5, pp. 99, 2020.

[15] Shanyun Mo, Lei Du, Zhiyin Huang, Junda Chen, Yangdong Zhou, Puwei Wu, Ling Meng, Ning Wang, Lixin Xing, Mingquan Zhao, Yunsong Yang, Junke Tang, Yuquan Zou & Siyu Ye, "Recent Advances on PEM Fuel Cells: From Key Materials to Membrane Electrode Assembly". Electrochem. Energy Rev., vol. 6, no. 28, 2023.

[16] M. Abdel-Salam, A. Ahmed, A. Elnozahy, and A. Eid, "Modeling and Simulation of Fuel Cell Electric Vehicles," in Proceedings of the 15th International Middle East Power Systems Conference (MEPCONâ•Ž12), Alexandria University, Egypt, 2012.

[17] Mitra U., A. Arya, S. Gupta and Gupta A. K., "A Brief Overview on Fuel Cell Electric Vehicles, "International Conference on Emerging Trends in Engineering and Medical Sciences (ICETEMS), Nagpur, India, pp 124-129, 2022.

[18] Yang, Cheng-Hao, Chang Shing-Cheng, Chan Yen-Hsin, and Chang Wen-Sheng , "A Dynamic Analysis of the Multi-Stack SOFC-CHP System for Power Modulation", Energies Vol. 12 no. 19, pp 1, 2019.

[19] Mohammad Waseem, Mohammad Amir, G. Sree Lakshmi, S. Harivardhagini, Mumtaz Ahmad, "Fuel cell-based hybrid electric vehicles: An integrated review of current status, key challenges, recommended policies, and future prospects", Green Energy and Intelligent Transportation,vol. 2 no. 6, 2023.

[20] Pala Rameez Hassan, **"**Fuel Cell System and Their Technologies: A Review", Published in International Journal of Trend in Scientific Research and Development (IJTSRD), vol. 3, Issue-2, pp 153-158., 2019.

[21] Rahaman Md. Ziaur and Islam Md. Mashrur, "Comparative Study of Different Fuel Cell Technologies", Asian Journal of Information Technology, Asian J.Con.Sci. Technol. Vol. 01 no. 01, pp. 29-32, 2019

[22] M. Hirscher, "FUELS – HYDROGEN STORAGE, Carbon Materials," in Encyclopedia of Electrochemical Power Sources, pp. 484–487, 2009.

[23] Manoharan Y, Hosseini SE, Butler B, Alzhahrani H, Senior BTF, Ashuri T, Krohn J. "Hydrogen Fuel Cell Vehicles; Current Status and Future Prospect", Applied Sciences. 2019; Vol. 9 no.11:2296, 2019.

[24] Selmi, T., Khadhraoui, A. & Cherif, A. "Fuel cell–based electric vehicles technologies and challenges", Environ Sci Pollut Res vol. 29, pp 78121–78131, 2022.

[25] R.-A. Felseghi, E. Carcadea, M. S. Raboaca, C. N. TRUFIN, and C. Filote, "Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications," in Energies, vol. 12, no. 23, pp. 4593, 2019.

[26] W. Huazhang, "Design and Implementation of Brushless DC Motor Drive and Control System," in Procedia Engineering, vol. 29, pp. 2219–2224, 2012.

[27] Ren K, Chen H, Sun H, Wang Q, Sun Q, Jin B. "Design and Analysis of a Permanent Magnet Brushless DC Motor in an Automotive Cooling System". World Electric Vehicle Journal, vol. 14 no. 8:228, 2023.

[28] J. N. Ansari and L. Sapna, "Speed Control of BLDC motor for Electric Vehicle," in International Journal of Engineering Research& Technology (IJERT), vol. 3, no. 5, pp. 1667-1671, 2014.

[29] L. Kumar and S. Jain, "A multiple input dc-dc converter for interfacing of battery/ultracapacitor in EVs/HEVs/FCVs," in IEEE 5th India International Conference on Power Electronics (IICPE), 2012.

[30] Xie, W.; Luo, W.; Qin, Y , "Integrated DC/DC Converter Topology Study for Fuel Cell Hybrid Vehicles with Two Energy Sources". World Electr. Veh. J. 2023, vol. 14, pp 9, 2023.

[31] Zhou, J.; Zhang, Q.; Li, J. "Topology and Control of Fuel Cell Generation Converters" Energies 2023, Vol. 16, pp 4525, 2023.

[32] I.-S. Sorlei, N. Bizon, P. Thounthong, M. Varlam, E. Carcadea, M. Culcer, and M. Raceanu, "Fuel Cell Electric Vehicles—A Brief Review of Current Topologies and Energy Management Strategies," in Energies, vol. 14, no. 1, pp. 252, 2021.

[33] Tabbat, Peyman alvi, Babaei, Ebrahim, Mohseni, Parham, Marzang, Vafa, "Study and analysis of a DC-DC soft switched buck converter", IET Power Electronics, Vol. 13, pp 1456-1465, 2020.

[34] Chou, Hsiao-Hsing, Jian-Yu Chen, Tsung-Hu Tseng, Jun-Yi Yang, Xuan Yang, and San-Fu Wang, "A New Control Scheme for the Buck Converter" Applied Sciences, vol.13 no.3: 1991, 2023

[35] Baharudin, Nor & Tunku Mansur, Tunku Muhammad Nizar & Hamid, F & Ali, Rosnazri & Irwanto, Muhammad, "Performance Analysis of DC-DC Buck Converter for Renewable Energy Application". Journal of Physics: Conference Series. 1019. 012020, 2018.

[36] T. Jain, S. Jain, G. Agnihotri. “Comparison of the PI-Controller and SMC-based Active filter response” IEEE International conference RACE. 2007.

[37] Huang, H., “PI Control Technology Principal Analysis and Simulation”. Highlights in Science, Engineering and Technology, vol. 71, pp 104-111, 2023.

[38] Xun Q., Liu Y. and Holmberg E., "A Comparative Study of Fuel Cell Electric Vehicles Hybridization with Battery or Supercapacitor," International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Amalfi, Italy, pp. 389-394, 2018

[39] N. M. BOYACIOĞLU, T. KOCAKULAK, M. BATAR, A. UYUMAZ, and H. SOLMAZ, “Modeling and Control of a PEM Fuel Cell Hybrid Energy System Used in a Vehicle with Fuzzy Logic Method”, International Journal of Automotive Science and Technology, vol. 7, no. 4, pp. 295–308, 2023.

[40] T. Porselv, J. Ashok, and A. Jith Kumar, "Selection of Power Rating of an Electric Motor for Electric Vehicles," in International Journal of Engineering Science and Computing, vol. 7, no. 4, pp. 6469-6472, 2017.