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Route Map Towards Road Freight Electrification: Developing a Dual-Energy Electric Vehicles

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ABSTRACT

In pursuit of carbon free future, Original Equipment Manufacturers (OEMs) are pioneering Dual Energy Electric Vehicles (DE-EVs) aimed at achieving net-zero emissions. DE- EVs integrate hydrogen and solar energy as primary and secondary sources, respectively, to revolutionize road freight electrification. This innovative dual energy model enhances operational efficiency, reduces emissions, and extends driving range. The hydrogen fuel cell stack ensures extended range and rapid refueling, while solar panels provide supplementary electricity during daylight. Key components include the hydrogen fuel cell stack, solar photovoltaic (SPV) system, an energy management system, and a battery storage unit. The energy management system dynamically switches between hydrogen and solar energy based on availability, driving conditions, and demand, optimizing performance and fuel economy. Hardware results demonstrate significant reductions in fossil fuel dependency and environmental impact. This paper also addresses the challenges of hydrogen storage and infrastructure, underscoring the potential of DE- EVs for sustainable, next-generation electric mobility.

1. INTRODUCTION

Electric vehicles (EVs) play a crucial role in mitigating climate change and improving air quality by significantly reducing greenhouse gas emissions and eliminating pollutants, in mobility sector. Traditional charging methods often rely on fossil fuels, undermining the environmental benefits of EVs. Harnessing renewable energies to charge EV batteries aims for achieving net-zero transportation emissions. However, renewable energy sources such as solar and wind are intermittent; for instance, solar power fluctuates with weather conditions, and wind energy varies with wind speeds. Therefore, a hybrid charging system is necessary to eliminate such drawbacks and provide a continuous charging system. A novel hybrid charging system is proposed, by integrating solar power and fuel cell technology to charge batteries based on their State of Charge (SoC). Solar panels provide renewable energy during daylight hours, while fuel cells offer a reliable alternative when solar power is insufficient. This dual energy approach ensures continuous and efficient battery charging, maximizing the utilization of renewable energy and providing a dependable backup. This innovative hybrid model advances the sustainability and practicality of next-generation EVs, contributing to a robust reliable charging ecosystem that supports the global shift towards clean energy mobility.

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A. *Motivation*

Aligned with global imperatives, the transition from traditional fossil fuels to alternative energy sources is crucial for reducing carbon emissions and mitigating climate change. Batteries play a pivotal role in enabling the widespread adoption of renewable energy technologies. However, conventional charging methods often depend on fossil fuels, thereby diminishing the environmental advantages of renewable energy. A novel hybrid charging system is proposed, integrating fuel cell technology and solar power to charge batteries based on their State of Charge (SoC). By harnessing the complementary strengths of these two alternative energy sources, this system optimizes battery performance, reduces greenhouse gas emissions, and enhances the overall sustainability of energy storage solutions. This paper presents the design, development, and empirical evaluation of the hybrid charging system, demonstrating its potential to revolutionize battery charging methods and support a low-carbon energy future in the mobility sector.

B. *Literature Review*

This review examines the integration of hydrogen fuel cells and solar panels in DE-EVs, highlighting the benefits and challenges of this dual energy model. Advancements in EV technology aim for sustainability, but issues like limited charging infrastructure, long charging times, and battery degradation persist [1], [2]. Renewable energy sources such as solar, wind, and hydro power can reduce EVs carbon footprint [3], with solar-powered EV chargers potentially achieving net-zero emissions [4]. However, solar power faces challenges like intermittency and high costs [5]. DC microgrids offer a reliable way to integrate renewable into EV charging, though they require complex management systems [6], [7].

Hydrogen fuel cells present a promising solution for net-zero emissions, offering high energy density and rapid refueling [8]. Despite infrastructure and production challenges, they support sustainable long-distance travel. Our proposed DE- EV concept integrates hydrogen and solar energy, optimizing efficiency and flexibility [9]. The design features solar panels on the vehicle's roof and a hydrogen tank at the back, with a dynamic energy management system (EMS) ensuring seamless transitions between energy sources [10]. Effective load sharing techniques enhance performance, and sophisticated control strategies in hybrid systems can significantly improve fuel economy and environmental impact [11].

C. Novelty

A groundbreaking hybrid system is proposed to revolutionize the charging infrastructure for electric vehicles (EVs) by seamlessly integrating two distinct energy sources, with the overarching goal of achieving net-zero transportation emissions. This innovative configuration merges sophisticated solar power technology and advanced fuel cell systems to effectively recharge EV batteries based on their State of Charge (SoC). The DE-EV features, fixed solar panels mounted on its upper surface and integrated fuel cell technology beneath, enabling continuous and adaptive charging regardless of the vehicle's operational state. During daylight hours, the solar panels operate at their Maximum Power Point (MPP), dynamically generating electricity tailored to the battery's SoC, while the fuel cell supplements power requirements as necessary. At night, the fuel cell operates at maximum capacity, proficiently meeting the vehicle's energy demands and ensuring uninterrupted performance. This cohesive approach not only optimizes energy efficiency but also reduces dependence on conventional fossil fuels, thereby advancing the sustainability and viability of next-generation electric vehicles.

D. Key Contributions

1) A novel hybrid system is proposed for charging electric vehicles (EVs) using two distinct energy sources, aiming to achieve net-zero transportation emissions.
2) A novel hybrid charging infrastructure is proposed, integrating both solar power and fuel cell technology to recharge batteries based on their State of Charge (SoC).
3) The DE-EV is equipped with fixed solar panels on its upper surface and integrated fuel cell technology beneath. These dual energy sources charge the vehicle both when stationary and during motion.
4) During the daytime, with optimal solar irradiance, the solar panels operate at Maximum Power Point (MPP) and contribute according to the State of Charge (SoC), while the fuel cell supplements any additional power demand. At night, the fuel cell operates at maximum power to meet the vehicle's energy requirements.

E. Organization

The rest of the paper is organized as follows. Section II discusses the operation of the proposed method. Section III consists of results and discussion and Section IV concludes the article.

2. PROPOSED METHODOLOGY

Figure 1 presents the block diagram of the proposed system, comprising two energy sources: a solar photovoltaic (SPV) system and a hydrogen fuel cell stack. These two energy sources are integrated to form a DC microgrid. This microgrid is connected at a point of common coupling (PCC), where the DE-EV battery is also connected, serving as the central node for all these components and allowing for coordinated energy distribution and storage within the system. This setup allows the system to charge DE-EV batteries efficiently. The charging strategy is designed to prioritize the use of the solar PV system based on its availability and to manage the charging process according to the State of Charge (SoC) demand of the EV battery. The specific configurations and specifications of the SPV system, the hydrogen fuel cell Stack, and the DE-EV battery are provided in Table 1. The solar PV system is connected to the DE-EV battery through a buck converter. This converter is configured to operate at the Maximum Power Point (MPP) of the SPV system. By doing so, it ensures that the solar PV system delivers the maximum possible power to the DE-EV, optimizing the use of available solar energy. Similarly, a boost converter is connected to the hydrogen fuel cell stack. This converter plays a crucial role in controlling the power flow from the fuel cell to the DE-EV. It ensures that the output from the fuel cell is stable and regulated, providing a reliable power source for battery charging when solar power is insufficient or unavailable. The system dynamically adjusts the power contributions from both the energy sources to maintain an optimal charging process. This approach not only enhances the efficiency of the system but also ensures the longevity and reliability of the DE-EV battery by preventing overcharging and deep discharging.

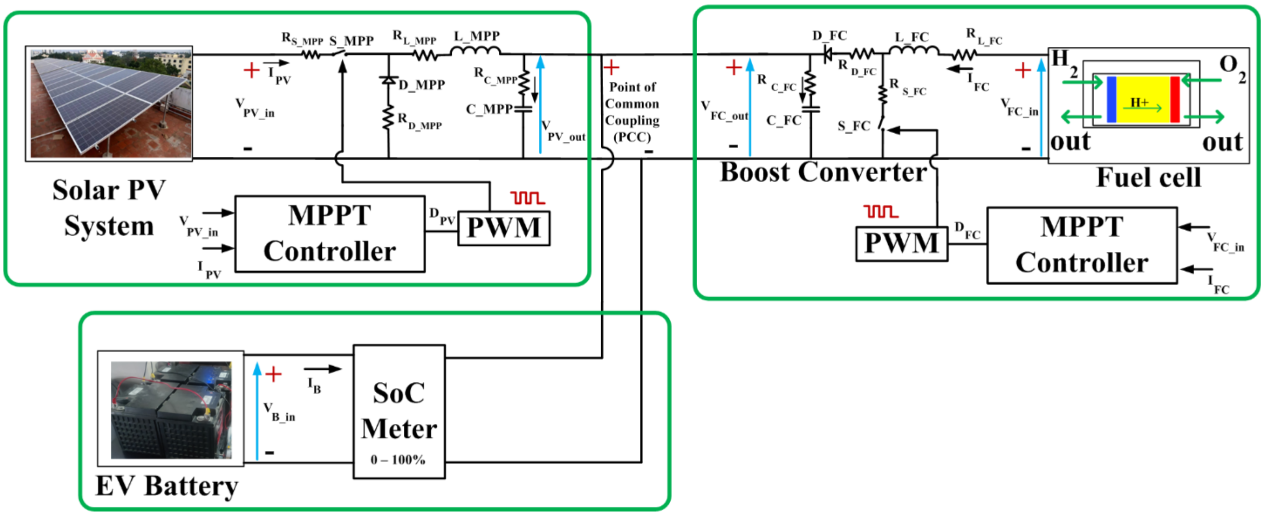

Fig. 1. Block diagram of proposed methodology.

Table 1. PV system specifications.

Parameter	Rating
Panel Specifications	
Maximum Power (*Pmax*)	100 Wp
Open circuit voltage (*Voc*)	21 V
Short circuit current (*Isc*)	6.35 A
Voltage at MPP (*Vmpp*)	18 V
Current at MPP (*Impp*)	5.56 A
No.of Cells	36 cells in series
Dimension (H x W)	1089 X 670 mm
PV Array Specifications	
Maximum Power (*Pmax*)	300 Wp
Open circuit voltage (*Voc*)	63 V
Short circuit current (*Isc*)	6.35 A
Voltage at MPP (*Vmpp*)	54 V
Current at MPP (*Impp*)	5.56 A
Array Size (No. of panels in a String X No.of strings in parallel)	3 x 1
Hydrogen fuel system specifications	
Type of fuel cell	Proton exchange
No of cells	20
Voltage at maximum power	28.8 V
Current at maximum power	11.12 A
Hydrogen pressure	0.45 0.55 bar
Hydrogen purity	99.995%
DE-EV battery specifications	
Type of battery	Lithium-ion
Nominal voltage	12V
Capacity	42Ah

Operation of the Dual Energy Electrical Vehicle (DE-EV) Charging

The proposed system employs a dynamic State of Charge (SoC) priority strategy to optimize the charging process of the DE-EV battery using a hybrid combination of a solar PV system and a hydrogen fuel cell stack. The charging priority is determined by the SoC levels of the battery, which are categorized into four distinct cases.

1) *Case 1:* When the SoC of the battery is below 20%, both the solar PV system and the fuel cell operate at maxi- mum capacity to charge the battery rapidly. This high-priority approach is crucial to avoid deep discharge, which can cause

significant damage to the battery and reduce its lifespan.

2) *Case 2:* When the SoC is between 20% and 50%, the system prioritizes the use of the solar PV system for charging. However, if the solar power is insufficient to meet the charging demand, the fuel cell supplements the energy supply. This strategy ensures that the battery continues to charge efficiently while maximizing the use of renewable solar energy.

3) *Case 3:* As the SoC increases to the mid-range of 50% to 80%, the system balances the load between the solar PV system and the fuel cell. This balanced approach maintains optimal battery health and charging efficiency by utilizing both energy sources effectively.

4) *Case 4:* Once the SoC exceeds 80%, the system primarily uses the solar PV system for charging, gradually reducing the use of the fuel cell. This phase involves implementing float charging as the SoC approaches 100%, ensuring that the charging rate slows down to prevent overcharging. Overcharging can lead to overheating and potential degradation of the battery. The solar PV system provides a gentle and sustainable charge during this stage, maintaining the battery at high SoC levels without risking damage.

During nighttime, when solar power becomes unavailable, the fuel cell system assumes responsibility for power delivery in all the aforementioned cases and operates at its maximum power output. This dynamic SoC priority strategy ensures that the DE-EV is charged in an efficient, sustainable, and safe manner, leveraging the combined strengths of the solar PV system and the hydrogen fuel cell while protecting the battery's health and optimizing its lifespan. The workflow of the algorithm is shown in Figure 2.

3. RESULTS AND DISCUSSION

The proposed design has undergone real-time testing, as depicted in Figure 3. The results indicate performance under both stationary and moving vehicle conditions.

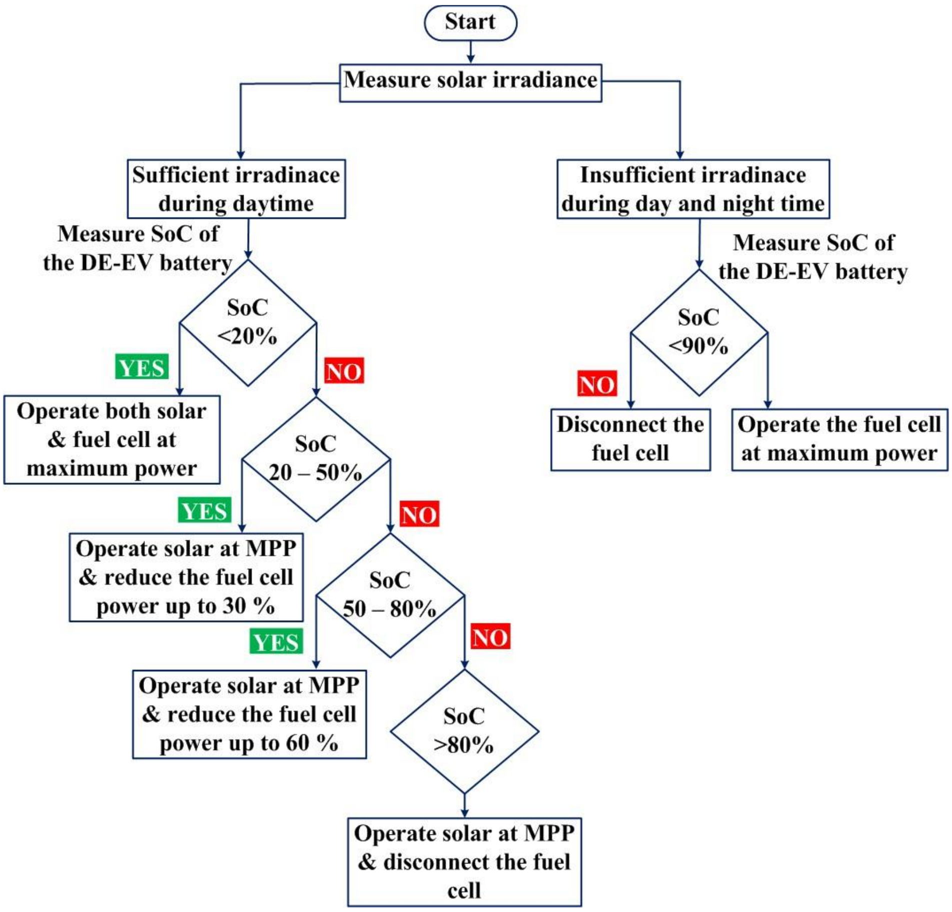

Fig. 2. Flowchart of the proposed algorithm.

Fig. 3. Real-time setup of proposed methodology.

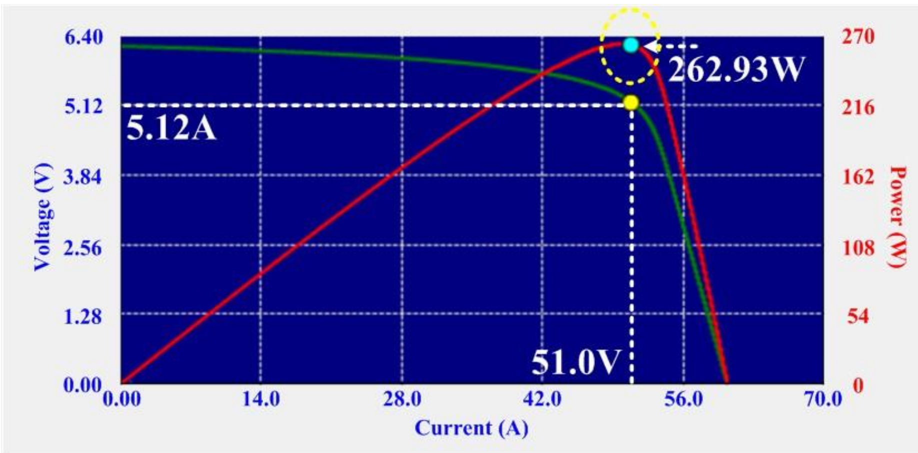

Fig. 4. I-V and P-V curves of SPV system.

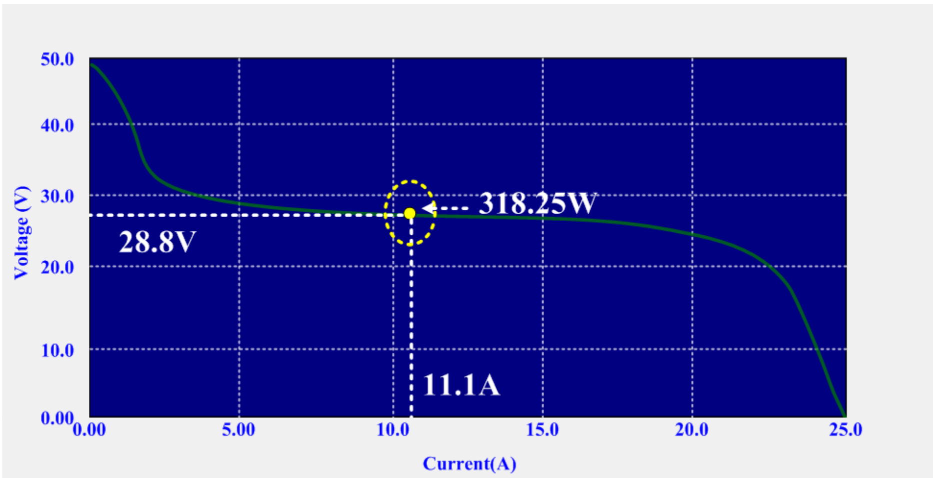

Fig. 5. U-I curve of fuel cell.

A. Sufficient Solar Irradiance During Daytime when the DE-EV is Stationary

Figure 6 illustrates the waveform for power delivery from the DC microgrid to the DE-EV during daytime or under sufficient solar irradiance when the DE-EV is stationary, across the four specified cases. The waveform is divided into four segments, each representing a different operational scenario.

In the first segment, SoC is below 20%, both photovoltaic and fuel cell systems function at their maximum power outputs of 262.93 W and 318.25 W, respectively. At this juncture, the I-V and P-V curves are illustrated in Figure 4, with a maximum power point tracking (MPPT) efficiency of 99.69%, and the U-I curve of the fuel cell is depicted in Figure 5 at its optimal operating power point.

In the second segment, where the SoC ranges between 20% and 50%, the solar panel maintains its peak power operation, whereas the fuel cell's power output is curtailed by approximately 30%, reducing from 318.25 W to 224.89 W, and the current diminishes from 5.91 A to 3.96 A.

In the third segment, with the SoC spanning from 50% to 80%, the solar panel perpetuates its peak power performance. However, the fuel cell's power output is further attenuated by approximately 60%, dropping from 318.25 W to 96.3 W, and the current declines from 5.91 A to 1.78 A.

In the fourth segment, where the SoC exceeds 80%, the solar panel persists in operating at peak power, while the fuel cell's power output is nearly nullified.

B. Insufficient Solar Irradiance During Day or Nighttime when the DE-EV is Stationary

Figure 7 illustrates the waveform for power delivery from the DC microgrid to the DE-EV during nighttime or insufficient irradiance when the DE-EV is stationary. In this condition, where solar PV power is almost zero, the system relies heavily on the fuel cell to maintain power delivery. During these periods, the fuel cell operates at its maximum power capacity of 318.25W to compensate for the lack of solar input. This operational mode is consistent across all conditions, from a SoC of 0% to 90%. The fuel cell's ability to sustain maximum power output ensures a stable and reliable power supply to the DE-EV, despite the absence of solar energy. This highlights the importance of the fuel cell in the energy management strategy of the DC microgrid, particularly during low irradiance conditions.

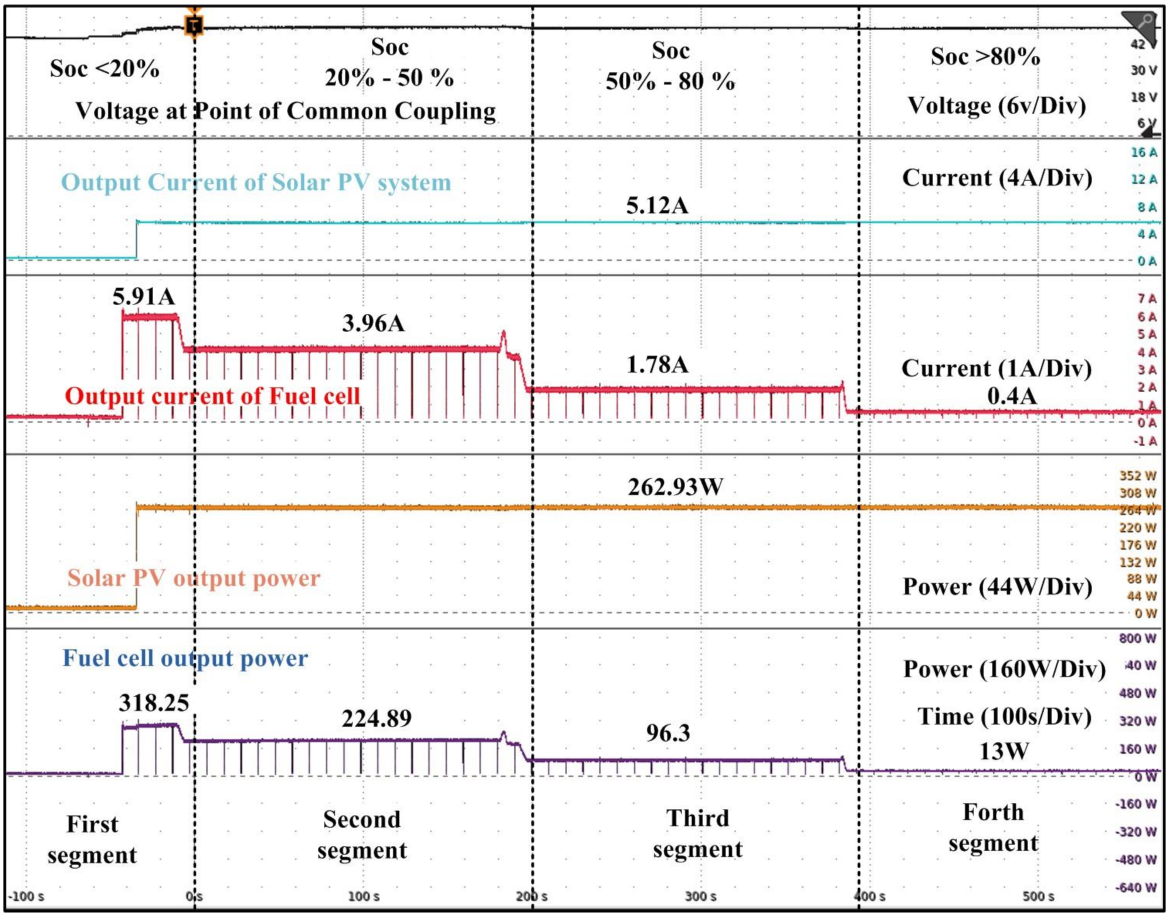

Fig. 6. SPV and fuel cell parameters during sufficient solar irradiance in daytime when the DE-EV is stationary.

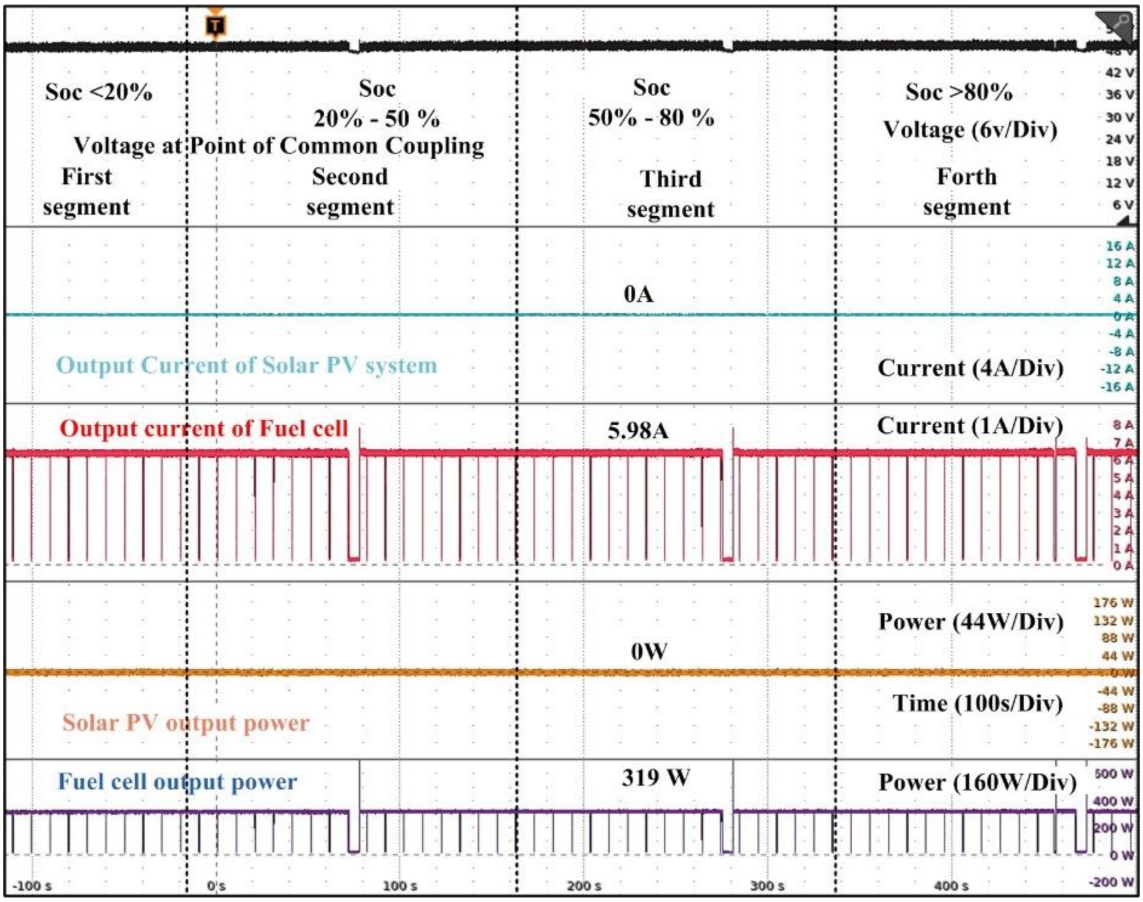

Fig. 7. SPV and fuel cell parameters during insufficient solar irradiance in day/nighttime when the DE-EV is stationary.

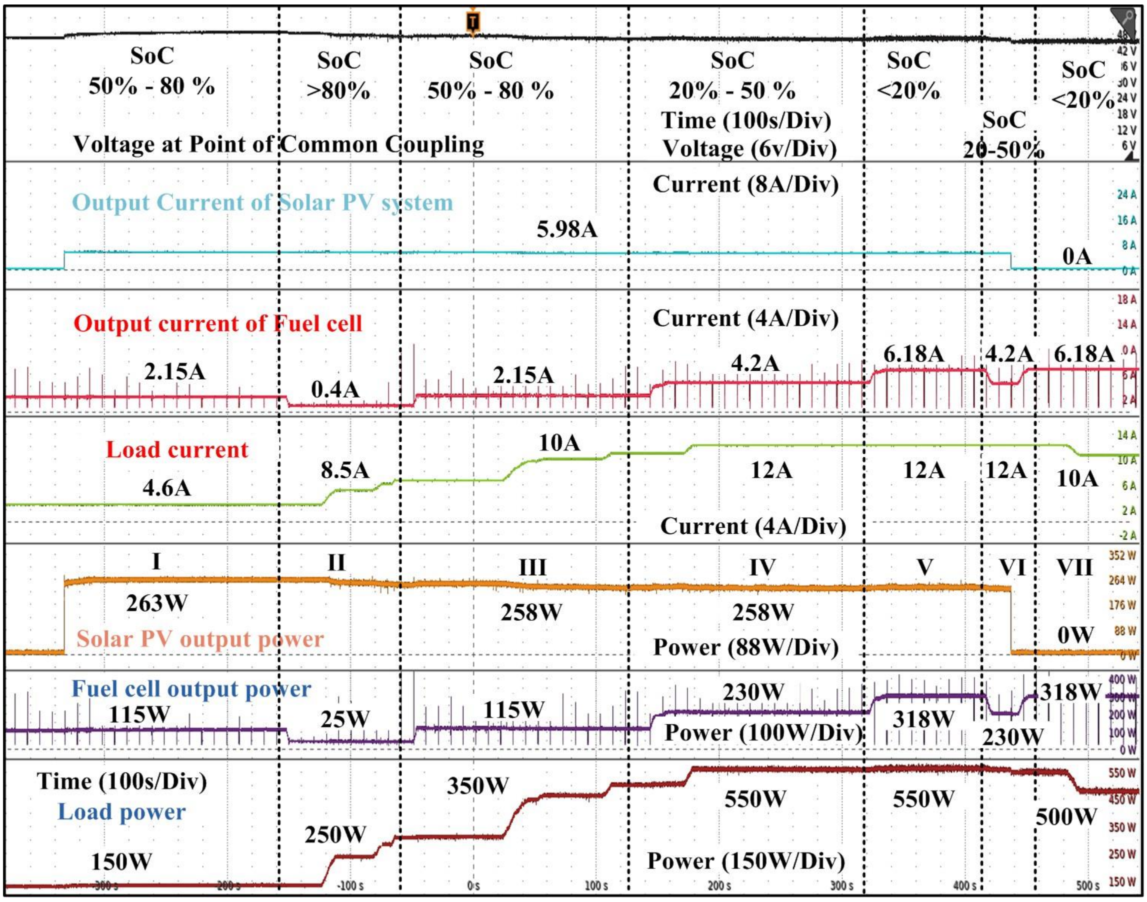

Fig. 8. SPV and fuel cell parameters during day and nighttime when the DE-EV is moving.

C. Load Sharing During Day and Nighttime when the DE-EV is Moving

Figure 8 illustrates the waveform for power delivery from the DC microgrid to the DE-EV during day and nighttime when the DE-EV is moving. The waveform is divided into four segments, each representing a different operational scenario.

In the first and third segments, with the SoC spanning from 50% to 80%, the solar panel perpetuates its peak power performance. However, the fuel cell's power output is further attenuated by approximately 60%, dropping from maximum of 318 W to 115 W, and the current declines from maximum of 6.12 A to 2.15 A.

In the second segment, where the SoC exceeds 80%, the solar panel persists in operating at peak power, while the fuel cell's power output is nearly nullified.

In the fourth and sixth segments, where the SoC ranges between 20% and 50%, the solar panel maintains its peak power operation, whereas the fuel cell's power output is curtailed by approximately 30%, reducing from maximum of 318 W to 230 W, and the current declines from maximum of 6.12 A to 4.2 A.

In the fifth segment, SoC is below 20%, both photovoltaic and fuel cell systems function at their maximum power outputs of 258 W and 318 W, respectively.

In the last segment, SoC is below 20%, and the solar power is almost zero (nighttime) and fuel cell systems function at their maximum power outputs of 318 W.

4. CONCLUSION

The development of DE-EVs marks a significant advancement in sustainable transportation. By integrating hydrogen fuel cells and solar energy, DE-EVs offer a viable path toward net-zero emissions in road freight electrification. Hardware results highlight the potential of DE-EVs to significantly lower environmental impact and reliance on traditional energy sources. However, challenges such as hydrogen storage and infrastructure development remain critical hurdles, necessitating substantial investment in research and development, alongside supportive government policies and incentives. Despite these obstacles, the innovative DE-EV model offers a promising solution for sustainable, next-generation electric mobility, paving the way for a cleaner, more efficient future in transportation:

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