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Dual-Input Dual-Output (DIDO) Converter PV–Battery Interface Converter

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Abstract: *To enhance the reliability and driving range of electric vehicles (EVs), hybrid energy systems combining solar photovoltaic (PV) panels, batteries, and ultra-capacitors have gained prominence as a sustainable solution. This study introduces a novel dual-input, dual-output (DIDO) DC-DC converter designed to efficiently manage power flow between multiple sources, EV loads, and the grid, while also enabling vehicle-to-vehicle (V2V) energy exchange. The converter's key innovation lies in its ten operational modes, achieved through intelligent switching control within a unified circuit topology. Each mode is rigorously analysed using equivalent circuits, waveform illustrations, and derived mathematical models to characterize its dynamic behaviour.The study includes a detailed loss analysis and efficiency evaluation, highlighting the converter's performance under varying conditions. When benchmarked against conventional converters, the proposed DIDO topology demonstrates superior component utilization, adaptability, and operational flexibility, making it a promising solution for next-generation EV power systems.*

Keywords: solar photovoltaic (PV) panels

I. INTRODUCTION

The increasing adoption of electric vehicles (EVs) in recent years is largely attributed to advancements in motor drives and energy storage technologies. Unlike conventional vehicles that rely on internal combustion engines, EVs feature fewer mechanical components and deliver several advantages such as quieter performance, lower maintenance requirements, and significantly reduced environmental impact.

To improve energy availability and extend operational range, modern EVs are being designed to accommodate multiple energy sources. In particular, solar-powered EVs have entered the market in several countries, leveraging photovoltaic (PV) panels as the primary energy source, complemented by batteries for energy storage. Managing such diverse energy inputs necessitates the use of sophisticated power electronic converters, which ensure optimal and efficient power distribution based on varying vehicle demands.

Converter Topologies in EV Systems

A typical EV converter configuration, as depicted in Figure 1, demonstrates the interconnection of energy sources with the drivetrain, auxiliary systems, and external charging interfaces. Conventional approaches often employ separate DC–DC converters at the input and output, linked by a shared DC bus. While effective, this method increases the system's cost, physical footprint, protection requirements, and overall control complexity [1–4].

To address these challenges, researchers have explored integrated multi-input single-output (MISO) converters [5–7]. These systems can continue delivering power even if one source is inactive. However, not all designs accommodate bidirectional power flow, a key requirement for features such as regenerative braking. For example, the converter in [5] lacks this capability, while [6] enables energy transfer using advanced switching techniques but introduces voltage stress through source cascading. The topology in [7] allows for either combined or separate use of energy sources but lacks the functionality to support mutual charging between them.

Expanding to Multi-Input Multi-Output Converters

Alternative designs include single-input multi-output (SIMO) topologies, such as buck [8] and boost [9] converters. More sophisticated architectures fall under the multi-input multi-output (MIMO) category, which are generally distinguished by their use of either single or multiple inductors.

Single-inductor MIMO converters are extensively studied in works like [10–17]. For instance, [10] introduces a buck–boost MIMO converter tailored for PV-battery systems but requires an additional converter to charge the battery when disconnected from the load. Meanwhile, [11] includes battery terminals at both the input and output sides, and [12] regulates output voltage using switches in series with the loads. Yet, the use of series-connected diodes in these designs often restricts power flow to a single direction.

In [13], a single-inductor boost-based converter is proposed, incorporating multiple diodes and capacitors to generate various outputs. However, its use of three capacitors for two outputs leads to a complex, cascaded configuration, which imposes high voltage stress and limits independent output control [13–14]. A similar trade-off appears in [15], which merges battery and fuel cell sources for EVs, supplying both drive and auxiliary systems. The series connection of capacitors in this design raises concerns about overall reliability.

Converter designs like [16] offer DIDO functionality for PV/fuel cell systems, though they suffer from limited output voltage regulation. The system in [17], with three inputs and two outputs, similarly lacks bidirectional power flow capabilities, constraining its versatility.

Multi-Inductor and Resonant Converters

Designs utilizing multiple inductors are covered in [18, 19]. The converter in [18] employs a buck–boost structure that continues power delivery even during source failure but involves a complicated switching arrangement. Meanwhile, the high-gain MIMO design in [19] adds intermediate stages that increase the component count.

Further, [20] introduces a resonant MIMO converter capable of zero-current switching and bidirectional power flow using six inductors and a resonant network. Another complex example, presented in [21], involves 11 switches and four capacitors for PV and fuel cell applications, yet its reliance on switched capacitors—without inductors—makes it unsuitable where precise current control is needed.

Although a wide range of MIMO converter topologies has been developed—including buck, boost, and buck–boost configurations—many are tailored to specific use cases. However, EV applications demand flexible converters that support multiple operating modes, energy regeneration, and efficient power management across various sources and loads.

Proposed D2M2 Converter

To address these evolving needs, this paper proposes a novel Dual Input–Dual Output Multi-Mode (D2M2) DC–DC converter. The D2M2 architecture offers broad operational flexibility, overcoming limitations of previous designs. It enables direct power transfer among energy sources, supports dynamic load management, and operates efficiently across multiple modes. The converter's ability to facilitate energy exchange, support regenerative braking, and manage real-time energy distribution makes it a promising solution for the next generation of multi-source EVs.

Need and Significance

- Efficient Energy Management
- Integration of Renewable Energy (Solar PV)
- Voltage Level Adjustment
- Enhancing Battery Life and Performance
- Significance
- Improved Energy Efficiency
- Enhanced Driving Range
- Fast and Dynamic Response

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- Sustainability and Reduced Carbon Footprint
- Cost-Effectiveness in the Long Run
- Reliable Power Supply for Auxiliary Systems

OBJECTIVES

The main objective of propose methodologies are as follows:

- Efficient power management
- Bidirectional power flow
- Voltage level regulation
- Maximum Power Point Tracking (MPPT)

Innovative Power Converter Architecture for Enhanced Multi-Source Integration in Electric VehiclesThe rise in popularity of electric vehicles (EVs) in recent years is closely linked to advancements in critical technologies such as battery systems and electric drive units. Unlike traditional vehicles powered by internal combustion engines, EVs are mechanically simpler and consist of fewer moving parts. This leads to multiple advantages, including reduced maintenance needs, quieter operation, and a significantly smaller environmental footprint.To ensure reliable and extended energy availability during operation, many modern EVs are being developed to utilize more than one energy source. Solar-powered EVs, for example, have already been launched for public use in various parts of the world. These vehicles generally rely on solar photovoltaic (PV) panels as the primary energy input, while onboard batteries act as storage units to stabilize and support energy delivery.In multi-source systems like these, power electronic converters serve a crucial role. They manage the interaction between energy inputs and ensure the energy is distributed effectively to meet the vehicle's power demand in real time. A general layout of such a converter system, shown in Figure 1, highlights how power sources are connected to components such as the vehicle's propulsion system, auxiliary circuits, and external charging interfaces.Traditional system architectures commonly employ distinct DC–DC converters at both the input and output ends, all linked by a common DC bus. While functional, this structure introduces drawbacks such as increased component count, higher system costs, added complexity in control, and stricter protection requirements [1–4]. To mitigate these issues, integrated multi-input single-output (MISO) DC–DC converters have been proposed in the literature [5–7]. These designs ensure power can continue to be delivered to the load even if one of the energy sources becomes unavailable. However, certain designs, like the one described in [5], do not support bidirectional energy flow, which is essential for capturing energy during regenerative braking. Another approach [6] uses controlled switching strategies for energy transfer but suffers from excessive voltage stress due to the cascaded source configuration. Meanwhile, the system described in [7] enables independent or simultaneous power delivery from the inputs but lacks the ability to allow energy sharing between sources.In addition to MISO systems, single-input, multi-output (SIMO) converters—such as buck [8] and boost [9] types—have been explored. Beyond these, multi-input, multi-output (MIMO) converter topologies have attracted significant interest [10–19]. These MIMO designs are typically categorized by their inductor configurations: (i) those with a single inductor, and (ii) those with multiple inductors.Several single-inductor MIMO designs have been detailed in studies [10–17]. For instance, [10] introduces a buck–boost MIMO converter that integrates PV and battery sources, although an extra converter is required to recharge the battery when it's not powering the load. In [11], the battery is connected across both input and output terminals. The configuration in [12] controls the output voltage using series switches, but diodes in series with the input sources restrict power flow direction.A boost-based MIMO converter using a single inductor is described in [13]. It utilizes multiple capacitors and diodes to create several output levels, but achieving just two outputs demands three capacitors. This setup involves a cascaded arrangement that limits the ability to independently control the outputs and places high stress on the diodes [13–14].The converter in [15] combines a battery and fuel cell, with one output driving the EV's motor and the other powering onboard accessories. However, the use of series-connected capacitors makes the system susceptible to single-point failures. In [16], a dual-input, dual-output converter is proposed for PV/fuel cell microgrid applications. But switch S1, when turned off, causes the inductor to constantly freewheel through the fuel cell, complicating voltage regulation for the second output despite a reduced switch count. A three-input, two-output converter design from [17] does not support bidirectional energy flow, limiting its use in regenerative systems.Designs employing multiple inductors are explored in [18–19]. For example, the buck–boost MIMO system in [18] ensures power continuity during input source failure, though it employs a complex switch matrix. The high-gain configuration described in [19] introduces several intermediate stages, increasing the overall component count and system complexity.Another approach appears in [20], which describes a resonant MIMO converter capable of bidirectional power transfer and zero-current switching. This system utilizes six inductors and a resonant circuit to manage energy flow. In [21], a converter that combines solar PV and fuel cell sources employs 11 switches and four capacitors. However, the lack of inductors and reliance solely on switched capacitors limits its use in applications where current regulation is criticalAlthough a broad range of MIMO converters—based on buck, boost, and buck–boost principles—have been developed, many are restricted by their specialized use cases or limited operational flexibility. Real-world EV systems require more versatile converters that can handle multiple modes of operation, including dynamic power sharing, energy recovery through regenerative braking, and inter-source energy exchange.To meet these demands, this paper introduces a new Dual Input–Dual Output Multi-Mode (D2M2) DC–DC converter. This advanced design enhances system adaptability and performance by allowing power sharing between inputs, dynamic load balancing across outputs, and seamless operation across various modes—all within a single, integrated structure, as represented in Figure 1.

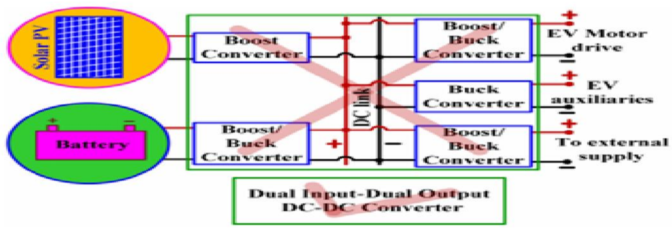

Fig. 1 Block diagram of the conventional and proposed approaches for solar PV/battery/ultra-capacitor powered EV

Figure 2 illustrates the circuit layout of the proposed Dual Input–Dual Output Multi-Mode (D2M2) DC–DC converter. The converter system is divided into three functional segments: the source input section, the motor drive/grid/secondary battery (EV2) interface, and the auxiliary load output section.The source section incorporates two independent input sources, denoted as Vs1V_{s1}Vs1 and Vs2V_{s2}Vs2, which are interconnected in a bridge configuration. This bridge employs two Insulated Gate Bipolar Transistors (IGBTs) without anti-parallel diodes (labelled Ss1S_{s1}Ss1 and Ss12S_{s12}Ss12), two solid-state relays (Rs1R_{s1}Rs1 and Rs2R_{s2}Rs2), and two diodes (DR1D_{R1}DR1 and DR2D_{R2}DR2). Through the strategic switching of the IGBTs, power can be selectively routed from either source independently or from both sources simultaneously. This feature is particularly beneficial for supporting high power demands, such as during rapid acceleration in electric vehicles.The motor drive/grid/EV2 interface provides bidirectional power flow, enabling energy transfer not only from the source to the motor drive, grid, or secondary EV battery but also in reverse, such as during regenerative braking. This segment utilizes two IGBTs with anti-parallel diodes (So1S_{o1}So1 and So1RS_{o1R}So1R) to manage the direction of power flow. A three-way circuit breaker (CB1) is implemented to selectively connect to either the grid, motor drive, or EV2, enhancing the system's adaptability. On the other hand, the auxiliary load section is designed as a unidirectional buck converter dedicated to powering auxiliary components within the EV, such as headlamps, indicators, and infotainment systems. This portion consists of two IGBT switches without anti-parallel diodes (So2S_{o2}So2 and So12S_{o12}So12), along with three diodes (Do2FD}Do2F, Do2s1D{o2s1}Do2s1, and Do2D_{o2}Do2) to guide current flow in the intended direction.In total, the D2M2 architecture incorporates six IGBTs—four without anti-parallel diodes and two with anti-parallel diodes—as well as five diodes to form a versatile and controlled power conversion unit. This configuration allows the converter to function under ten distinct operating modes, each enabling specific energy transfer scenarios based on source availability and load demand.

- SPV drive (PV) mode
- Battery drive (B) mode

- SPV + Battery drive (PVB) mode
- Regenerative braking (RB) mode
- SPV to Battery charging (PV2B) mode
- Grid-Battery interactive (G2B) mode
- Vehicle to Vehicle interactive (V2V) mode

Operating Modes of the Proposed D2M2 Converter

- **PV Mode:** This mode is ideal when the solar photovoltaic (PV) array produces enough power to run the EV motor, typically during low acceleration scenarios. A parallel-connected ultra-capacitor supports this setup by providing short bursts of energy during transient events, such as shading or temporary drops in solar output.
- **Battery (B) Mode:** Battery-only operation is employed when solar PV energy is either unavailable or insufficient. The battery must have an adequate State of Charge (SOC) to ensure it can meet the vehicle's power demand reliably.
- **PV-Battery (PVB) Mode:** During high load conditions—such as vehicle startup or driving uphill—solar PV alone may not suffice. In such cases, both the battery and PV system jointly supply power. The D2M2 converter allows concurrent energy delivery from both sources to meet high torque demands.
- **Regenerative Braking (RB) Mode:** In urban driving conditions, a significant portion of travel involves braking. This mode captures kinetic energy during braking through regenerative mechanisms and stores it back into the battery. Utilizing this mode enhances the vehicle's overall energy efficiency and extends range.
- **PV-to-Battery (PV2B) Mode:** While the vehicle is idle or parked during daylight, solar PV output can be used to charge the battery, preventing energy waste. If solar generation exceeds the battery's charging capacity, the excess energy can be redirected to the grid using the PV2G mode.
- **Grid-to-Battery (G2B) / Battery-to-Grid (B2G) Mode:** Due to the increasing integration of renewables, grid stability is becoming a challenge. EV batteries can support the grid in balancing supply and demand. In this mode, the battery either receives energy from the grid (G2B) or supplies power back to it (B2G), depending on grid conditions. Effective energy management is crucial to ensure optimal battery lifespan and uninterrupted vehicle operation.
- **Vehicle-to-Vehicle (V2V) Mode:** In emergency scenarios, such as a depleted battery or the absence of a nearby charging station, this mode enables energy transfer between two EVs. The D2M2 converter allows direct battery-to-battery interaction, providing charging or discharging capabilities without requiring external chargers.
- **PV-to-Grid (PV2G) Mode:** When the vehicle is not utilizing solar power for charging (i.e., PV2B is inactive), surplus solar energy can be fed into the utility grid. This not only prevents wastage but also creates opportunities for monetary benefits through energy export.
- **Grid-to-Load (G2L) Mode:** If the EV is parked at night and its auxiliary systems (e.g., audio or lighting) are in use, this mode allows these systems to operate using grid power. This prevents draining the battery, ensuring the EV is ready for use the next day.
- **PV-to-Load (PV2L) Mode:** During daytime parking, solar energy can be used to power the vehicle's auxiliary loads directly. This mode can function concurrently with PV2B mode, allowing simultaneous battery charging and auxiliary load operation from solar PV.

Solar Plant simulation

The solar plant subsystem models a photovoltaic (PV) array composed of several parallel-connected strings, each containing multiple solar panels. Each individual panel is represented using the Solar Cell block from the Simscape™ Electrical™ library. The model determines the number of panels per string and the number of parallel strings required based on parameters such as the desired DC bus voltage, solar cell specifications, and targeted output power.

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To maintain efficient simulation performance, especially when scaling up the number of panels, the model avoids detailed simulation of each individual unit. Instead, it assumes uniform irradiance and temperature conditions across the entire array. With this assumption, the Solar Panel subsystem uses controlled voltage and current sources to emulate the behavior of the entire PV array, thus simplifying the computational load without compromising on accuracy for system-level analysis.

Maximum Power Point Tracking (MPPT)

To maximize energy extraction from the PV array under variable environmental conditions, the model implements two MPPT algorithms, encapsulated within variant subsystems. A variant control variable named MPPT governs which strategy is active during simulation. These MPPT methods dynamically adjust the system's operating point to ensure it consistently tracks the maximum power point despite fluctuations in solar irradiance or temperature.

Boost DC–DC Converter

A boost-type DC–DC converter is used to manage power transfer from the PV array to the rest of the system. This converter supports two operational modes:

MPPT Mode – Active when the system is harvesting the maximum possible power from the PV source.

Voltage Regulation Mode – Engaged when the load demand is lower than the available solar generation, maintaining a stable output voltage.

The transition between these two modes is handled dynamically based on real-time comparison of solar generation potential—determined by incident irradiance and panel temperature—against the system's actual power demand.

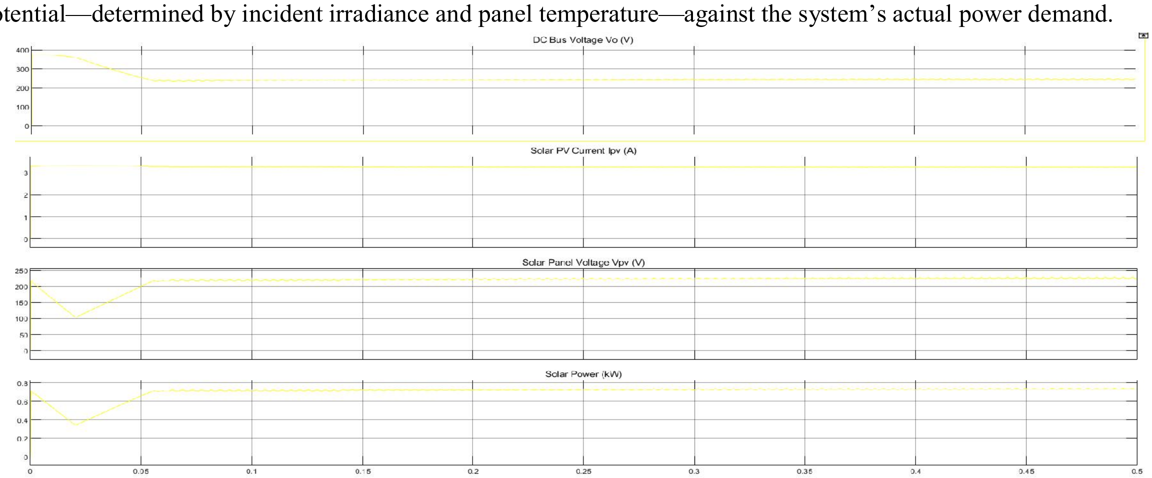

Fig.1 shows the result of DC BUS voltage, Solar PV current

The Figure shows:Startup transient behavior,MPPT controller in action, adjusting PV voltage and current to maximize output.Stable DC bus once control settles.This is typical of a PV-fed DC-DC converter feeding a regulated DC bus. DC Bus Voltage Vo(Top Plot) Solar PV Current Ip {pv} Ipv (Second Plot Solar Panel Voltage Vpv, Vpv (Third Plot), solar Power (Bottom Plot).

II. CONCLUSION

This paper introduces a novel Dual Input–Dual Output (D2M2) DC–DC converter developed specifically for electric vehicle (EV) power systems. The converter enables seamless integration of a hybrid energy setup that includes solar photovoltaic (PV) modules, batteries, and ultra-capacitors, thereby providing a reliable and continuous energy supply for EV operation. Its architecture supports ten distinct operational modes, allowing the system to adapt dynamically to varying conditions such as battery charge level, solar generation, and vehicle load requirements.Using voltage-second balance principles and detailed waveform analysis, the study derives expressions for output voltages across all operational modes, confirming the converter's adaptability and efficiency under diverse conditions. Specifically, it enables operational modes that are not feasible with traditional designs, including PVB (PV to battery), G2L (Grid to load), PV2B (PV to battery with load sharing), V2V (Vehicle-to-vehicle), and B2G (Battery to grid).

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