A REVIEW: BI-DIRECTIONAL DC-DC CONVERTER TOPOLOGIES

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Abstract- Bidirectional DC-DC power converters are increasingly being used in a wide range of applications that require power flow in both forward and reverse directions. These applications encompass various fields such as energy storage systems, uninterruptible power supplies, electric vehicles, and renewable energy systems, among others. The objective of this paper is to meticulously evaluate these converters from both a topological and control scheme perspective. In terms of topology, these converters can be classified into two main categories: non-isolated and isolated configurations. The non-isolated category is further divided into eight distinct groups, each accompanied by their respective schematics and a summary table. Similarly, the isolated configuration category is also divided into eight groups, each with their own schematics and summary table. This comprehensive categorization provides a comprehensive overview of the various converter topologies. In summary, this paper provides a comprehensive review of bidirectional DC-DC power converters, focusing on their topologies. By categorizing the converters into non-isolated and isolated configurations, and thoroughly analyzing their respective schematics and summary tables, the paper offers a holistic understanding of the subject matter.

Keywords: Converters, Bidirectional Power Flow, DC-DC Power Converters.

1. INTRODUCTION

The realm of research in power electronics has witnessed a significant growth in the study of bidirectional power converters [1-3]. Unlike conventional unidirectional converters, bidirectional converters allow power to flow in both directions. This flexibility has made them widely used in various applications such as electric vehicles (EVs) or hybrid electric vehicles (HEVs), smart grids, uninterruptible power supplies (UPS), aerospace applications, and renewable energy systems including photovoltaic (PV) arrays, fuel cells (FCs), and wind turbines [4-5]. By serving as an interface between power sources and energy storage elements, bidirectional configurations not only reduce the size of the system but also enhance its efficiency and performance by eliminating the need for separate converters for forward and reverse power flow [6-7]. Fig 1.1 illustrates the general structure of bidirectional DC-DC converters [8]. Depending on the location of the energy storage system, the converter can function as a buck or boost type, with the respective control system regulating the voltage or current of the system.

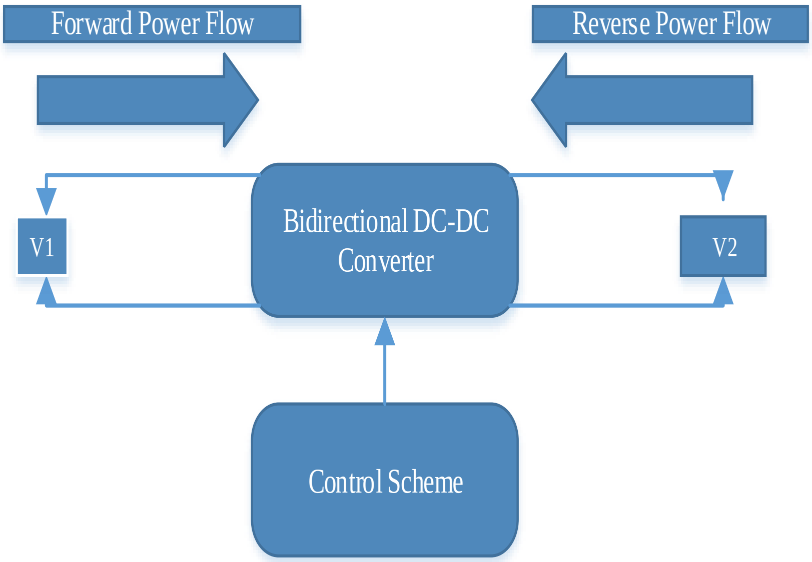

Fig. 1.1 Fundamental Structure of bidirectional DC-DC Converter

The unique features of bidirectional converters make them suitable for systems that require current to be supplied in both directions depending on the operating mode [57-60]. To initiate, accelerate, or facilitate uphill driving, additional power is required to boost the high voltage bus [9]. This additional power can be obtained from the auxiliary battery of a bidirectional DC-DC converter, which supplies peak current from the battery during motor startup. Unlike unidirectional topologies, bidirectional converters are capable of reversing the direction of current flow and power. In this case, the auxiliary energy storage battery absorbs the regenerative energy fed back by the electric motor during deceleration [10-11].

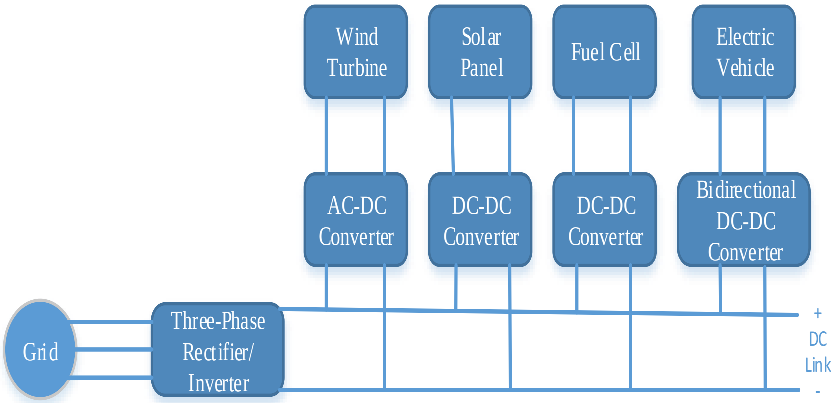

Fig. 1.2 The layout of the bidirectional DC-DC converter in PHEV Charging Station

Furthermore, bidirectional DC-DC converters find utility in smart grids and plug-in hybrid electric vehicle (PHEV) charge stations, as depicted in Fig. 1.2. In the vehicle-to-grid (V2G) architecture, bidirectional DC-DC converters facilitate charging the vehicles from the grid side and feeding back the energy stored in PHEV batteries to the grid when required [61-66]. Hence, the development of bidirectional DC-DC converters with low cost, high efficiency, and high reliability is crucial for the effective functioning of charging stations [12-14].

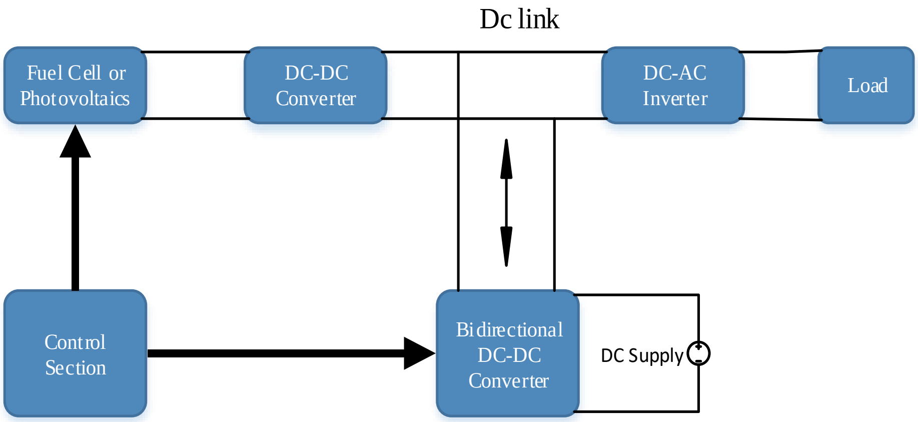

Fig. 1.3 The layout of the bidirectional DC-DC converter for FC and PV

It is worth noting that the application of bidirectional power converters is not limited to electric vehicles. Figure 1.3 demonstrates another application of these converters within the broad domain of renewable energy systems, such as FC or PV-based systems that supply either DC load or AC load via an inverter [15]. In order to combine these energy sources effectively, a multi-input version of a unidirectional DC-DC converter can be employed to regulate the output DC voltage. The bidirectional DC-DC converter plays a vital role in processing power from batteries to the load during transient and overload conditions in the forward mode, while also charging the battery pack in the reverse mode. Therefore, due to their versatility and widespread use in electrical systems, the study and development of bidirectional power converters hold great importance in the field of power electronics. This paper aims to undertake a comprehensive examination of the bidirectional converters, exploring them from various angles and perspectives, delving into the intricacies and nuances of their functioning. In order to achieve this, the paper is meticulously organized in a manner that fosters clarity and logical progression of ideas. Section 2, which forms a pivotal part of this paper, delves into the topology perspective of bidirectional DC-DC converters, presenting a systematic classification that serves as a foundation for further analysis. Within this framework, these converters are effectively segregated into two distinct categories, namely the isolated and non-isolated converters. In order to facilitate a comprehensive understanding of these categories, the paper goes above and beyond by providing detailed explanations, accompanied by visually appealing layouts and tables of comparisons that serve as valuable aids for comprehension and analysis.

2. TOPOLOGIES AND CLASSIFICATION OF BI-DIRECTIONAL DC-DC CONVERTERS

The bi-directional DC-DC converters (BBDC) classified into two configurations, namely are Isolated and Non-isolated bi-directional DC-DC converter. In Non-isolated DC-DC converter topologies the power transfer in both directions without magnetic isolation. So without using of transformer, it has lack of galvanic isolation such as high step up voltage gain ratio. It has a simple configuration, less weight and also do not suffer as a magnetic interference.

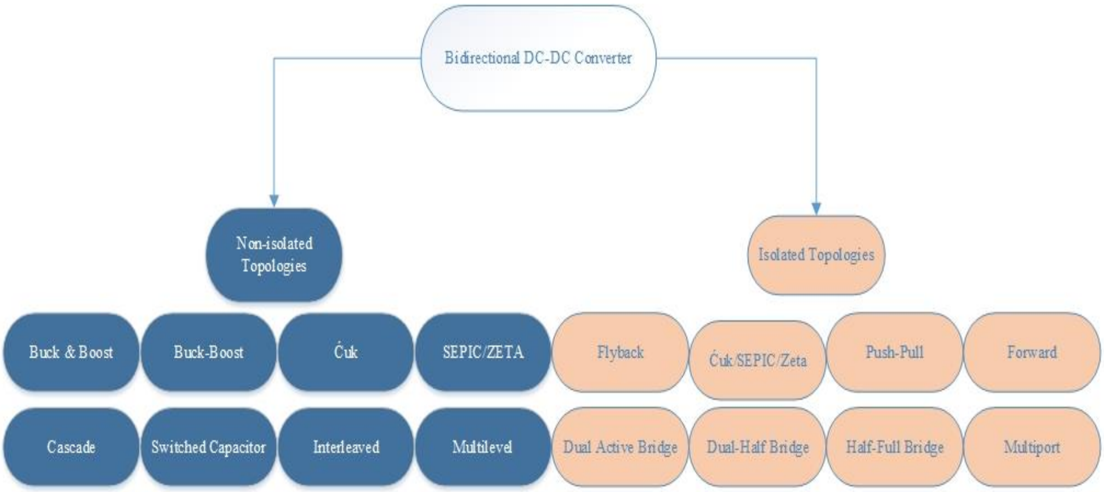

Fig. 2.1 Bi-directional DC-DC converter topologies

In isolated DC-DC converter topologies the power can be transfer in both directions with a magnetic isolation. By using high frequency transformer, it converts DC voltage to AC voltage then converts AC voltage to DC voltage by using rectifier circuit. Voltage gain ratio of isolated topologies are more as compared to non-isolated topologies. But the major concern in this topologies are design a transformer, alleviating the leakage inductance and voltage spikes on input side of the transformer.

2.1 Non-Isolated Bi-Directional DC-DC Converter Topologies

The non-isolated bidirectional DC–DC converter has a fundamental topology of buck and boost converter coupled in anti-parallel connection. This topology enables power transfer in both directions. Several configurations are presented by the researchers of non-isolated bidirectional DC–DC converters such as buck, boost, buck-boost, ĆUK, sepic etc. There are more configurations are there of non-isolated converters on the basis of voltage boosting technique such as switched capacitor, interleaved multilevel etc. So non-isolated bidirectional DC–DC converters are configured into eight groups are below.

2.2 Non-Isolated Buck and Boost Derived Bi-Directional DC-DC Converter

The fundamental BDDC was configured based on buck and boost converter by adding power switch. In other words, traditional buck and boost converter has unidirectional switch which was replaced by power switches [12]. So this converter works as a boost mode from V_L to V_H and buck mode from V_H to V_L.

2.3 Non-Isolated Buck-Boost Derived Bi-Directional DC-DC Converter

Based on the similar fundamental method that was used to develop a unidirectional converter to the bidirectional converter, the bidirectional buck-boost converter may be derived [13], i.e. using a bidirectional power switch instead of any unidirectional power switch in its topology. Buck-Boost converter have benefits to power flow in both directions also ability to buck or boost the negative voltage level.

2.4 Non-Isolated ĆUK Derived Bi-Directional DC-DC Converter

In this topology main advantage is continuity of input current and output voltage, by using two bidirectional power switches in the position of the power switch and diode of the original circuit of BDDC. To eliminate input-output current ripple of the converter coupled inductor is used in basic topology of ĆUK derived BDDC [14-16].

2.5 Non-Isolated Sepic and Zeta Derived Bi-Directional DC-DC Converter

By rearrangement of ĆUK converter elements (capacitor, switches & inductor) Single-ended primary-inductor (SEPIC) and Zeta converter are realized with a positive voltage output [17]. When power flows from high voltage to low voltage then then converter act as a Zeta and act as a SEPIC converter when power flow low voltage to high voltage [18].

2.6 Cascade Bi-Directional DC-DC Converter

This topology finds the EVs system application with two buck-boost bidirectional converter connected back to back. By using this converter output side current stress is reduced and boost the voltage in circuit [19]. Number of passive element increases in this converter as compare to traditional buck-boost bidirectional converter [20].

2.7 Switched–Capacitor Bi-Directional DC-DC Converter

To increase a voltage boosting ability and voltage conversion ratio switched-capacitor is used in a converter [21]. Using this technique involved in a converter weight of converter is reduced and also achieve continuous current. But switching frequency current ripple appears [22].

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2.8 Interleaved Bi-Directional DC-DC Converter

Interleaved technique remove switching frequency current ripple problem from the circuit which was appears in switched-capacitor based bidirectional converter [23-26]. Electromagnetic interference also cancelled in this type of converter. To increase a fast dynamic performance of the converter pattern of switch are changed. Due to inductor current ripple removed in circuit so transient response is increased.

2.9 Multilevel Bi-Directional DC-DC Converter

This topology mostly used in electrical vehicle battery charging application where two voltage bridges are used. This converter weight is low because of no inductor used. This converter obtain a high voltage gain also [28].

Table-2.1 Analysis of non-isolated bi-directional dc-dc Converter

Topology	V_H/V_L	Inductors	Capacitors	Switches
Basic buck & boost	$1/1-D$	1	2	2
Buck-boost	$-D/1-D$	2	2	2
Ćuk	$-D/1-D$	2	3	4
SEPIC/Zeta	$D/1-D$	2	3	2
Cascade	$1/1-D$	1	2	4
Switched capacitor	2	0	3	4
Interleaved	$1/1-D$	$n=2$	2	$2n=4$
Multilevel	$n=3$	0	$n(n+1)/2=6$	$n(n+1)=12$

3. ISOLATED BI-DIRECTIONAL DC-DC CONVERTER TOPOLOGIES

An isolated bidirectional DC-DC converter is a power electronic device that can transfer power bidirectionally between two DC voltage sources while providing electrical isolation between them. This isolation ensures that there is no direct electrical connection between the input and output circuits, providing safety and allowing for different ground potentials between the input and output sides.

These converters are used in various applications where bidirectional power transfer with isolation is required.

3.1 Energy Storage Systems

In applications like battery energy storage systems (BESS) or supercapacitor energy storage systems, isolated bidirectional converters enable efficient power transfer between the energy storage device and the load or grid.

3.2 Hybrid and Electric Vehicles

Isolated bidirectional converters play a crucial role in electric and hybrid vehicle systems by managing power flow between the traction battery and the vehicle's electrical system, including the motor drive and auxiliary systems.

3.3 Renewable Energy Integration

In renewable energy systems like solar or wind power installations, these converters enable bidirectional power flow between the renewable energy source (e.g., solar panels or wind turbines) and the grid, while providing isolation to ensure safety and compatibility with grid standards.

3.4 Grid-Connected Applications

Isolated bidirectional converters can be used in grid-tied applications such as microgrids or distributed energy resources (DERs) to facilitate bidirectional power flow between the grid and local energy sources or storage systems.

The design of isolated bidirectional DC-DC converters typically involves transformers to achieve galvanic isolation between the input and output circuits. Topologies commonly used for isolated bidirectional converters include full-bridge, half-bridge, and flyback configurations. These converters often employ advanced control techniques, such as phase-shift modulation or resonant control, to regulate the voltage and current while maintaining high efficiency and reliability.

Overall, isolated bidirectional DC-DC converters are essential components in modern power systems, enabling efficient and safe bidirectional power transfer across various applications while ensuring electrical isolation between different voltage domains.

4. ISOLATED BUCK-BOOST BIDIRECTIONAL DC-DC CONVERTER (FLYBACK BIDIRECTIONAL CONVERTER)

To obtain a higher voltage gain without isolation, there are several ways to improve the buck-boost converter's voltage boost capability. However, when the buck-boost converter's inductor is swapped out for a transformer, the well-known Flyback converter is made possible in the event that the magnetic isolation condition is met. [29-31].

4.1 Isolated ĆUK & Sepic/Zeta Bidirectional Dc-Dc Converter

To add the advantages of magnetic isolation to the first iteration, an isolated bidirectional Ćuk converter was created based on the non-isolated bidirectional Ćuk converter [29]. It has a continuous input/output current and isolates the input and output sides with a high voltage gain ratio that takes the transformer's turn ratio into account [32]. It is strongly advised in renewable energy systems to couple the input and output inductor to eliminate input and output current ripples. An isolated version of the bidirectional SEPIC/Zeta converters was created using the same theory [33].

4.2 Push-Pull Bidirectional DC-DC Converter

To allow electricity to flow in both directions, a bidirectional push-pull converter was proposed as an alternative to the unidirectional push-pull converter. Similar to push-pull converters that operate in a single direction, bidirectional [28]. A multi-winding transformer is used by push-pull converters to convert power[34].

4.3 Forward Bidirectional DC-DC Converter

A bidirectional forward converter was introduced as an alternative to the unidirectional forward converter. This converter utilizes a clamped circuit to enable zero voltage switching [35]. Further exploration of bidirectional forward DC-DC converters was conducted, where the transformer leakage inductance was leveraged as the resonant inductor to propose a resonant version of the converter [36]. Various hybrid configurations of isolated topologies have been documented in the literature, tailored to specific applications and requirements. Examples include Forward-Flyback, Push-pull-Forward, and Flyback-Push-pull [37]. These configurations involve deriving the primary side of the transformer from one isolated topology and the secondary side from another, which could be either current-fed or voltage-fed [38-39].

4.4 Dual Active Bridge (DAB) Bidirectional DC-DC Converter

One of the most commonly used methods involves utilizing bidirectional topologies that are isolated by a high-frequency transformer [40]. These converters can be either voltage-fed or current-fed, half-bridge or full-bridge. The DAB converter, utilizes two full-bridge topologies on both sides of the transformer. The power transmission of bidirectional converters is directly related to the number of switches [41]. Therefore, having eight power switches in this configuration, along with galvanic isolation, makes it suitable for high-power applications with a high voltage gain ratio, such as automotive systems [42]. Concerns regarding the loss of a high number of switches can be addressed by using low-loss silicon carbide (SiC) or gallium nitride (GaN) power switches. The energy transfer of this converter is regulated by adjusting the phase shift between the AC voltage waveforms of the transformer's primary and secondary windings [43-44]. Efficient control schemes can lead to optimization of efficiency, emphasizing the importance of studying control schemes for this converter [45].

4.5 Dual Half Bridge Bidirectional DC-DC Converter

In contrast to DAB, the half-bridge topology can be advantageous for lower power applications, allowing for a reduction in the number of power switches from eight to four [46-48]. This bidirectional isolated converter that utilizes voltage-fed half-bridge topologies on both sides of the transformer. By eliminating the need for an inductor in the topology, the converter exhibits no right half-plane zero (RHPZ), resulting in a minimum-phase behaviour that simplifies the controller design process [49]. This converter is based on the dual half-bridge converter proposed in employing a current-fed half-bridge topology on the primary side and a voltage-fed half-bridge topology on the secondary side of the transformer. As anticipated, the dual-half bridge converter also has a variant that employs a voltage-fed topology on the primary side and a current-fed topology on the secondary side of the transformer. The use of a current-fed topology allows for a continuous current waveform, which may be desirable in certain applications. Further research has been conducted on dual-half bridge converters, including the interleaved dual half-bridge topology, which aims to enhance voltage boost capability and reduce transformer ratio and current stress [50].

4.6 Half Bridge-Full Bridge Bidirectional DC-DC Converter

In the context of DAB, a UPS design was proposed that utilizes an isolated bidirectional DC-DC converter [51]. This converter employs a voltage-fed half-bridge topology on the primary side and a voltage-fed full-bridge topology on the secondary side of the transformer [52]. Compared to DAB, this design requires simpler control requirements due to its reduced number of switches. Specifically, it is well-suited for integrating a two-switch buck-boost converter on the half-bridge side to achieve a complete UPS topology. There have been other variations of this configuration, such as the full-bridge half-bridge bidirectional DC-DC converter, which has been combined with impedance networks to enhance its performance [53].

4.7 Multiport Dab Bidirectional DC-DC Converter

The integration of multiple input voltage sources in renewable energy systems and hybrid electric vehicles can be effectively achieved by using multi-input converters. In a study conducted, a bidirectional DC-DC converter based on DAB and utilizing a multi-winding transformer was proposed. In the field of multiport converters, the control of power flow and the utilization of duty cycle control play a crucial role in optimizing system behavior [54-56].

Table-4.1 Analysis of isolated bi-directional dc-dc Converter

Topology	V_H/V_L	Inductors	Capacitors	Switches	Windings
Fly back	$ND/1-D$	0	2	2	2
Ćuk	$ND/1-D$	2	4	2	2
Push-pull	ND	1	1	4	4
Forward	ND	1	1	3	3
DAB	Differs W.R.T to method of control	0	2	8	2
Dual Half-bridge	Differs W.R.T to method of control	0	6	4	2
Half-full Bridge	Differs W.R.T to method of control	0	4	6	2
Multiport DAB	Differs W.R.T to method of control	0	$n=3$	$4n=12$	$n=3$

CONCLUSION

Bidirectional DC-DC converters can be explored and investigated from a multitude of perspectives, delving into the intricate intricacies and complexities that lie within their design and operation. This paper sets forth an all-encompassing and comprehensive review, shedding light on the multifaceted nature of these converters, examining not only their topological structure. At their core, the fundamental bidirectional converters manifest themselves as non-isolated topologies, a manifestation that materializes through the simple act of substituting the unidirectional switches of the basic converter with a bidirectional switch. However, the introduction of galvanic isolation injects an additional degree of freedom into the equation, bestowing upon the converter the transformative power of the transformer turn ratio, enabling it to achieve unparalleled voltage boost capabilities. Moreover, this isolation also brings with it the invaluable gift of separating the input-output side, opening up a realm of possibilities for the introduction of multi-input versions of these converters, a feat that was previously unattainable. Among the vast array of bidirectional converters, one particular configuration stands out as the most popular choice, leveraging the prowess of two full-bridge topologies strategically positioned on either side of the transformer. This configuration, known as the DAB converter, has garnered immense popularity and acclaim, proving to be particularly well-suited for high-power applications, where its unparalleled performance shines through. From a circuit topology standpoint, the current research focus for bidirectional converters, much like its counterparts in the realm of DC-DC converters, revolves around the perpetual quest to minimize weight, volume, losses, and cost while simultaneously maximizing reliability and power density. To this end, an arsenal of various techniques has been harnessed and employed, each meticulously crafted to propel the converters towards the pinnacle of efficiency. These techniques span a wide spectrum, ranging from augmenting the voltage boost capabilities of the converter to introducing innovative multi-cell topologies, all the way to harnessing the power of advanced solid-state semiconductors, such as GaN, unlocking new frontiers of performance. As if this weren't enough, bidirectional converters have also become the focal point of ground breaking research in the realm of wireless power transfer, specifically within the realm of charger applications that span the gamut from low power to high power ranges. This burgeoning field of study holds immense promise, with researchers dedicating their time and expertise to unravelling the mysteries that lie within, seeking to revolutionize the way power is transferred wirelessly, paving the way for a future where the constraints of traditional wired charging become a thing of the past. To summarize, the exploration of bidirectional DC-DC converters is a journey through the annals of engineering marvels, where the intricacies of their topological structure and control schemes intertwine to create a symphony of efficiency and performance. With each passing day, researchers push the boundaries of what is possible, utilizing innovative techniques and cutting-edge technologies to unlock the true potential of these converters, all while laying the groundwork for a wireless charging revolution that promises to reshape the way we power our devices.

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