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Battery-ultracapacitor hybrid system for electric vehicles using new bidirectional quadratic DC-DC converter

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ABSTRACT

Hybrid energy storage system is used with the objective of taking advantage of the best characteristics of each device, creating a system that is superior, than any of the devices used alone. Due to operational requirements of distributed generation systems, energy storage devices like batteries and super-capacitors, need bidirectional DC-DC converters to allow charge or discharge according to with the necessary conditions. A new battery-ultracapacitor hybrid energy storage system is proposed for electric vehicles. The main objectives of using ultra-capacitors in alongside batteries are: improving performance, increase the system efficiency and extend the battery life. In many applications, conventional bidirectional converters are inadequate since the specified range of input voltages and the specified range of output voltages call for an extremely large range of conversion ratios. A new bidirectional quadratic converter with high voltage gain in both step-down and step-up operation modes is used along with the ultra-capacitor. This converter is also characterized by a simple control technique since it is only necessary to control one power semiconductor for each mode. The additional power semiconductors remain always on or always off. In this project, an Ultra Capacitor is integrated with the battery in an Electric Vehicle using the new bidirectional quadratic buck-boost converter to improve the dynamic performance of the vehicle system and enhancing the battery life. The system model and the implemented control strategy has been simulated in MATLAB/SIMULINK software. The hardware of the proposed system is made. The control strategy is implemented using TMS320F28027.

Keywords: *Ultra-capacitor(UC), Energy storage systems (ESS), Electric vehicles.*

1. INTRODUCTION

The role of Energy Storage Devices (ESDs) in modern technology is increasing as renewable and sustainable energy sources are widely used. Such devices are considered as one of the key technologies for emerging markets as the use of more renewable energy sources, in order to minimize fossil fuel consumption and appropriate integration of clean energy sources in the grid and off-grid applications. Undesirably the coating nature of most renewable energy facilities, such as solar and wind, makes them unsuitable for standalone operation since they are strongly affected by weather conditions, causing energy variations and stability problems in the power network.

Energy storage systems (ESS) have been a major research area in electric, hybrid electric, and plug-in hybrid electric vehicles for a long time. Of all the energy storage devices, the battery is one of the most widely used. However, using the battery as the sole energy storage system has several disadvantages. In order to approach the performance of a conventional car, the energy storage system of a hybrid or electric vehicle shall have an equivalent or similar power capability as a gasoline engine. Unfortunately, most available batteries have relatively low power density. Although there are high power density batteries available, the price is much higher; also with the increased power density, the thermal management of the battery will be a challenge. The life of the battery is another major area of concern. In advanced automotive applications, because the load profile varies rapidly according to the road conditions and the driver's behavior, the energy storage system suffers from random charges (regenerative braking) and discharges (acceleration command), which have a negative effect on the life of the battery.

To solve the problems listed above, hybrid energy storage systems (HESS) have been proposed by many researchers. The basic idea of a HESS is to combine ultra-capacitors (UC) and batteries to achieve a better overall performance. This is because, compared to batteries, ultra-capacitors have a high power density but low energy density.

Hybrid energy storage system of electric vehicles (EVs) has great potential to take full advantages of high power density with super-capacitor and high energy density with battery to improve the dynamic performance and energy efficiency of electric vehicles. In this project, a Super/ Ultra Capacitor is integrated with the battery in an Electric Vehicle using a New Bidirectional DC-DC Converter [1] to improve the dynamic performance of the vehicle system and enhancing the battery life.

2. PROPOSED BATTERY-UC HYBRID SYSTEM FOR ELECTRIC VEHICLES

Fig.1 presents the Battery-Ultracapacitor hybrid system for an electric vehicle. There are two input sources, two bidirectional DC-DC converters, a dc bus and finally the PMDC motor. The project is focused on the New Quadratic Bidirectional DC-DC converter [1]. The main objectives of using ultracapacitors alongside batteries are: improving performance (i.e., acceleration), increase the system efficiency (through the use of regenerative braking) and extend the battery life. The system uses a 24V battery and a 5.4V ultra-capacitor. The DC bus is rated to a voltage value of 24V.

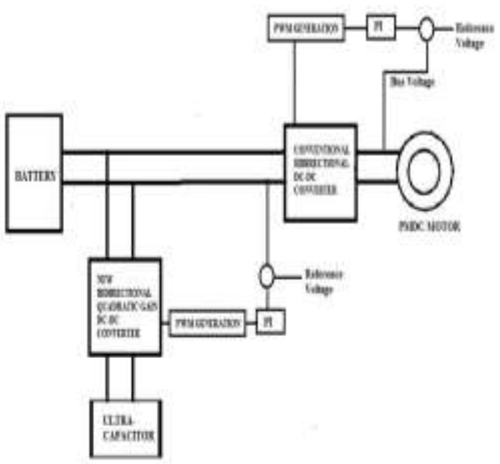

Fig 1: Block Diagram of proposed battery-ultracapacitor hybrid system

The conventional bidirectional DC-DC converter in addition to performing bidirectional buck-boost also facilitates speed control of the PMDC motor by varying the armature voltage. Because batteries have a high energy density, but limited power density, are capable of supplying the main power to drive the motor; however is not able to supply peaks of power in short time periods. Moreover, ultracapacitors (UC) have a low energy density but high power density. Therefore, by combining these two devices an efficient, light, and high-performance vehicle can be obtained. By means of this combination, it is possible to use a smaller battery with less peak-output power capability. The ultra-capacitor/battery configuration is the most studied and researched Hybrid Energy Storage Systems (HESS). By using the new quadratic bi-directional DC-DC converter to interface the UC, the voltage of UC can be used in a wide range. In addition, the use of the new quadratic bidirectional DC-DC converter facilitates high voltage gain eliminating the need of costly UC bank. Thus ultra capacitors with low voltage rating can be used instead of UC banks. The conventional bidirectional DC-DC converter in addition to performing bidirectional buck-boost also facilitates speed control of the PMDC motor by varying the armature voltage.

2.1 New Bidirectional Quadratic DC-DC converter

The project is focused on the New Quadratic Bidirectional DC-DC converter [1]. New Quadratic Bidirectional DC-DC converter with quadratic DC conversion ratio offers a wider conversion range, continuous input and output current (depending on the operational mode). This converter is also characterized by a simple control technique since it is only necessary to control one power semiconductor for each operational mode. The additional power semiconductors remain always on or always off. The high gain of this converter can be used to boost the ultra-capacitor voltage and supply the motor load and also buck and store the energy during regenerative braking. Circuit configuration of the New DC-DC Converter with Quadratic Gain and Bidirectional Capability, which consists of four power switches (S1, S2, S3 and S4), two diodes (D1 and D2), two inductors (L1 and L2), two capacitors (C1) and one resistive load (R) is shown in Fig.2.

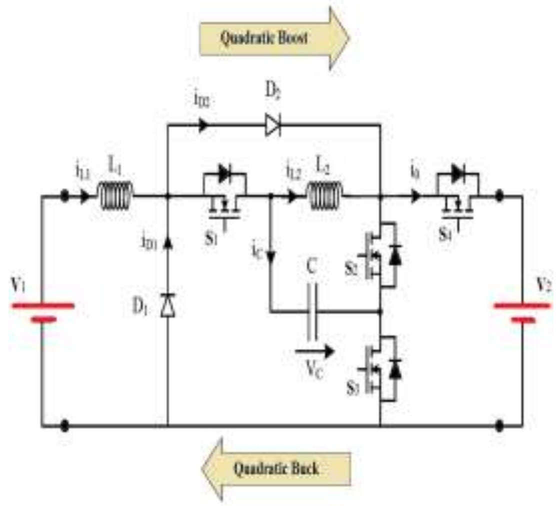

Fig. 2: Circuit diagram of New Bidirectional Quadratic DC-DC Converter

There are two modes, that is, boost mode and buck mode, in the New Bidirectional DC-DC Converter when it operates in CCM operation.

To simplify this analysis it is assumed that the proposed converter is operating in steady-state, continuous conduction mode (CCM), ideal components and in discharge power mode, transferring the energy from the storage device (V_1) to the load (V_2). It is also assumed that capacitor C is large enough and the voltage across it can be considered constant in one switching period (T_S). In boost mode, switches S1 and S4 are always turned-off and the switch S3 is always turned-on avoiding additional switching losses. Switch S2 is the single semiconductor responsible for energy transfer through duty cycle switching, D, in this operation mode (Fig 3).

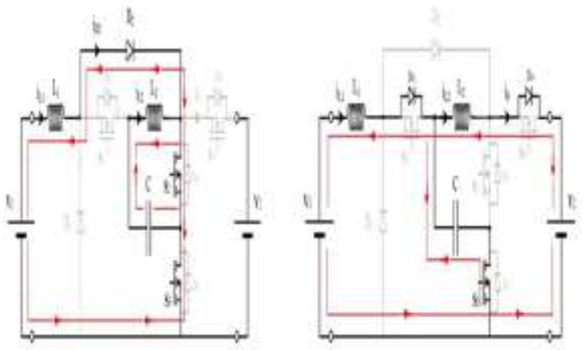

Fig 3: Boost mode (a) S2 ON (b) S2 OFF

The operation of the converter in Buck mode is characterized by the energy transfer from the load to the storage device. Similar to the previous operation mode, only a single transistor controls the output voltage through duty cycle switching. In this case, the switch S1 is responsible for this operation. Thus, the transistors S2 and S3 are now always turned-off and transistor S4 is always turned-on (fig.4).

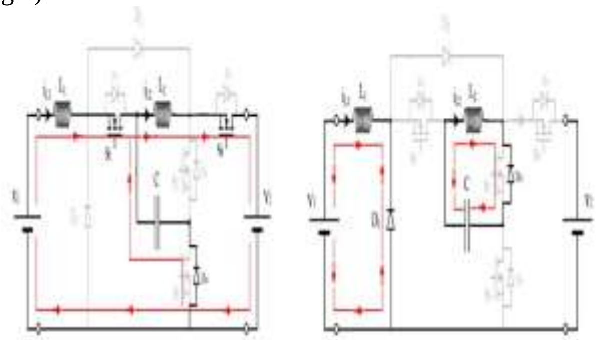

Fig 4: Buck mode (a) S1 ON (b) S1 OFF

2.2 Conventional Bidirectional DC-DC Converter

The conventional bidirectional DC-DC converter forms an important part in the proposed battery-ultracapacitor hybrid system. In addition to performing the bidirectional buck-boost operation, this converter also facilitates speed control of the PMDC motor by varying the armature voltage.

Basic DC-DC converters such as buck and boost converters (and their derivatives) do not have bidirectional power flow capability. This limitation is due to the presence of diodes in their structure which prevents reverse current flow. In general, a unidirectional DC-DC converter can be turned into a bidirectional converter by replacing the diodes with a controllable switch in its structure.

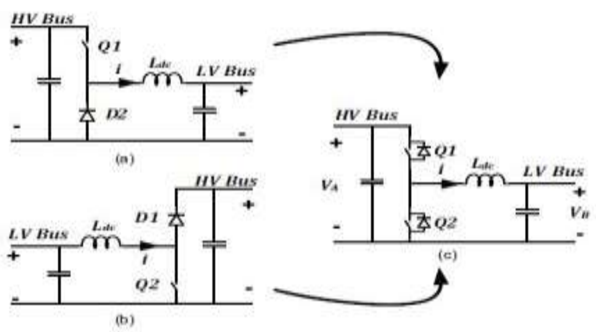

Fig 5: (a) Elementary unidirectional buck converter, (b) elementary unidirectional boost converter and (c) transformation to conventional bidirectional converter by substituting diodes with a controllable switch

Fig.5 shows the structure of elementary buck and boost converters and how they can be transformed into bidirectional converters by replacing the diodes in their structure. It is noteworthy that the resulted converter has the same structure in both cases.

In the buck mode of operation, i.e. when the power is transferred from the high voltage (HV) to the low voltage (LV) side, Q1 is the active switch while Q2 is kept off. In the boost mode, i.e. when the power is transferred from LV to HV side, Q2 acts as a controlled switch and Q1is kept off.

3. SIMULATION AND RESULTS

The system model and the implemented control strategy has been simulated in the MATLAB/ Simulink as shown in Fig.6. The main components in the system model are a new bidirectional quadratic DC-DC converter, a conventional bidirectional DC-DC converter, two sources (battery and UC) and finally the PMDC motor. Various parameters that are considered for the simulation has been given in Table 1 and Table 2.

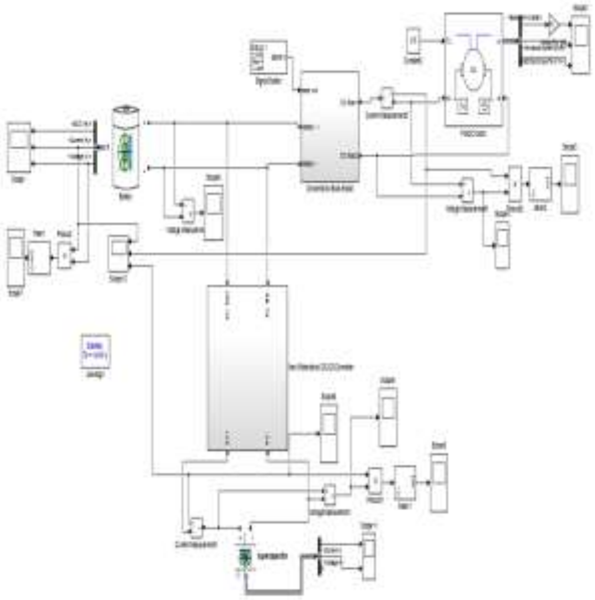

Fig 6: Simulation of UC-Battery Hybrid

Table -1: Simulation parameters used in new bidirectional quadratic converter

Sl. No.	Parameters	Values
1	Input Voltage, V1 (boost) V2 (buck)	2.7V 24V
2	Inductor, L1 L2	2.4µH 8.8µH
3	Capacitor, C1	2.2 mF
4	Load	250 W
5	Switching frequency, fs	15kHz

Table -2: Simulation parameters used in conventional bidirectional converter

Sl. No.	Parameters	Values

Sl. No.	Parameters	Values
1.	Input Voltage, V1 (boost) V2 (buck)	10V 24V
2	Inductor, L1	50 µH
3	Capacitor, C1 C2	4.7 mF 2.2 mF
4	Load	250 W
5	Switching frequency, f_s	15 kHz

Table -3: PMDC motor parameters

Sl. No.	Parameters	Values
1	Armature Voltage, V	24V
2	Armature Inductance, La	28 mH
3	Armature Resistance, Ra	1.4 Ω
4	Torque Constant, K	0.5 Nm/A
5	Moment of Inertia, J	0.05215 Kgm^2
6	Viscous Friction Coefficient, Bm	0.002953 Nms
7	Load Torque, T_L	0.5 Nm

The subsystem new bidirectional DC-DC converter and its gate pulse generation are shown in fig. 7. The high voltage side of this subsystem is connected to the DC bus and low voltage side to the Ultra-capacitor (UC).

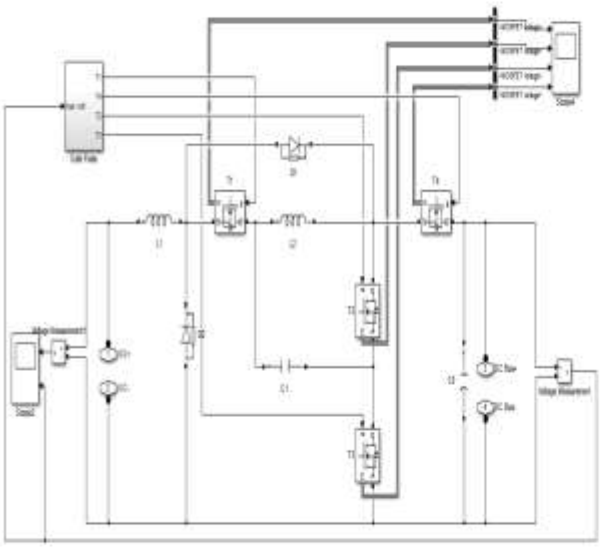

Fig 7: Subsystem New bidirectional quadratic converter

The subsystems Conventional DC-DC converter and its gate pulse generation are shown in fig. 8. One side of this subsystem is connected to the battery and another side to the PMDC Motor.

To illustrate the working of the system, the speed of the motor is varied by changing the voltage applied to the motor using a signal builder. Initially, a terminal voltage of 20V is applied and is stepped down to 5V at 0.3 sec. This 5V is again stepped to 20Vat 0.6 sec.

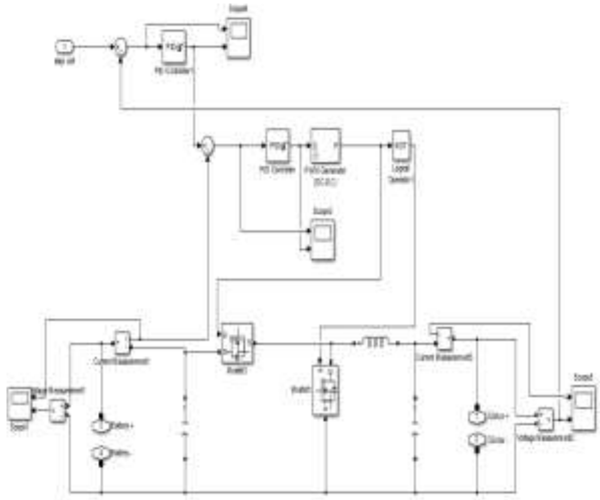

Fig 8: Subsystem Conventional bidirectional

Ultra-capacitor is initially taken to be uncharged and initial voltage is set as 0V. The battery supplies the PMDC motor during this time and the new bidirectional converter is idle. At 0.3 sec as the terminal voltage is stepped down to 5V, the regenerative action takes place and the new bidirectional converter becomes active and buck operation takes place and charges the Ultra-Capacitor (UC). At 0.6 second, the terminal voltage is again stepped to 20V. The new bidirectional converter again becomes active and it boosts the Ultra-Capacitor voltage and supplies the bus. The initial demand will thus be met by the ultra-capacitor and the battery follows. Fig.9 shows battery characteristics while using this UC-battery hybrid system for EV. Fig. 10 shows the ultra-capacitor getting charged at 0.3 sec during regeneration and discharging during 0.6 sec.

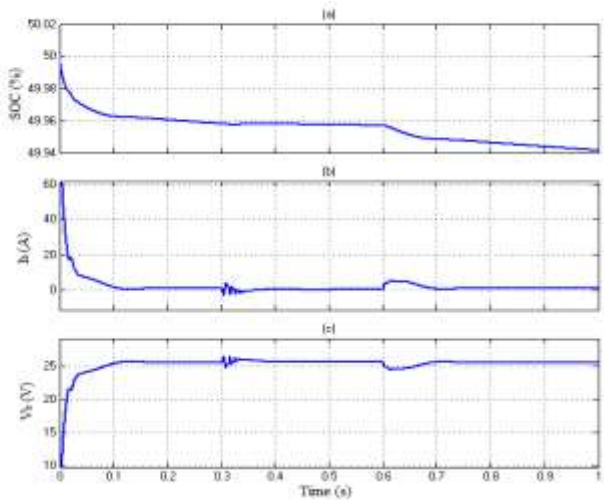

Fig. 9: Battery characteristics while using UC-battery hybrid: (a)SOC, (b)Battery Current and (c)Battery Voltage

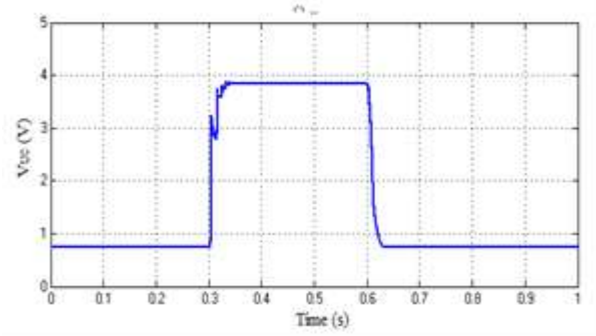

Fig 10: UC Voltage

Fig. 11 shows different characteristics while using battery alone (without UC and new bidirectional DC-DC converter) as a source to run the PMDC motor.

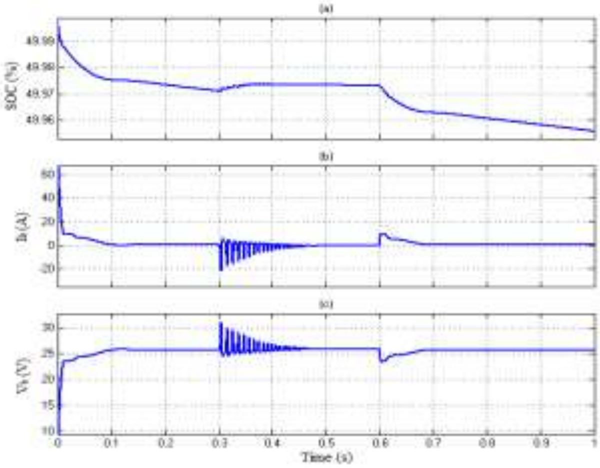

Fig. 11: Battery characteristics while using battery alone: (a)SOC, (b)Battery Current and (c)Battery Voltage

Comparing the battery characteristics in fig. 9 and 11, it is observed that the heavy oscillations in battery voltage and current during regeneration while using battery alone is reduced while using a UC-battery hybrid. Terminal voltage oscillations are also reduced while using a UC-battery hybrid.

4. EXPERIMENTAL SETUP AND RESULTS

The experimental setup for a battery-ultracapacitor hybrid system for electric vehicles using new bidirectional quadratic converter is shown in fig.12. A 24V, 450W PMDC motor is used in experimental setup instead of 24V, 250W PMDC motor so as to reduce the size of the flywheel to obtain the required inertia for regeneration.

Fig 12: Experimental Setup

The motor speed is controlled using the conventional bidirectional converter by changing the input to the motor. While the motor is running if the speed of the motor is suddenly reduced, regeneration occurs and there is a slight increase in bus voltage and if the motor is suddenly accelerated there occurs a sag in bus voltage. This is shown in fig. 13.

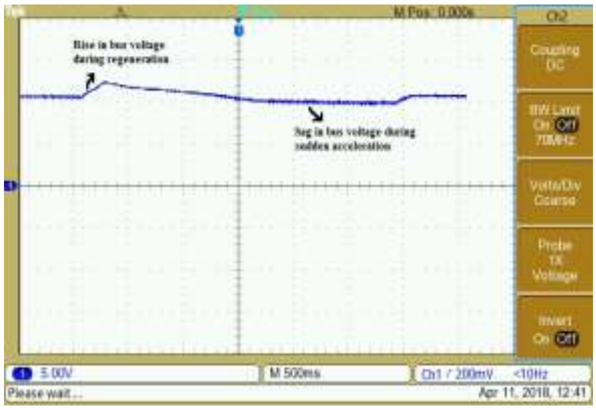

Fig 13: Bus Voltage

When ultra-capacitor is charged, it's voltage increases. During regeneration, the ultra-capacitor gets charged which is evident from the increase in voltage. When the motor is suddenly accelerated the ultra-capacitor discharges thereby there is a reduction in ultra-capacitor voltage. This is shown in fig.14.

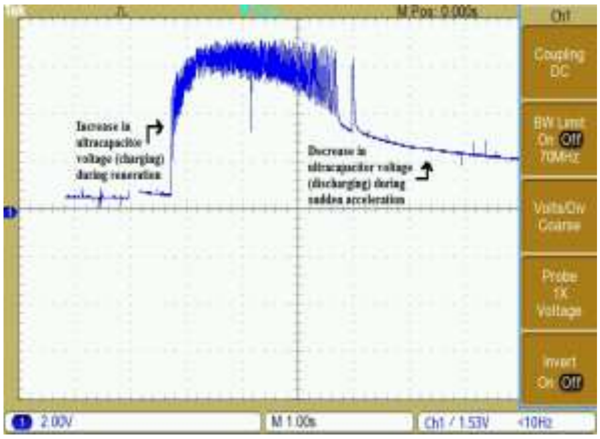

Fig 14: UC Voltage

5. CONCLUSION

The hybrid energy storage system is used with the objective of taking advantage of the best characteristics of each device, creating a system that is superior, than any of the devices used alone. In this paper, Battery-Ultra-capacitor Hybrid System for Electric Vehicles using New Bidirectional Quadratic DC-DC Converter has been introduced. The combination of an ultra-capacitor and a battery is more suitable to applications with fast transients and high peak-to-average power ratio, allowing the ultra-capacitor to act as an energy buffer for the battery. The experimental model of the proposed battery-ultracapacitor hybrid system for electric vehicles is made and the hardware results match the simulation results. Such a system allows us to store the regenerated energy more effectively and use this energy when required. It is suitable for battery charging of electric vehicle.

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