International Journal of Psychosocial Rehabilitation, Vol. 22, Issue 04, 2018
ISSN: 1475-7192

A Contemporary Bi-Face Dc to Dc Converter for Zero Voltage Switching

M. Susila, Dr.B. Karthik and G. Angelo Virgin

Abstract--- *A novel bi-face DC-DC converter for zero voltage switching has been presented in this paper. This design has a good isolation, efficiency and power density compared to existing bi-face DC-DC converter (BDC) modules. The reliability and low weight power converters are of high need to achieve this demand our proposed system has necessary capabilities. To describe this we have simulated a 348 V to 48 V and 48 V to 348 V BDC. The maximum power supplied to the components is 1.65 kW for both the proposed system and to the currently available system. The proposed system provides good efficiency numbers of +1.5% increase at 100% load, a +3.4% increase at 50% load and a +13.5% increase in efficiency at 10% load in both forward and backward mode and more than double power density.*

Keywords--- *Bi-face DC-DC Converter (BDC), Power Conversion Modules, Power Electronic Building Blocks, Isolation, Low Weight, Reliability.*

I. INTRODUCTION

A. What is the need ?

The bi-face DC-DC converter (BDC) along with energy storage has become a promising option for many high power systems, including battery applications in hybrid and electric vehicle, ups, telecom and grid, fuel cell and solar cell applications in renewable energy and so forth. All these high power systems call for high efficiency from light load to full load, high power density and lightweight.

B. Existing solution

Most existing ZVS bi-face [1] and unidirectional [2] DC-DC converters are low power and their narrow input voltage range makes operation difficult to source and load in transient and steady state conditions. They often are paralleled to meet the high power requirements in the above applications as shown in Fig. 1. Parallel arrays are very efficient under high load conditions, but can suffer from inefficiency under light load or no load operation. Many techniques have also been developed to limit the no load power dissipation and improve the light load efficiency. However, these techniques are not effective in dealing with the fast load current increase. Moreover, AC distribution does not benefit renewable energy generation that generates DC power, such as solar cells, fuel cells and wind turbine due to an increased number of energy conversion steps. Furthermore, using an AC line frequency transformer for isolation and voltage matching in the AC grid applications makes the bi-face energy storage system heavy and bulky.

M. Susila, Assistant Professor, Department of Electronics and Communication Engineering, BIST, BIHER, Bharath Institute of Higher Education & Research, Selaiyur, Chennai. E-mail: Susila.ece@gmail.com

Dr.B. Karthik, Assistant Professor, Department of Electronics and Communication Engineering, BIST, BIHER, Bharath Institute of Higher Education & Research, Selaiyur, Chennai.

G. Angelo Virgin, Assistant Professor, Department of Electronics and Communication Engineering, BIST, BIHER, Bharath Institute of Higher Education & Research, Selaiyur, Chennai.

Received: 04 Apr 2018 | Revised: 03 May 2018 | Accepted: 04 June 2018

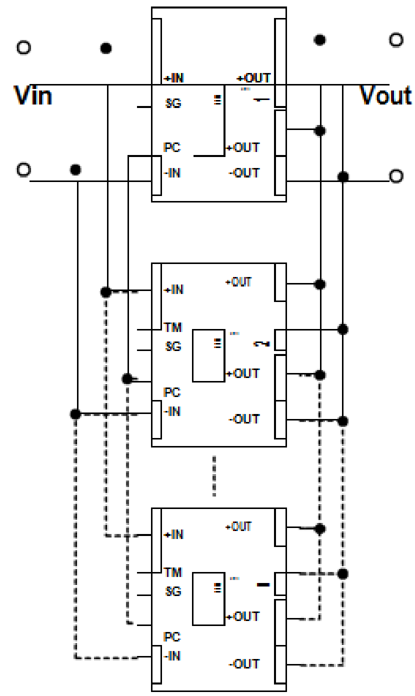

Fig. 1. Existing Bi-face DC-DC Converter for high power applications

The proposed new designed BDC solves the problems of old and existing BDCs by utilizing its own technical attributes such as high efficiency, high power density and lightweight. It benefits the solar cell, fuel cell and battery systems in various application markets by reducing the number of conversion steps.

II. ROPOSED CONBI-FACE DC-DC CONVERTER

A. Theory of operation

This new BDC as shown in Fig. 2 is a fixed ratio DC-DC converter. It supports a wide input voltage range and high power [3], [4]. It is one of the important power electronic building block of the 384 V DC distribution. It uses unique Sine Amplitude Converter (SAC) Topology [5] with open loop control. Its primary and secondary circuit is transformer coupled to provide high frequency galvanic isolation. Primary circuit is stacked half bridge and secondary is center tap with synchronous rectification. Its voltage and current ratios are defined by following equation in ideal condition.

$$\frac{V_{OUT}}{V_{IN}} = \frac{I_{IN}}{I_{OUT}} = K$$

Where V_{IN} = Input Voltage, V_{OUT} = Output Voltage, I_{IN} =Input Current, I_{OUT} = Output Current and K = Turns ratio or Transformation factor of fixed ratio DC-DC converter.

This new BDC works like a DC-DC transformer which uses a ZVS and ZCS soft switching techniques and operates at 1.1 MHz fixed switching frequency to provide low noise output voltage, high efficiency and high power

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ISSN: 1475-7192

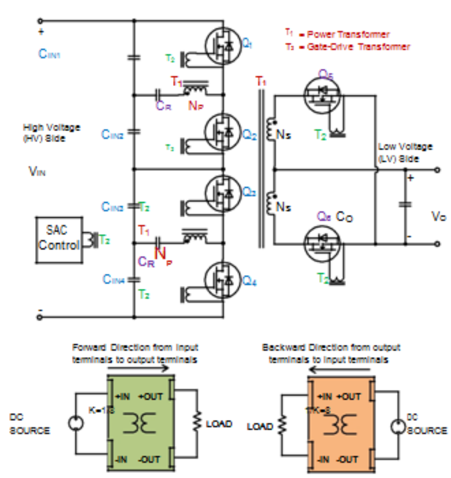
density. All four input capacitors (C_{IN}) have the same characteristics to balance the voltage in stacked half bridge primary circuit. Voltage balancing helps to store the same energy in the inductor of both primary windings. The output voltage is proportional to the input voltage, minus the voltage drop due to the resistance. The resistance term is due to PCB resistance, MOSFET's R_{DS-ON} and transformer's winding resistance. Because of the resistance term and open loop control, output voltage has a natural drop in output voltage vs. output current graph.

So in order to realize the benefits and needs, the new BDC is designed with the following technical attributes.

1. Primary (input) side stacked half bridge to obtain low voltage MOSFET to achieve reduced conduction losses
2. ZVS/ZCS technology to achieve low switching losses with high frequency operation across the entire load range from light load to full load
3. Planar transformer design to achieve low transformer losses as well as solid galvanic isolation and therefore enhanced reliability
4. Resonant sine amplitude converter (SAC) topology control to achieve smooth Bi-face power flow control

Circuit implementation

This new BDC operates in two modes to provide Bi-face power flow as depicted in Fig. 2. The first is forward mode and the second is backward mode. It provides step-down DC-DC conversion when operating in a forward mode direction from input to output terminals. Forward mode is implemented by connecting a high voltage source to the input terminals and low voltage load to the output terminals. The BDC turns on in a forward direction by applying the voltage to its input terminals between low line and high line. To enable backward mode, the BDC first needs to be turned on in forward mode because SAC control is on the input side. This is done by applying the low line voltage to the input terminals. When the voltage applied to output terminals exceed the turns ratio times the input voltage then the BDC starts processing the current in backward direction. It provides step-up DC-DC conversion when operating in a backward mode direction from output to input terminals. Backward mode is implemented by connecting a low voltage source to the output terminals and high voltage load to the input terminals. So in the backward mode, output is the input and input is the output.



In order to enable the backward power flow from the low voltage side, a flyback topology based start up circuit may be designed. The startup circuit receives its input from the low voltage side. It powers the high voltage side to provide the bias voltage and current to SAC control. The low line of BDC on the high voltage side is 260 V. There is

International Journal of Psychosocial Rehabilitation, Vol. 22, Issue 04, 2018
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an undervoltage turn on point below the low line where the BDC turns on. The startup circuit is designed to provide current of about 50 to 100 mA and a voltage of about 260 V.

The new BDCs are interfaced between high voltage bus (e.g. 384 V DC) and low voltage energy sources like solar cells, fuel cell, wind turbines and 12 V, 24 V and 48 V batteries. The BDC with transformation factor (K) of 1/8 is used to implement 384 V to 48 V Bi-face conversions.

III. SIMULATION

Simulation of existing and new BDC is performed using Vicor's power-bench whiteboard tool. Efficiency and power loss are analyzed for both BDCs at 384 V DC input, 50% load and 25 °C operating temperature as shown in Fig. 3 and Fig. 4.

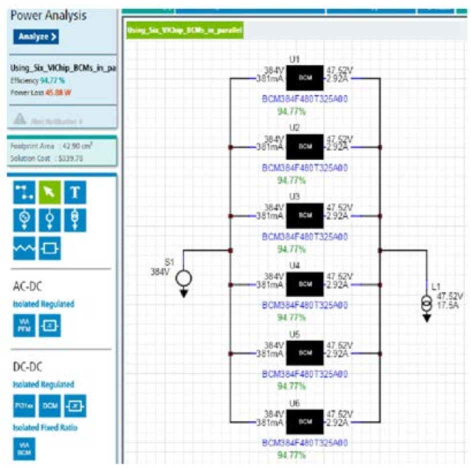

Fig. 3. Power analysis of existing Bi-face DC-DC converter using Vicor's six BCM384x480T325A00 modules

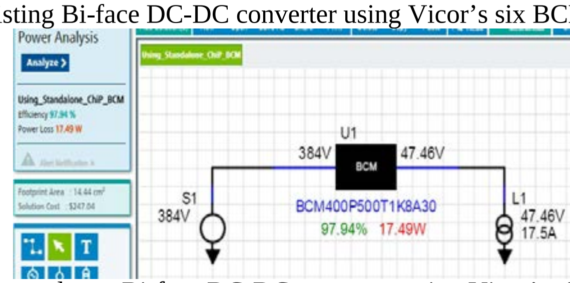

Fig. 4. Power analysis of proposed new Bi-face DC-DC converter using Vicor's single BCM400P500T1K8A30 module

The performance of both BDCs is noted in Table I based on power analysis simulation.

TABLE I. SIMULATION PERFORMANCE

Parameters	**Existing BDC**	**New BDC**
Efficiency (%)	94.77	97.94
Power loss (W)	45.88	17.49
Footprint Area (cm^2)	42.90	14.44
Solution Cost ($)	339.78	247.04

Received: 04 Apr 2018 | Revised: 03 May 2018 | Accepted: 04 June 2018

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IV. SYSTEM IMPLEMENTATION AND EXPERIMENTAL RESULTS

Two PCB prototypes have been designed as shown in Fig. 5 and Fig. 6 to implement the existing BDC and new proposed BDC. This section also presents the experimental results of the existing and new BDC. The input voltage is 384 V in the forward mode direction and 48 V in backward mode direction. The load current range is 0 to 35 A in forward direction and 0 to 4.5 A in backward direction.

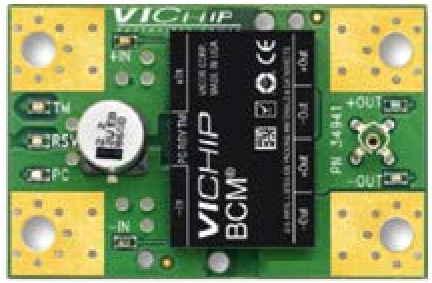

Fig. 5. System implementation of existing Bi-face DC-DC converter using six such boards

Fig. 6. System implementation of proposed new Bi-face DC-DC converter using single such board

The new BDC operates at 1.1 MHz switching frequency, compared to existing BDC at 1.75 MHz. This results in 37% lower switching frequency, which helps to lower the core losses and ultimately no load losses in new BDC.

A comparison in terms of measured efficiency between the proposed new and existing BDC is shown in Fig. 7 and Fig. 8. As can be seen, the proposed new BDC can achieve more than 96% efficiency from 15% load to 100% load in both directions, whereas the efficiency of the existing BDC approaches 96% at 100% load. In forward mode, at 384 V input and 25 °C temperature, the efficiency of the new BDC is maximum when its no load losses (9 W) are equal to resistive losses (I^2_{OUT}*26.5 mΩ). So the output current at peak efficiency point for a given condition is 18.4 A (52.6% load). The measured peak efficiency of the new BDC is 98% at 17.5 A (50% load) output current, which matches closely with analysis.

A comparison in terms of measured power loss between the proposed new and existing BDC is shown in Fig. 9 and Fig. 10. As can be seen, the new BDC has 30 W lower no load power dissipation than existing BDC in both directions. Lower no load power dissipation improves its efficiency in light load conditions. The power dissipation of new BDC is not only lower at no load, but also at other load conditions. The new BDC has 27 W lower power dissipation at 50% load and 19 W lower power dissipation at 100% load as compared to existing BDC.

A comparison in terms of power density between proposed new BDC, existing old BDC and old unidirectional DC-DC converter is shown in Fig. 11. Power density is measured at 1.65 kW power levels. As can be seen, the proposed new BDC provides the highest power density of 157.4 w/cm^3, which is more than double the existing BDCs and old unidirectional DC-DC converters.

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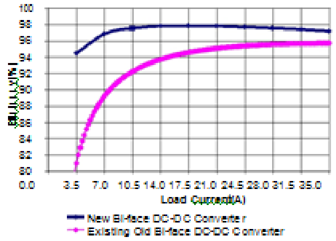


Fig. 7. Measured efficiency in forward mode at 384 V input

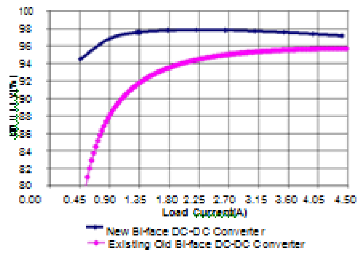


Fig. 8. Measured efficiency in backward mode at 48 V input

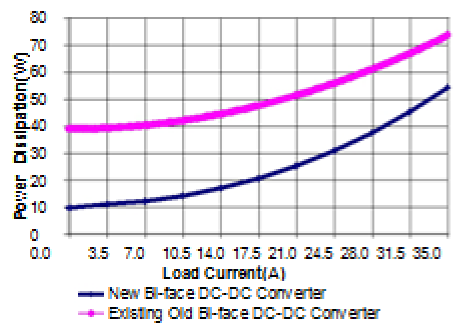


Fig. 9. Measured power dissipation in forward mode at 384 V input

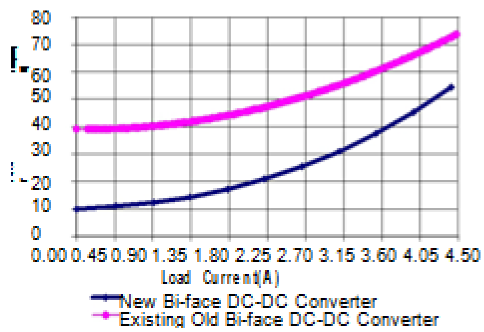


Fig. 10.Measured power dissipation in backward mode at 48 V input

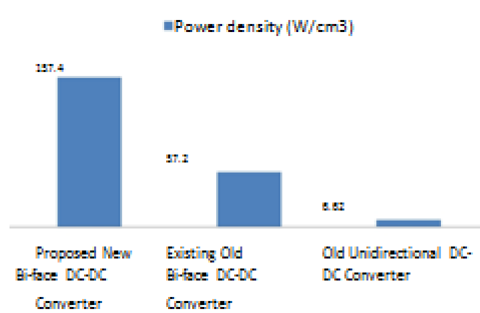


Fig. 11. Power density comparison between proposed new BDC, existing BDC and old unidirectional DC-DC converters

BENEFITS

The proposed new ZVS/ZCS Bi-face DC-DC converter has the following benefits for 384 V to 48 V Bi-face conversions.

A. Higher power capability

Maximum output current rating of existing BDC is limited to 7 A. Where as a proposed new BDC is rated up to 35 A. This higher output current rating provides higher output power.

B. Less number of converters

Existing BDC is rated for low power level up to 325 W. Six such BDCs are paralleled to achieve the power level of 1.65 kW where as a new BDC processes up to 1.65 kW of power in a single converter housed in a package.

C. Higher efficiency over extended load range

The total no load power dissipation of existing BDC is 39 W for 1.65 kW output power. The proposed single new BDC has lower no load power dissipation (fixed loss) and lower resistance (variable loss I^2R). Therefore, the efficiency of new BDC is higher than the existing BDC. High efficiency minimizes the need for cooling to remove heat generated by the converter.

D. Higher power density

The total volume of existing BDC is 28.9 cm^3, whereas the volume of new BDC is 10.48 cm^3. The new standalone BDC provides high power density by processing more power in a smaller form-factor.

Following Table II notes the performance gains of 384 V to 48 V new BDC for power level up to 1.65 kW.

TABLE II. PERFORMANCE GAINS OF NEW BDC

Parameters	Existing BDC	New BDC	Gains of New BDC
Number of converters	6	1	Less number of converters
Input Voltage Range (V)	360 to 400	260 to 410	Wider input voltage range
Efficiency at 10% load (%)	81	94.5	13.5% better
Efficiency at 50% load (%)	94.4	97.8	3.4% better
Efficiency at 100% load (%)	95.7	97.2	1.5% better
Output resistance (mΩ)	28.3	22.6	Lower resistive losses
No load power dissipation (W)	39	10	Lower no load losses
Volume (cm^3)	28.86	10.48	Occupy less PCB space
Power density (W/cm^3)	57.2	157.4	2.75 times more
Weight (g)	84	41	Weight is half

V. APPLICATIONS

A. The future DC home model

The DC micro-grid [6], [7], depicted in Fig. 12, has two major sides: the high-voltage DC (HVDC) and the low-voltage DC (LVDC). The high voltage side is to be established at 384 V and the low voltage side is to be established at 48 V, 24 V or 12 V. The external AC Grid is expected to be supplying the majority of energy to the household at 230 V AC source. The rectifier will convert the AC voltage to DC and enter through the HV Bus and then proposed

Received: 04 Apr 2018 | Revised: 03 May 2018 | Accepted: 04 June 2018

new BDCs in forward mode will convert the 384 V to 48 V, 24 V or 12 V for the electrical and electronic devices that are to be operated at 48 V, 24 V or 12 V. The ratings of rectifiers and BDCs will be based on the household loads.

In order to power the DC home, the AC voltage from the grid has to be converted into DC. A PFC boost rectifier is utilized to convert 230 V AC to 384 V DC. This is a centralized component, so any home electric and electronic devices utilizing the high voltage side of the micro grid will not require the rectification at each point of use, allowing for maximum efficiency by reducing the number of energy conversions. Also, by utilizing centralized rectification, the grid rectifiers are to be designed for higher load and capacity, which improves efficiency as well.

The proposed new BDC can also be easily interfaced between 384 V Bus and renewable energy sources such as solar cells, fuel cells and wind turbines for step-up DC-DC conversion. If renewable energy is utilized in the micro grid, then a 48 V, 24 V or 12 V battery should be attached as well in order to maximize the energy usage by storing unused energy from renewable sources. Once again, the proposed new BDC can be easily interfaced between a 48 V, 24 V or 12 V battery and 384 V Bus. The grid rectifier implemented is a Bi-face rectifier and capable of inversion, allowing for the grid to receive power from the home.

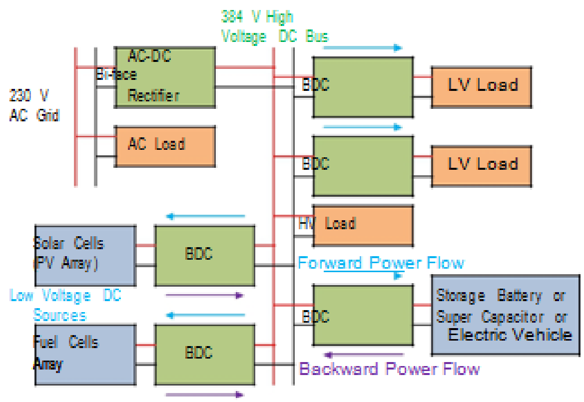


Fig. 12. Typical power distribution application in microgrid renewable energy system

B. The smart office buildings and commercial facilities

The above DC home model can also be utilized in smart office buildings or commercial facilities. Smart buildings are also part of the green energy trend. In the USA, for example, some supermarkets are capturing solar energy on their rooftops, distributing it at 380 V DC and converting to a bus voltage that is typically 48 V, 24 V or 12 V. The proposed new BDC can provide significant gains in energy efficiency throughout the facility as described in [6], [7].

C. The hybrid and electric vehicle (HEV and EV)

In HEVs and EVs, there are two or more different voltage buses for vehicle operation in different conditions. There are needs of galvanically isolated BDCs to link different DC voltage buses and transfer energy back and forth. The high efficiency, compact size, lightweight and high reliability of new BDC is a key technology for several automotive manufacturers [8].

D. The AC/DC grid system

As described in [9], [10] using a 50 or 60 Hz line frequency transformer in an AC grid system of Fig. 13 provides voltage matching and isolation which makes it heavy and bulky. This problem can be overcome by using a proposed new high frequency transformer as an isolation stage as shown in Fig 14. In this way, the isolation barrier moves from the low frequency bulky transformer to the high frequency transformer integrated into the new BDC. Using high frequency transformers lead to more compact and flexible systems. Furthermore, this configuration provides more flexibility in terms of selection of DC voltage amplitude in different stages for optimized operation.

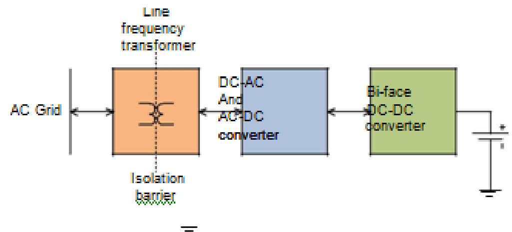


Fig. 13. Using line frequency transformer in the AC grid system for isolation

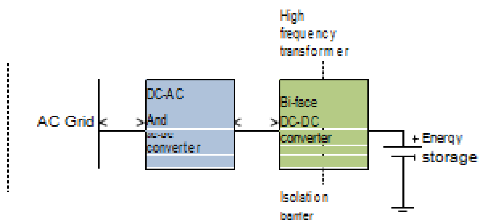
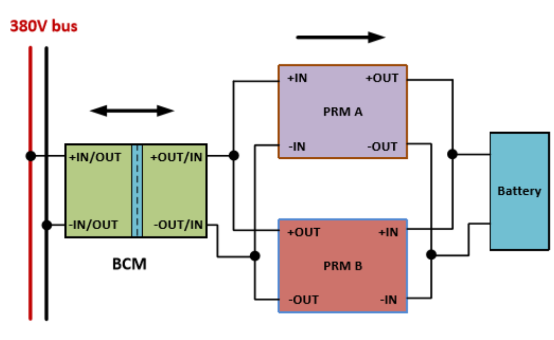


Fig. 14. Using New Bi-face DC-DC Converter in the AC grid system

E. Battery backup system (BBS)

The proposed new BDC is the promising option for Bi-face power processing in energy storage systems. In such systems it would provide current to charge a battery bank in the forward direction and then provide energy from the battery bank to hold up a bus voltage in the backward direction. Similar to BBS as described in [11] for the 48 V DC bus, one new BDC with two post regulator modules (PRMs) [12] can form Bi-face BBS as shown in Fig. 15 for the 384 V DC bus. New BDC runs Bi-facely while PRM A and PRM B are in opposite directions. In such system, BDC provides fixed ratio conversion where as PRM provides regulation against line and load and it is implemented using Vicor's ZVS buck-boost regulator modules. In one direction, 384 V bus charges a battery when PRM A is ON and PRM B is OFF. In the other direction, battery supports 384 V bus when PRM A is OFF and PRM B is ON.



Received: 04 Apr 2018 | Revised: 03 May 2018 | Accepted: 04 June 2018

In all above applications, new BDC instead of existing BDC with transformation factor (K) of 1/8 can be utilized to implement 384 V to 48 V Bi-face conversions as needed. Besides K of 1/8 BDC, there are BDCs with K of 1/16 and 1/32 available and can also be utilized based on the line and load requirements in the end applications and systems.

VI. CONCLUSION

This paper demonstrates a new ZVS and ZCS DC-DC converter for 384 V to 48 V and 48 V to 384 V Bi-face DC-DC power systems. This new BDC is built on an inherently Bi-face topology. It can allow current to flow in both directions and stepping the voltage up or down as required. Using new BDC as a Bi-face converter is much simpler and more compact than having two separate unidirectional converters. A new BDC provides a +13.5% increase in efficiency at 10% load, a +3.4% increase at 50% load and a +1.5% increase at 100% load in both forward and backward mode and more than double power density. It has the clear advantage of higher efficiency, higher power density, lightweight and smaller form factor. In many real world applications of battery, fuel cell and solar cell systems where Bi-face power transfer is needed, the existing 384 V to 48 V, 24 V or 12 V converters and AC line transformers can be easily transformed by proposed new Bi-face DC-DC converter to achieve better system performance in terms of system efficiency, power density and light weight.

ACKNOWLEDGMENT

The author would like to thank Maurizio Salato and colleagues for giving an opportunity to write this paper and also like to thank the APEC reviewers for reviewing the digest for this paper.

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