Reducing Output Voltage Ripple by using Bidirectional Sepic/Zeta Converter with Coupled Inductor

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Abstract— With the increase of population the energy demand is also increasing rapidly so it is necessary to switch to the renewable energy resources like solar, wind, hydel etc. Energy storage systems are used to overcome the demand of usage of storage in the renewable energy resources. In this paper sepic/zeta bidirectional converter with coupled inductor is proposed to reduce ripple in the output voltage and also voltage stress across the switches. This paper compares the performance of bidirectional sepic/zeta converter with and without coupled inductor for different values of coupling coefficients. From the simulation results the modified converter is more reliable than conventional converters for renewable energy storage systems.

Key words: Renewable Energy Sources, Energy Storage Systems, Bidirectional Sepic/Zeta Converter, Coupled Inductor, Energy Storage Systems (ESS)

I. Introduction

The non-renewable energy sources like crude oil, coal, natural gas are available only for next 100 years. So it is necessary to switch to the alternate energy sources to supply the rising energy demand. The renewable energy sources like photovoltaic, wind power, hydel are used for clean electric power generation. Energy storage systems are required to deal the intermittent nature of the resources related to the system reliability [1], stability and power quality. The bidirectional power flow capability is required by the ESS to store the excess energy generated by renewable energy resources and to supply the load, when the energy is not sufficient. The bidirectional DC-DC converter in renewable energy storage systems is shown in Fig.1. In the normal operation the power flows from the source to load by a boost converter which helps in step up the generated voltage to a higher DC bus voltage level. If there are deviations in the supply it will directly affect the load so ESS will supply the load, when the power requirement is more than the power availability, by using energy stored in it. The bidirectional converters are classified in to two types namely isolated and non-isolated converters. An isolated converter uses transformers to provide high voltage conversion ratio by adjusting the turn's ratio.

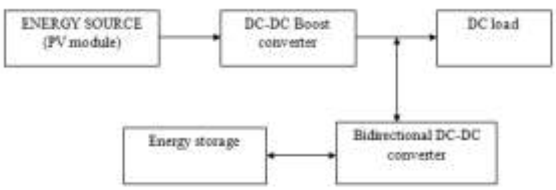


Fig. 1: Bidirectional DC-DC converter in renewable energy storage systems

The series resonant DC-DC converter [2] is a dual active bridge and the bidirectional flyback converter is simple and is of low cost [3].

The multilevel, sepic/zeta, buck boost and switched capacitor type are the examples for the bidirectional DC-DC converter. More number of switches is required in multilevel inverter which leads to complicated control circuit [4]. In the conventional buck boost converter the parasitic elements significantly reduces the conversion ratio so it is not suitable for non-isolated applications [5].

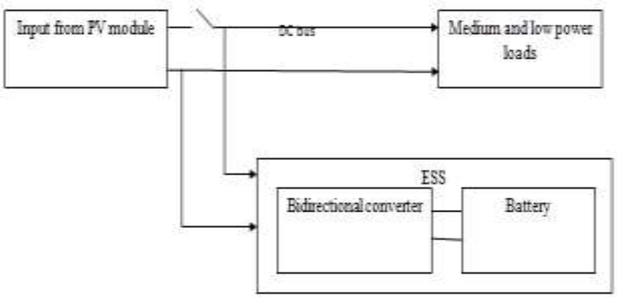
Sepic/zeta converter is an efficient non inverting DC-DC converter which can be operated in buck or boost mode also it requires minimum component count [6] and cost is also less. The main drawback of this converter is the output voltage ripple and voltage stresses across the switches are high. By using the coupled inductor topology it is possible to reduce the stress across the switches [7]-[10].

In this paper some additional features are incorporated to the sepic/zeta converter. The properties like improved output voltage profile and reduced voltage stress on the power switches are incorporated to the conventional sepic/zeta converter. To achieve these features modifications has been done by replacing the individual inductors by a single coupled inductor to reduce voltage stress across the power switches, to improve the output voltage profile and to reduce the overall size of the converter. In order to select the mode of operation of the converter automatically a mode selection algorithm is developed depending on the variations on the source mode of operation is selected. Working and design equations of the modified converter is same as that of conventional converter.

The coupled inductor based sepic/zeta converter is tested for 200V DC bus, 200W load and 24V lead acid battery. The performance of conventional sepic/zeta converter is carried out for different values of coupling coefficients and simulation results are provided to verify the performance. The result shows that the converter with coupled inductor reduces output voltage ripple, reduces voltage stress across switches.

II. Bidirectional Sepic/Zeta Converter with Coupled Inductor

The block diagram of renewable energy storage system is shown in Fig.2 (a). It consists of source, energy storage systems and the load. This system has two modes of operation. If the output of the PV module is sufficient to supply the load then the converter is in zeta mode (charging) and power flows from source to load and the battery charges as shown in Fig.2 (b). If the output of the source is lower than the required rate then the load is energized from ESS. Here the power flows from battery to bus as shown in Fig.2 (c) which is in sepic mode (discharging). The mode of operation of the bidirectional converter is controlled by mode selection algorithm.



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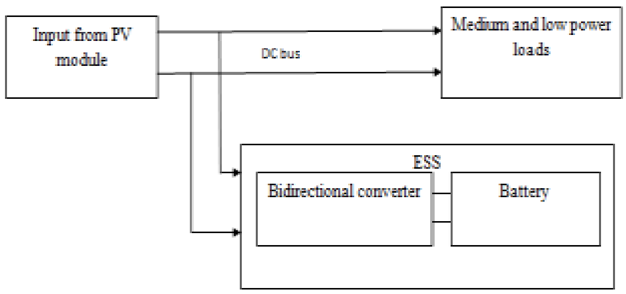

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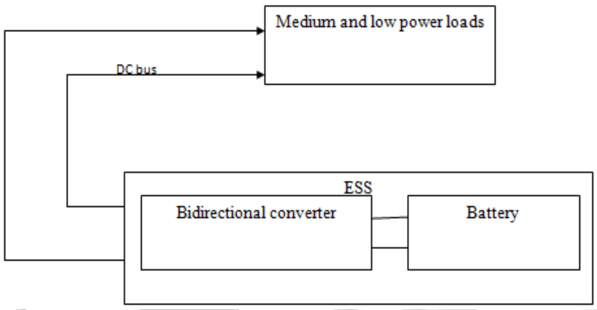


(c)

Fig. 2: Block diagram of (a) PV system with ESS (b) ZETA mode (c) SEPIC mode

Bidirectional SEPIC/ZETA converter consists of SEPIC/ZETA and coupled inductor features. The coupled inductor feature is obtained when the coupled inductor replaces the two individual inductors (L1, L2) which results in better output voltage profile and also the stress on the power switches reduces. Constant bus voltage is maintained constant by the mode selection algorithm as the converter works in two operation modes. The algorithm is verified for different values of voltages.

The bidirectional SEPIC/ZETA DC-DC converter is shown in Fig.3.The converter works in sepic mode in case of forward power flow and acts as a zeta converter in backward power flow.

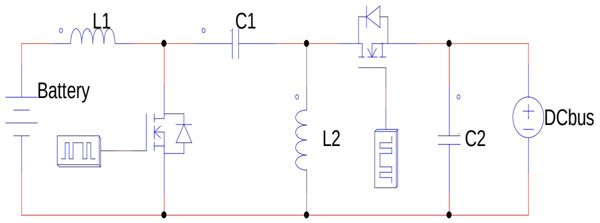


Fig. 3: circuit diagram of conventional sepic /zeta converter

This converter has same transfer function as that of the buck-boost converter. Assuming that the converter operates in continuous conduction mode and there is a galvanic insulation between input and output provided by capacitor and assuming any breakdown of load or short circuits doesn't affect the supply.

$$\frac{vo}{vi} = \frac{D}{1-D} \quad (1)$$

A. Mode 1: SEPIC mode

As shown in Fig.2 (c) the power flows from battery to DC bus voltage which is a forward power flow operation. It is a voltage step up operation from a lower battery voltage level to a higher DC bus voltage. The battery used here is a lead acid battery which discharges through the converter. During discharging MOSFET 1 is turned ON and MOSFET 2 is turned OFF. The sepic converter acts as boost converter.

B. Mode 2: ZETA mode

As shown in Fig.2 (b) power flows from DC bus voltage to battery that is backward power flow. It is a voltage step down operation from higher DC bus voltage to lower battery voltage. The sepic and zeta modes are selected automatically by a mode selection algorithm when there are variations in the supply voltage. Here the zeta converter acts as buck converter MOSFET 1 is turned OFF and MOSFET 2 is turned ON during charging period.

The parameter values are selected using design equations of converter.

$$C1 = \frac{DM}{2fR\rho} \qquad C2 = \frac{D}{2fR\rho1} \quad (2)$$

$$L1 = \frac{DR}{2M^2 f\varepsilon} \qquad L2 = \frac{(1-D)R}{2f\varepsilon1} \quad (3)$$

Where,

$$\rho = \frac{\Delta Vc1/2}{Vc1} \qquad \rho1 = \frac{\Delta Vc2/2}{Vc2} \quad (4)$$

$$\varepsilon = \frac{\Delta Il1/2}{Il1} \qquad \varepsilon = \frac{\Delta Il2/2}{Il2} \quad (5)$$

$$M = \frac{D}{1-D} \quad (6)$$

R is the load resistance, f is the switching frequency, D is the duty ratio $\Delta IL1$ and $\Delta IL2$ are the allowable ripple in the inductor currents IL1 and IL2 respectively and VC1 and VC2 has a ripple of $\Delta VC1$ and $\Delta VC2$ respectively.

Bidirectional SEPIC/ZETA converter with coupled inductor circuit is shown in Fig.4.

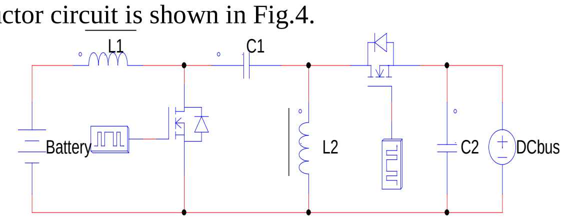


Fig. 4: Circuit diagram of coupled inductor based sepic/zeta converter

Coupled inductor winding 1 has same value as that of L1 and winding 2 carries same value of L2. Lk1 and Lk2 are the leakage inductances of winding 1 and winding 2 and Lm is magnetizing inductance. The working principle is same as that of the conventional converter.

III. MODE SELECTION ALGORITHM

Mode selection algorithm is used to select the mode of operation that is sepic and zeta modes of converter. When there are variations in the supply voltage mode selection algorithm selects required mode of operation. The hardware implementation of mode selection algorithm is bulky and complicated hence software implementation is preferred. Mode selection depends on state of charge (SOC) and the input voltage. The SOC of the battery shows available amount of charge in battery. If the input voltage ripple is greater than the limit and cell voltage is more than that of threshold value then discharge (sepic) mode is carried out. Otherwise if SOC is not fully charged then charging (zeta) mode is selected.

Fig. 5: Flow chart of mode selection algorithm

The control algorithm flow chart is shown in Fig.5. assuming the conditions if DC bus voltage variations is greater than the tolerance limit and there is no sufficient voltage is available in battery then the converter will move to idle mode means no charging or discharging takes place. And if the variation in DC bus voltage is less than the tolerance limit and if the battery is fully charged then there will be no need of charging or discharging. MATLAB/SIMULINK can be used to develop the control algorithm and this can be implemented by using micro controller in the hardware part.

IV. SIMULATION STUDY

A sepic/zeta converter with coupled inductor model is developed in the MATLAB to feed 200w load from a DC bus voltage of 200V. The battery that is being used here is lead acid battery and the nominal voltage is selected as 24V.In conventional sepic/zeta converter we are using 2 separate inductors. In this model 2 separate inductors are replaced by the coupled inductor. Here the design parameters and the self inductances of windings are kept same as that of conventional converter. Since most of the loads works satisfactorily within the variations of $\pm$5% of bus voltage that is the tolerance limit given to the bus voltage is 200$\pm$5%V. the variations in the tolerance band is due to the variations in the renewable energy source output. Whenever the source is less than that of load then battery will feed the load by using energy stored in it. The converter will work in discharge mode (boost or sepic). Thus an uninterruptable power supply can be maintained at the load by control algorithm. The switching frequency is selected as 50 kHz and duty ratio of sepic mode is 11% and that of zeta mode is 89%.

A wide range of input voltage is applied to verify the mode selection algorithm of the system. To verify the effect of coupling coefficient 'k' on the converter performance, 'k' is varied to different values. The values of parameters used for simulation study is given in the Table 1. Simulation of conventional sepic/zeta converter and coupled inductor type sepic/zeta converter are carried out to compare the performance of both.

V. RESULTS

The bidirectional converter is operated as sepic mode and zeta mode with 200V DC bus, resistive load of 200w and a24V lead acid battery. The system has to maintain constant supply to the load with the help of converter. In simulations when the variations in DC bus voltage is maximum than the allowable limit that is 220$\pm$10V then the converter mode is changed from charging to discharging mode by the mode selection algorithm.

Parameters	Value
L1	8.571mH
L2	1.029mH
C1	8.925µF
C2	74.375 µF
Load	200W,200V
DC bus voltage	200V
Battery voltage	24V

Table 1: Converter Parameters

A. Effect of Coupling Coefficient

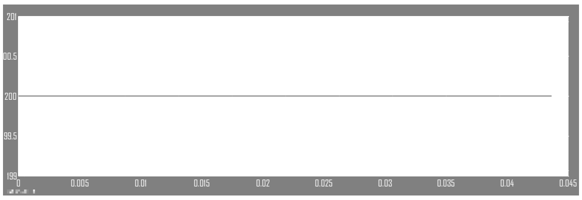
To study the effect of 'k' simulation of coupled inductor sepic/zeta converter is carried out for different values of 'k' where k ranges from 0.85 to 1. Reduction of output voltage ripple is observed. When the coupling co-efficient is in between 0.91-0.92 the voltage ripple is minimum. Hence the value of 'k=0.92' is selected for analysis.

B. Performance of Mode Selection Algorithm

The mode selection algorithm is verified for wide range of DC bus voltages in order to check the performance. Both modified and conventional converter performance are verified with normal bus voltages (200V) and if the voltage greater than that of tolerance limit (2.5V) and the bus voltage is at 200V then the converter is in charging mode of operation and the source supply the load. The output at the load side is shown in Fig.6. When the bus voltage is at (2.5V) source is removed from the bus and the converter changes to discharging mode and load is fed by battery as shown in Fig.7. The SOC state of charge shows the positive slope while charging and negative slope while discharging indicating charging and discharging mode respectively.

C. Comparison of Sepic/Zeta Converter with and Coupled Inductor

The performance of bidirectional converter is improved when 2 separate inductors are replaced by a coupled inductor the coupling coefficient is selected as 0.92 for the analysis. The compared results at steady state operation are shown in table 2. When the coupled inductor is used instead of 2 separate inductors the output voltage ripple is reduced by 95% and the voltage stress across the power switches is reduced by 15%. The limitation of the modified converter is mean value of the output voltage is reduced as compared to the conventional converter and decrease in the voltage is within the limit.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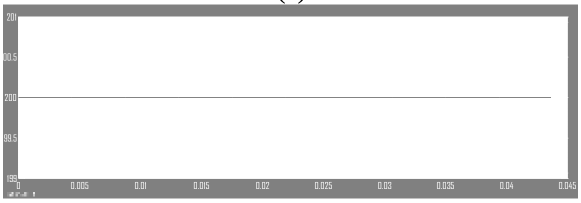
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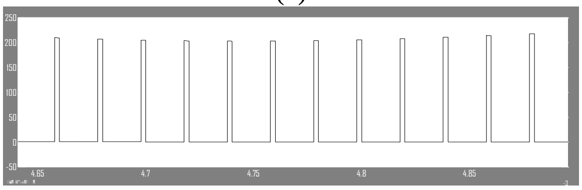
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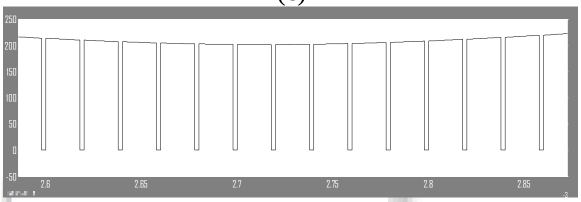
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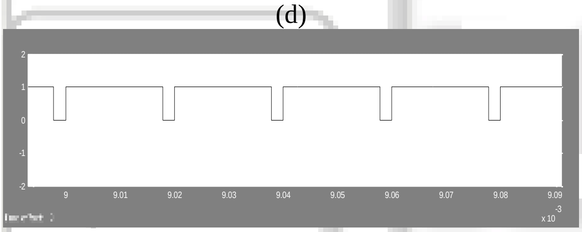
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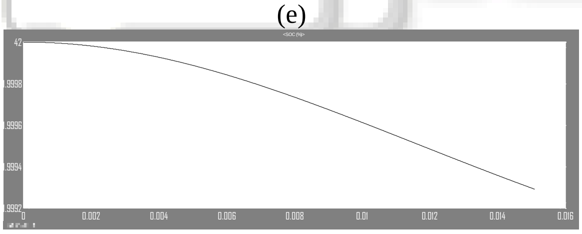
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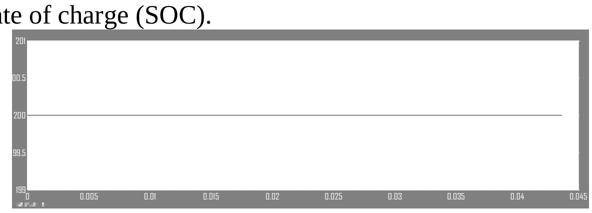
Fig. 6: Simulation results for sepic mode: a) input voltage b) output voltage c) voltage across sepic switch d) voltage across zeta switch e) switching pulses for sepic switch f) Battery state of charge (SOC).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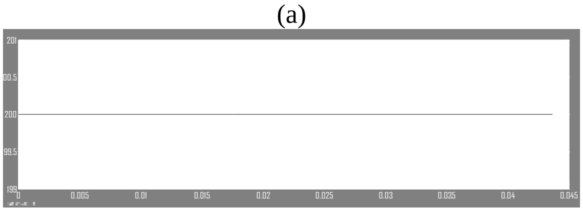
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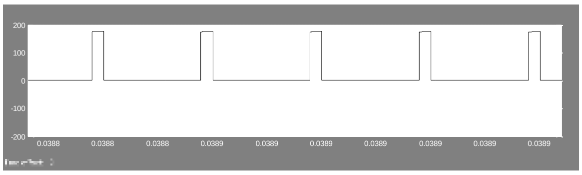
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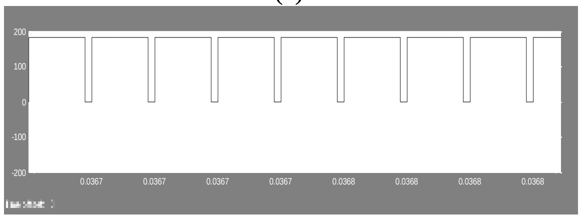
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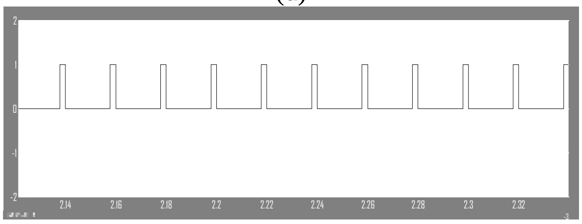
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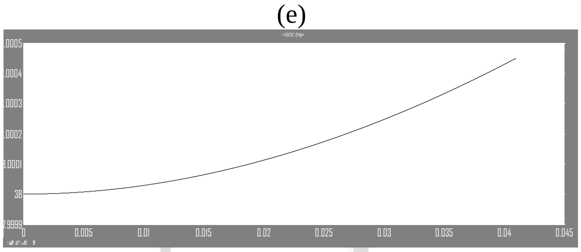
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Fig. 7: Simulation results for zeta mode: a) input voltage b) output voltage c) voltage across sepic switch d) voltage across zeta switch e) switching pulses for zeta switch f) battery state of charge (SOC)

VI. CONCLUSIONS

The coupled inductor based sepic/zeta converter is an efficient non inverting DC-DC converter that can be operated in buck or boost mode with minimum component count and minimum cost. The ripple at the output voltage is less when compared with that of the conventional converter cost and size of the filter capacitor is also reduces by using coupled inductor instead of 2 individual inductors with coupling coefficient of 0.92 provides better performance reduces stress across the switches and size of the converter also reduces. The quality of the output voltage is improved even though the mean value of the output voltage is reduced by using coupled inductor. The steady state operation of the system satisfies for wide range of variations in the DC bus voltages. However the initial voltage and current in switches will rise when the variations are high which requires high rating switches.

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