Simulation of High Efficiency Switched Capacitor AC to DC SEPIC Converter for Improved Power Quality

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Summary
A new topology of single-phase two stage AC to DC SEPIC converter in step down configuration with high efficiency at extremely low voltage gain is proposed with high input power factor and low input current total harmonic distortion. In this work, proposal has be given to modify conventional two stage AC to DC SEPIC converter introducing a switched capacitor branch in between the stages. The input current THD is kept low. The input power factor is high with two-loop feedback control. The proposed schemes can be used in the application of battery charging of electric motor vehicles.
Key words:
AC-DC converters; electric motor vehicles; battery charger circuits; total harmonic distortion (THD); passive filters.

1. Introduction

In modern days, much emphasis is given towards the use of eco-friendly vehicles. The use of such vehicles not only reduces the environmental pollutions but also reduces the use of the fossil fuel. The every declining nature of the fossil fuel [1] focuses the production of the electrical energy from the renewable energy sources like wind, solar, wave etc. The battery charging of the electric motor vehicles has to be done with high efficient system for maximum utilization of the available resources. Battery charging at low voltage gain affects the supply voltage with low efficiency, low input power factor and high THD [2].
Single phase AC to DC converters are common in modern day power supplies. The converter forms interface between the utility power supply and electronic equipment connected to them. The process of rectification used to be simple, but recently, rectifiers have become much more sophisticated, and are now systems rather than mere circuits [3] because of the requirement of the power quality. In practice, conventional rectifiers are harmonic polluters of the AC power distribution systems, because these converters absorb energy from the AC line whereas the rectified line voltage is higher than the DC link voltage. The adverse effects of power system harmonics are: unsafe neutral current in three phase systems, heating and reduction in life in transformers and induction motors, degradation of system voltage waveforms, unsafe current in power factor correction (PFC) capacitors and malfunctioning of certain power system protection elements. In order to solve the harmonic pollutions caused by AC to DC converters, various methods have been proposed. The use of filter in the input side is one simple solution, but the size of the filter component (capacitor and inductor) required are large. Use of the passive filter keeps THD in tolerable limit but power factor in the input side remains poor. To sort the problem out, a number of AC to DC converters with power factor correction have been developed and proposed [4]–[10]. Generally, techniques involving two power-processing stages are used to solve the problems. The input PFC stage improves the power factor as well as maintains a constant voltage at DC link. The most common PFC stage employ a Boost converter [6], [7], [11]. Common converters for step-up and step-down along with SEPIC and ZETA converters are also used for the similar objective with different voltage gains. In high frequency DC to DC converter output stage, [12], [13] reflects chopped high frequency AC current at the input. A small filter in the input side is used to keep the input current near sinusoidal with improved input power factor [14], [15]. The reported solution only works with full wave pulsed DC output. Quality power refers low ripple DC output voltage. As a result, filter (capacitor) required in output side is necessarily large. Because of large capacitor in the output filter pulsed AC current is drawn from the input side. To retrain the input current in sinusoidal form, feedback control will be required. The unidirectional switch used in the DC to DC converters for step-up (boost) AC to DC conversion must operate in critical mode [16], [17] that is, the power switch should be turned ON at zero current crossing of the boost diode. Thus in DC to DC converter operation constant switching frequency with not work, rather the switch should be operated with variable frequency due to input or output changes. Different approach for step-up rectifier comprises maintaining a constant average current in converter's boost diode. Modulated duty cycle keeps that fixed average current in the diode. The converter configurations without using bridge [4], [18] and configurations using two switch, two diode employed in rectifiers are also reported to have

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the above features of step-up (boost) rectifier. The single phase AC to DC converters without bridgeless use one bidirectional switch or more unidirectional switches. The bidirectional switch is made of two unidirectional anti-parallel switches with two diodes.

Recently most advanced cities are eager to use the battery driven eco-friendly electric motor vehicles to have a clean environment [19], [20]. Battery charging is operated in very low voltage gain, therefore efficient power electronic circuit is necessary to obtain optimum energy management. Conventionally these applications use a transformer to reduce the voltage and then AC to DC converter is used. Efficiency suffers due to the use of the transformer. Transformer-less control techniques suffers from a poor power factor in the input side and distorted input current. The conversion efficiency of conventional AC to DC converter changes with a variation in duty cycle. The efficiency tends to reduce with extremely low voltage gain [21]. Switched-capacitor DC to DC converter suggested an improvement in efficiency at low duty cycles in the reported work [22].

With the widespread development of electronic equipment harmonics of rectifier have become significant and measurable problem. In addition, conventional single-phase AC to DC converters suffer from problems of low conversion efficiency at extremely low voltage gains and low input power factor [3], [23], [24]. Thus a quality rectifier is needed which will operate with high efficiency, high input power factor and minimum generation of harmonics. In this paper, a novel two stage AC to DC SEPIC converter is designed for single phase operation introducing switched capacitor circuitry to achieve high efficiency at extremely low voltage gains. A suitable feedback control technique is also used to achieve higher input power factor and the THD for input current is kept within the tolerable limits specified by IEEE-519 [25].

2. Proposed Circuit Configuration

Modern rectifier technology now incorporates many of the DC to DC converter fundamentals in between the diode bridge configuration and the load to form the two stage converter. The conventional two stage converter suffers from low efficiency at extremely low voltage gains. Fig 1 demonstrates the proposed two stage single phase AC to DC converter using modified SEPIC topology. The first stage is basic single phase rectifier followed by high frequency modified switched capacitor DC-DC second stage. The value of duty cycle needs to be selected to achieve specific low output voltage from a conventional two stage converter is smaller than that of proposed converter. Addition of the switched capacitor branch helps to obtain same output voltage level with relatively high duty cycle. Thus the efficiency of the proposed converter should be higher than that of conventional two stage converter for same voltage gain.

The proposed two stage converter circuit includes three inductors (L1-L2 and Lin), five capacitors (C1-C4 and Cin), eight diodes (D1-D8) and one unidirectional switch M1. Here L1 and L2 are SEPIC inductors. The input filter comprises with inductor Lin and capacitor Cin. R1 and C1 are the load resistance and output filter capacitor of the proposed circuit respectively. Resistive load has been selected for this investigation because this type of load offers highest harmonic distortion in the input side when output is filtered. On the other hand, R-L or R-C type of load has built-in filter property to reduce the distortion. So in practice the converters are designed with resistive load.

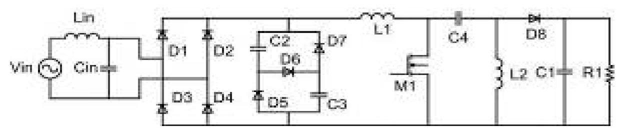
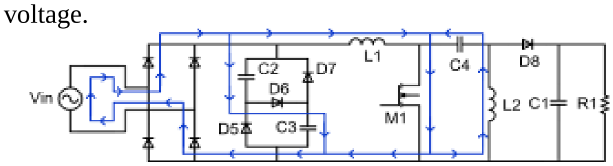


Fig. 1 Proposed two stage SEPIC converter.

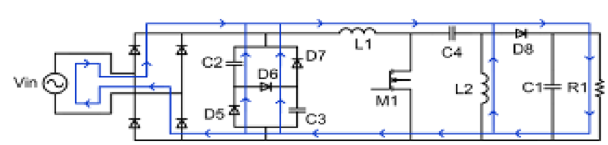
3. Principle of Operation

In modern converters the high frequency input AC chopping provides chopped input current. A small input filter makes the shape near sinusoidal. Thus the input current THD reduces. To increase the input power factor proper feedback is required. The operating principle of the proposed converters is described below.

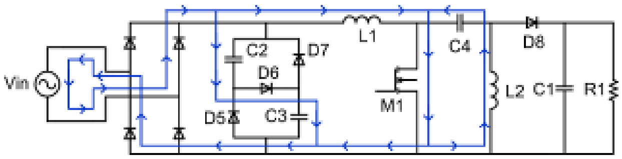
The four operating steps of the proposed two stage SEPIC topology are shown in Fig 2. Step A and Step B, circuit when the switch is ON and OFF respectively during positive half cycle of the supply AC voltage. Step C and Step D, circuit when the switch is ON and OFF respectively during negative half cycle of the supply AC voltage.



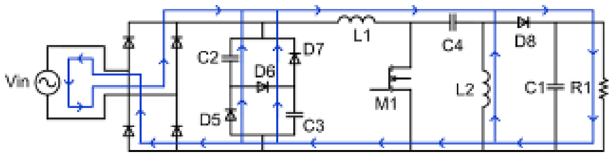
(A)



(B)



(C)



(D)

Fig. 2 Four steps (Step A, B, C and D) of operating principle of the proposed two stage single phase AC to DC SEPIC converter.

4. Open Loop Simulation Results

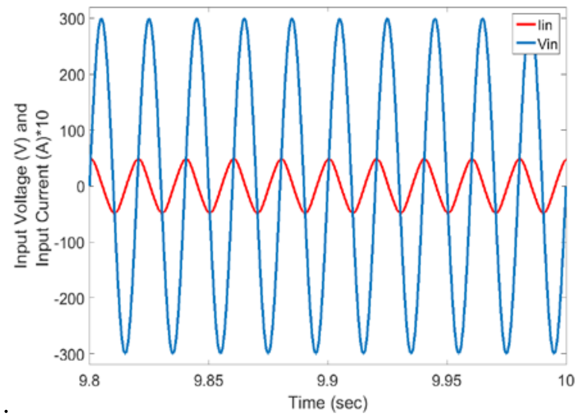
The mathematical model of the converter is highly nonlinear and complex. It is usual practice to simulate this type of converters using software like Cadence Orcad 16.6, PSIM Professional version 9.1.1.400 or Proteus Professional 8.1. The simulation of the proposed circuit is carried out using PSIM Professional version 9.1.1.400.

4.1 Circuit Parameters

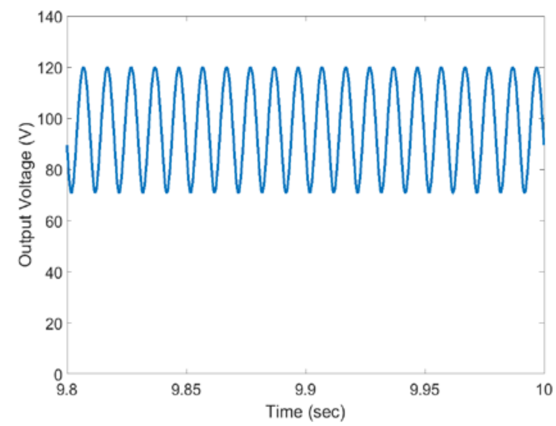
For the open loop simulation of two stage AC to DC SEPIC converter in step down operation, an input AC supply of 300V amplitude and line frequency of 50 Hz is used. As unidirectional switch a MOSFET is used. In two stage converter the SEPIC inductors L1 and L2 have the value of 400uH and input filter inductor Lin have the value of 40mH respectively, the output filter capacitor C1 with a value of 50µF and capacitors C2 to C5 have values of 1µF each. The load the converter has a value 100Ω. For comparative analysis the proposed converter circuit has been compared with the conventional single phase AC to DC SEPIC configuration converter.

4.2 Results from Open Loop Simulation

The input voltage-current and the output voltage waveforms of the proposed two stage AC to DC SEPIC converter is given in Fig 3 for a voltage gain of 0.3



(a)



(b)

Fig. 3 Waveforms of input voltage-input current x 10 (a) and the output voltage of the proposed two stage SEPIC converter at a voltage gain of 0.3.

4.3 Quantitative Comparison

The input voltage-current of the Fig 3(a) clearly shown the THD (%) of the input current of the proposed converter is considerably low, but the input power factor is very low. The input current is approximately 81.27^0 out of phase with the input voltage. The average output voltage of the proposed converter is shown in Fig 3(b) Average output voltage is approximately 96.95V.

For comparative analysis between the proposed and conventional scheme, results are estimated in terms of % conversion efficiency, input power factor and % THD of input current. The outcomes of the experimentation are discussed below with diagrams in Fig 4 to 6.

The performance curve shown in Fig 4 indicates that the conversion efficiency is reasonable high for the proposed scheme at extremely low voltage gains (0.05-0.40) which is the point of interest of this research. The proposed converter shows low input power factor throughout all the voltage gains as well the conventional one (Fig 5). Though the THD (%) of input current of the proposed converter are relatively high compare to conventional one but still within the tolerable limit (Fig 6). Feedback control scheme needs to adopt to improve the input power factor and to reduce the size of the input filter which will be discussed in the next section.

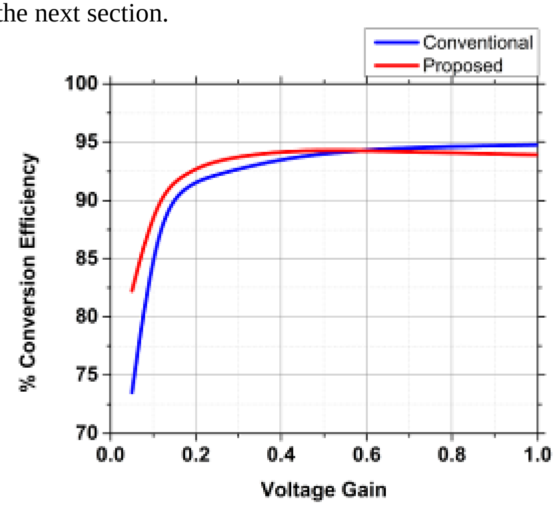


Fig. 4 Comparison of conversion efficiency (%) of the proposed and conventional two stage SEPIC converter.

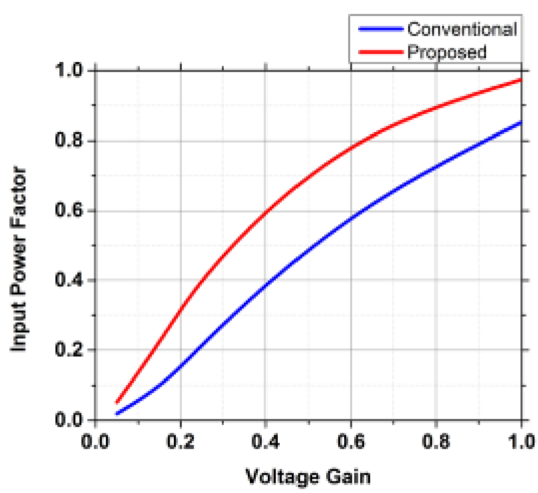


Fig. 5 Input power factor comparison of the proposed and conventional two stage SEPIC converter.

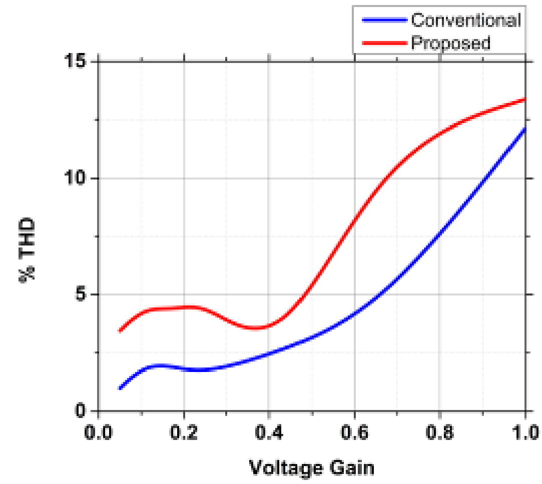


Fig. 6 Comparison of THD (%) of the proposed and conventional two stage SEPIC converter.

5. Feedback control to Improve Input Power Factor

The input power factor of the proposed converter schemes are very low. Proper feedback control can improve the input power factor of the converters. The PFC feedback control consists of two loop [22]. The inner current loop and the outer voltage loop. Average current mode control is applied to the inner current control loop. The small signal model of the two stage proposed SEPIC converter is given in Fig 7. The feedback control loops are designed using MATLAB.

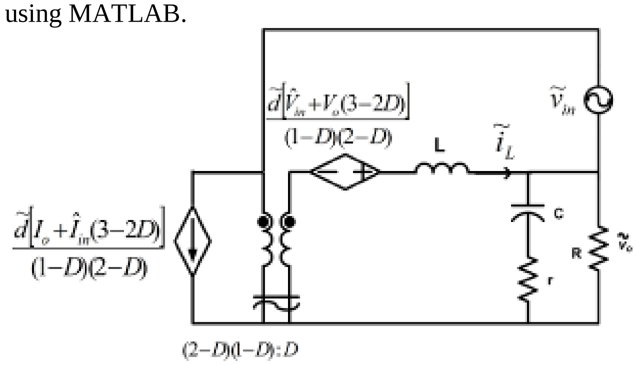


Fig. 7 Small signal model of proposed two stage SEPIC converter.

The power stage transfer function for the inner current control loop and outer voltage control loop are derived and shown in equation (1) and (2),

$$G_{PSi}(s) = \frac{\tilde{i}_L(s)}{\tilde{d}(s)} = \frac{1}{(D^2 - 3D + 2)} \times \frac{\hat{V}_{in} + V_0(3 - 2D)}{sL} \quad \ldots\ldots(1)$$

$$G_{PSv}(s) = \frac{\tilde{v}_0(s)}{\tilde{i}_L(s)} = \frac{(D^2 - 4D + 2)}{(D^2 - 3D + 2)} \times \frac{R}{(sRC + 1)} \quad \ldots\ldots\ldots\ldots(2)$$

Where,

$G_{PSi}(s) =$ Transfer function of the converter (power stage) for current control loop,

$G_{PSv}(s) =$ Transfer function of the converter (power stage) for voltage control loop,

$\hat{V}_{in} =$ Peak input voltage,

$V_0 =$ Average output voltage,

$\tilde{i}_L(s) =$ Inductor current perturbation,

$\tilde{d} =$ Duty cycle perturbation,

$\tilde{v}_0 =$ Output voltage perturbation,

$D =$ Duty cycle.

The power stage transfer function for the current control loop in equation (1) is an approximation, valid at high frequencies and not a pure integrator. Therefore to have a high DC loop gain and a zero DC steady state error, the current controller transfer function must have a pole at the origin. In the current control loop the phase due to the pole at the origin of the controller and that of the power stage transfer function of equation (1) add up to -180^0. Hence the current controller in average current mode control introduces a pole-zero pair to provide a phase margin of approximately 60^0 at the loop crossover frequency. The Bode plot of the inner current control loop is shown in Fig 8. The phase boost of 60^0 is provided at crossover frequency of 10 kHz.

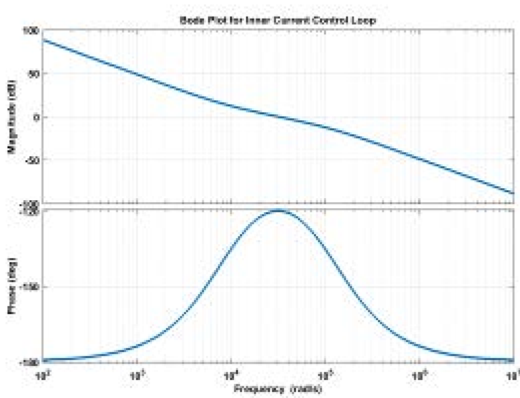


Fig. 8 Compensated bode plot for current control loop for proposed two stage AC to DC SEPIC converter.

The objective of the outer voltage control loop is to generate the peak of the reference current for the current control loop. In the voltage loop the bandwidth is limited to approximately 15Hz. The power-stage transfer function for the voltage control loop at these low perturbation frequency is shown in equation (2). Because of such low bandwidth it is perfectly reasonable to assume that the current loop to be ideal at low frequency around 15 Hz. To achieve zero steady state error, the voltage controller should have a pole at the origin. A transfer function is used for the voltage controller, where a pole is placed at the voltage-loop crossover frequency (which is below 15 Hz) is often used for simplicity. The Bode diagram of the voltage control loop is shown in Fig 9. The PFC controller with the two stage AC-DC SEPIC converter is shown in Fig 10.

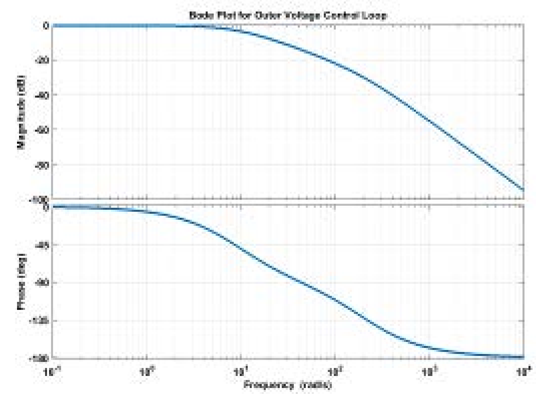


Fig. 9 Compensated bode plot for outer voltage control loop for proposed two stage AC to DC SEPIC converter.

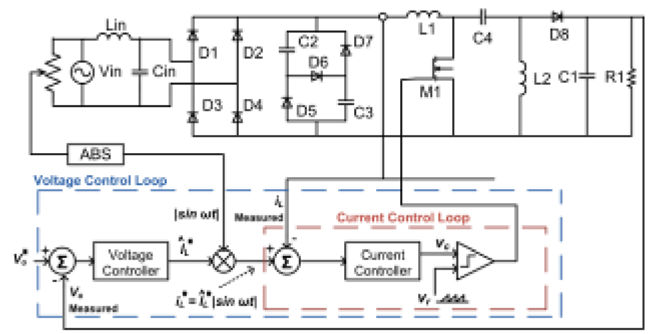
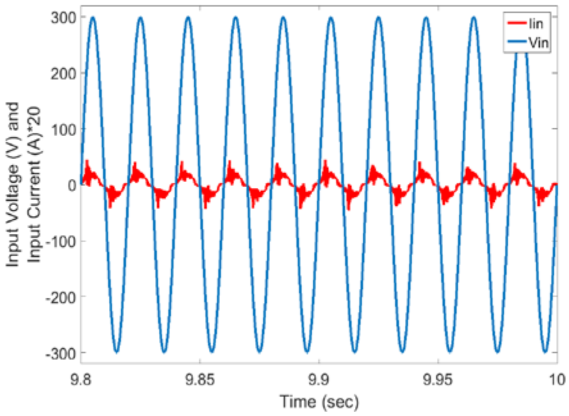


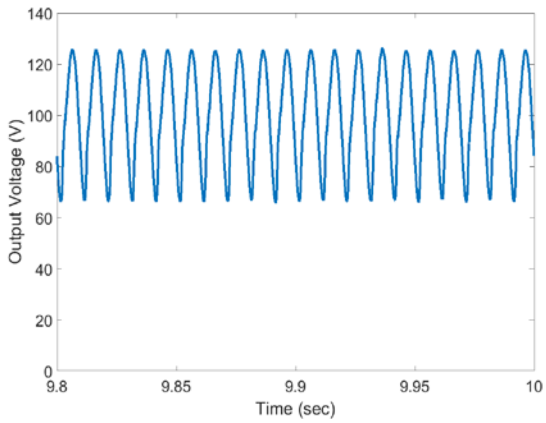
Fig. 10 Proposed two stage AC to DC SEPIC converter with feedback control for improvement of input power factor.

6. Close Loop Simulation Results

The control circuit is designed to achieve an average output voltage of 100V. The simulation result of the input current and voltage are shown in Fig 11(a) where input current is multiplied with 20 to show in the same scale with input voltage. The average output voltage is shown in Fig 11(b). The comparison of the input power factor with and without the feedback control is shown in Fig 12.



(a)



(b)

Fig. 11 Waveforms of input voltage and input current x 20 (a) and output voltage of the proposed two stage SEPIC converter at a voltage gain of 0.3.

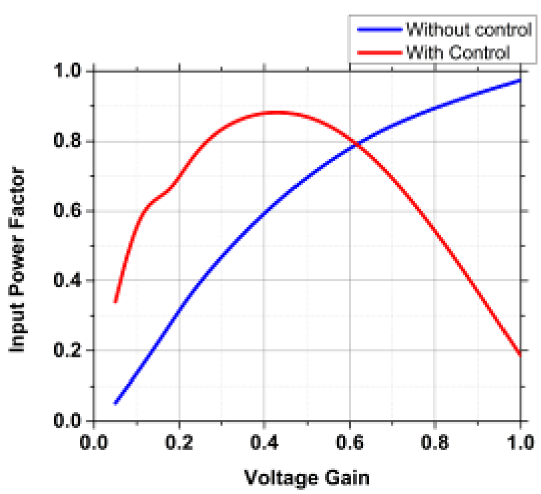


Fig. 12 Input power factor comparison of the proposed AC-DC SEPIC converter in two-stage with and without the feedback control.

The input power factor improved significantly for the proposed scheme at extremely low voltage gains (0.05-0.43) with the adopted feedback controller compared to the uncontrolled converter. Also the inductor and the capacitor of the input filter reduces to 1mH and 1μF respectively without affecting converter efficiency and THD (%).The THD of the AC mains current increases a little but still remains around 20% thereby complying with the standard IEEE-519. The input power factor of the proposed converter is comparable with recent works [9], [26], [27].

7. Conclusion

A new topology for single phase AC-DC SEPIC converters is proposed in this paper. The conventional double-stage converter is modified to design the topology. The proposed converter shows significant improvement in the conversion efficiency at extremely low voltage gains. THD (%) of the input current is kept low but the input power factor was found to be very low. Therefore suitable feedback control is adopted to improve the input power factor. Significant improvement of input power factor is noticed at low voltage gains (0.05-0.43) and achieved maximum input power factor of 0.921 at the voltage gain of 0.43. The conversion efficiency and the THD (%) was not affected by the feedback control. In addition, the feedback control reduced the size of the input filter. Proposed AC to DC SEPIC converter with higher efficiency at low voltage gain can be used for battery charging of the eco-friendly electric motor vehicles.

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