

# International Journal of Innovative Research in Science, Engineering and Technology

(A High Impact Factor, Monthly, Peer Reviewed Journal)

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Vol. 8, Issue 3, March 2019

## Power Factor Correction Using DC-DC SEPIC Converter Optimized With Fuzzy Logic Controller

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**ABSTRACT:** Single phase diode rectifiers are widely used in industrial, commercial, utility and domestic applications. Many input wave shaping methods have been proposed to solve the problem of poor power factor which can be classified as active and passive methods. Six different DC-DC converter topologies have been studied to solve the low efficiency, poor input power factor and total harmonic distortion problems of single phase AC-DC converters. The proposed topologies showed superior performance over passive filtering techniques and output regulated single phase AC-DC converters. Some of the input switched topologies have been reported earlier, whereas, new input switched topologies with reduced component number are proposed in this thesis. Five reduced component input switched single phase AC-DC rectifier has been studied. The topologies used are Boost configuration-2, Buck-Boost configuration-3, Ćuk configuration-2, SEPIC configuration-2 and Inverse SEPIC configuration-2. Results are compared with the reported ones. Proposed topologies show lower input current THD, higher PF compared to previously reported topologies. However efficiency remains almost the same for both previous and proposed topologies. All the newly reported topologies are easier to implement. Typical output voltage and input current waveforms are shown. It has been found that without feedback control, the input switched single phase rectifiers perform better than output regulated single phase AC-DC converters in terms of input current THD, input power factor and conversion efficiency. Input switched single phase AC-DC converters reported earlier and proposed in this thesis are expected to perform better with feedback control circuit as well. As an example an input switched Boost regulated single phase AC-DC converter is studied and its performance is briefly compared with output regulated Boost single phase AC-DC converter.

### I. INTRODUCTION

#### Background and present status of the problem

Single phase AC-DC converters (rectifiers) are common in power supplies that form interface between utility power supply and electronic equipment connected to them [1]. Uncontrolled single phase diode bridge rectifiers with output capacitive filter draw non-sinusoidal currents [2-7]. This causes high input current THD and low input power factor which is detrimental to utility power supply. In the past passive filters consisting of large L and C at the input was used to reduce current distortion (THD) at the cost of further power factor and efficiency reduction [1,4-5]. With the development of power electronics, active filtering techniques have been used to alleviate these problems [5-8]. These included harmonic current injection and use of DC-DC converter between rectifier and load. The DC-DC converter between rectifier and load has many possible configurations [8-9] including those of bridgeless configuration. Recently some configurations and techniques are being investigated for input current switching by providing switch between source and rectifier [8-9]. So far Boost, Buck, Buck-Boost and Ćuk configurations have been investigated for single phase rectifier input current switching.

The rectifier with output filter capacitor is called a conventional AC-DC utility interface. The filter capacitor reduces the ripples present in the output voltage. Although a filter capacitor significantly suppresses the ripple from the output

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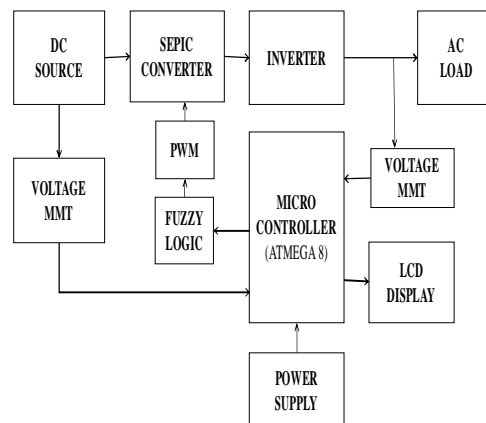
voltage, it introduces distortions in the input current and draws current from the supply discontinuously in short pulses. This introduces problems including reduction of available power and increased loss.

### Problems of conventional interface:

The large harmonic content and the consequent poor power factor (PF) of operation of the conventional rectifier--capacitor type interface causes several problems to the utility supply. Some of them are listed below .Due to harmonic components - Because of the non-zero source impedance in the utility supply, the harmonic currents flowing through the conventional AC-DC utility interface will cause a distortion in the voltage waveform at the point of common coupling. This may cause malfunction of power system protection, loads and metering devices. Besides voltage waveform distortion, harmonic components may also cause the problems of overheating of neutral line, distribution transformers and distribution lines, interference with communication and control signals, over voltages due to resonance conditions.

(i) Due to poor PF - Poor power factor of operation implies ineffective use of the volt-ampere ratings of the utility equipment such as transformers, distribution lines and generators. Also, it places a restriction on the total equipment load that can be connected to a typical home or office wall-plug with specified maximum r.m.s current rating.

## II. BLOCK DIAGRAM



### FUZZY CONTROLLER BASED DVR:

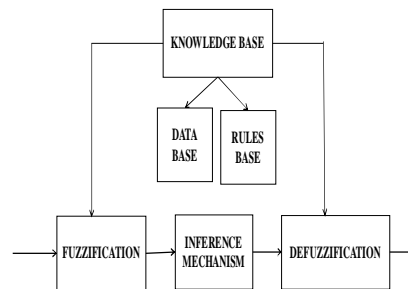
The drawback suffered by PI controller is overcome by Fuzzy. In comparison to the linear PI controller, this is a non-linear controller that can provide satisfactory performance under the influence of changing system parameters & operating conditions [8][9]. The function fuzzy controller is very useful as relieves the system from exact & cumbersome mathematical modeling & calculations. The performance of fuzzy controller is well established for improvements in both transient & steady state [10]. The fuzzy controller comprises of four main functional modules namely; Knowledge base, Fuzzification, Inference mechanism & Defuzzification.

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### Knowledge Base:

It consists of data base & rule base that maps all the input & output with certain degree of uncertainty in process parameters & external disturbances to obtain good dynamic response. Data base scales the input-output variables in the form of membership functions that defines it in a range appropriate to provide information to the fuzzy rule-based system & output variables or control actions to the system under observation. Fuzzy rule-based system utilizes a collection of fuzzy conditional statements derived from a knowledge base to approximate and construct the control surface.

### Fuzzification

It is the process of defining a crisp data or digital data operating on discrete values of either 0 or 1 in terms of logical variables that take on continuous values between 0 and 1 i.e. fuzzy set. Fuzzy set maps the input-output variables into membership functions & truth values. It is the first process in this controller.

### Inference Mechanism:

It is referred to as approximate reasoning that uses knowledge to conduct deductive inference of IF-THEN rules. This mechanism encodes knowledge about a system in statements form of linguistic IF -THEN propositions with antecedents & consequents. There are three types of fuzzy inference mechanism:

Mamdani System (1975)

Sugeno models: Takagi and Sugeno(1985) & Sugeno & Kang(1988)

Tsukamoto models( 1979)

### Defuzzification

It is a conversion process of fuzzy quantity to a precise quantity and is reverse process of fuzzification. A logical union of two or more membership functions in the universe of discourse requires a crisp decision with approximate solution for the output of fuzzy which is uncertain in nature to be a single scalar quantity. Various methods for defuzzifying the output membership functions have been proposed; out of them four of widely used are summarized as follows:

Centroid method

Centre of sums method(cos)

Weighted average method

The FLC controller of the tested system exploits the Mamdani type of inference method. It defuzzifies the crisp input-output variables into fuzzy trapezoidal membership function and reverse process of Defuzzification is based

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upon the Centroid method. The controller core is the fuzzy control rules as shown in table I. which are mainly obtained from intuitive feeling and experience.

## SINGLE PHASE UNCONTROLLED AC-DC CONVERTERS

AC-DC converters are commonly known as rectifiers. A rectifier converts AC to DC. The purpose of a rectifier may be to produce an output that is DC, or the purpose may be to produce a voltage or current waveform that has a specific DC component. Single Phase Rectifiers are of two kinds:

Half wave rectifier

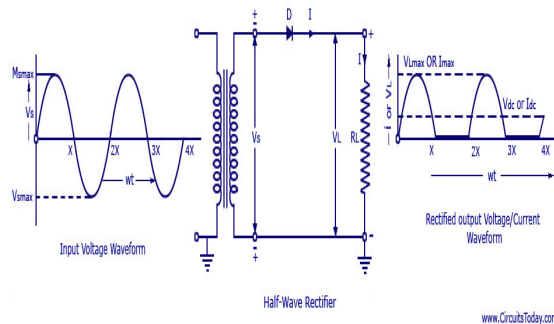
Full wave rectifier

Each of these rectifiers can either be uncontrolled or controlled by SCR, IGBT or by power semiconductor switches. In practice, the half-wave rectifier is used most often in low power applications because the average current in the supply will not be zero, and nonzero average current may cause problems in supply performance due to magnetic saturation.

### Half Wave Rectifier:

A basic half-wave rectifier with a resistive load is shown in Fig. 2.1. The source is AC, and the objective is to create a load voltage which has a nonzero DC component [27]. The diode is a basic electronic switch that allows current in one direction. For the positive half cycle of the source in this circuit, the diode is on (forward biased). Considering the diode to be ideal, the voltage across a forward-biased diode is zero and the current is positive. For the negative half cycle of the source, the diode is reverse-biased, making the current zero. The voltage across the reverse biased diode is the source voltage, which has a negative value.

$$\text{Output Voltage, } V_o = V_m/\pi$$



The dc component of the current for the purely resistive load is

$$I = V_o/R = V_m/\pi R$$

When the voltage and current are half-wave rectified sine waves then

$$V_{rms} = V_m/2$$

$$I_{rms} = V_m/2R$$

### Full Wave Rectifier:

The objective of a full-wave rectifier is to produce a voltage or current which is dc or has some specified dc component. While the purpose of the full-wave rectifier is basically the same as that of the half-wave rectifier, full wave rectifiers have some advantages. The average current in the AC source is zero in the full-wave rectifier, thus avoiding problems associated with nonzero average source current in transformers. The output of the full-wave rectifier has inherently less ripple than the half-wave rectifier.

Full wave rectifiers may be of two configurations: [29]

- Bridge rectifier

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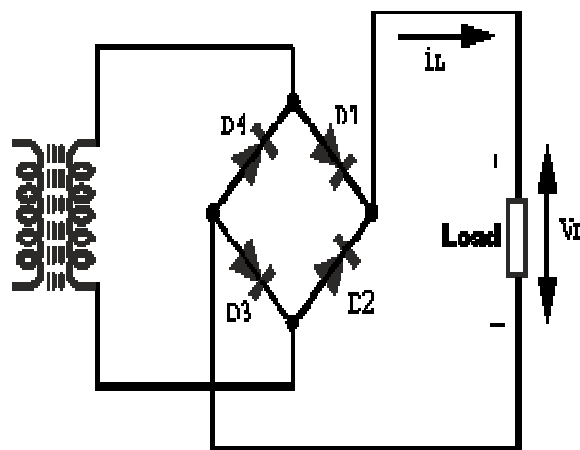
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□ Center-tapped transformer rectifier

A basic full-wave bridge rectifier with a resistive load is shown in Fig. 2.3. The dc component of the output voltage is the average value, and the load current is simply the resistor voltage divided by resistance:

$$\begin{aligned} \text{Output Voltage, } V_o &= 2V_m/\pi && \text{Load} \\ \text{current, } I_o &= V_o/R = 2V_m/\pi R \\ \text{RMS Source current} &= \text{RMS Load current} = I_{rms} = I_m/\sqrt{2} \end{aligned}$$

The source current for the full-wave rectifier with a resistive load is a sinusoid which is in phase with the voltage, so the power factor is 1. The average source current is zero. The fundamental frequency of the output voltage is  $2\omega$ , where  $\omega$  is the frequency of the AC input, since two periods of the output occur for every period of the input. The Fourier series of the output consists of a DC term and the even harmonics of the source frequency. The voltage waveforms across the source and load.



Placing a large capacitor in parallel with a resistive load can produce an output voltage that is essentially DC (Fig. 2.5). In the full-wave rectifier circuit, the time that the capacitor discharges is smaller than for the half-wave circuit with a capacitor because of the rectified sine wave in the second half of each period. The output voltage ripple for the full wave rectifier is approximately one-half that of the half-wave rectifier. The peak output voltage will be less in the full wave circuit because there are two diode voltage drops rather than one. The ripple voltage is calculated as peak-to-peak ripple voltage,  $\Delta V_o = V_m \pi / \omega RC$ . An example of output ripple voltage. Input voltage ( $V_2$  in Fig. 2.7) and input current ( $I_1$  in Fig. 2.7) reveal the problem of supply interface due to discontinuous current pulses. Input Power Factor is found to be very poor ( $<0.6$ ). Input current THD is also found to be very high ( $>140\%$ ). Efficiency is also very low ( $<60\%$ ). Therefore the power quality is very poor.

### DC-DC CONVERTERS:

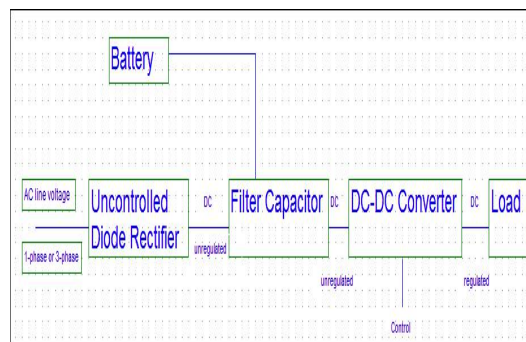
The DC-DC converters are used in regulated switch-mode DC power supplies and in DC motor drive applications. As shown in Fig.3.1, the input to these is unregulated DC voltage, which is obtained by rectifying the line voltage, and therefore it will fluctuate due to changes in the line-voltage magnitude. Switch-mode DC-to-DC converters are used to convert the unregulated DC input into a controlled dc output at a desired voltage level.

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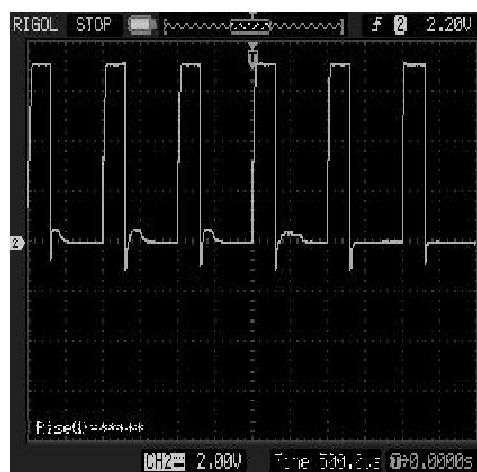
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The converters are analyzed in steady state. The switches are treated as being ideal, and the losses in the inductive and capacitive elements are neglected. The DC input voltage to the converters is assumed to have zero internal impedance. In DC-DC converters, the average DC output voltage must be controlled to a desired level despite fluctuation of the input voltage and output load. Switch-mode DC-DC converters utilize one or more switches to transform DC from one level to another. In a DC-DC converter with a given input voltage, the average output voltage is controlled by controlling the switch on and off (Ton and Toff) durations. In this method, called pulse-width modulation (PWM) switching, the switch duty ratio  $D$ , which is defined as the ratio of the on duration to the switching time period, is varied.

$$\text{Duty Cycle, } D = \text{Ton}/T$$



A typical PWM generated signal is shown in Fig.3.2. A constant switching frequency,  $f$ , in a PWM control is chosen to be in a few kHz to a few hundred kHz. The dc-dc converters can have two distinct modes of operation:

- Continuous Current Mode(CCM)
- Discontinuous Current Mode(DCM)

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In practice, a converter may operate in both modes, which have significantly different characteristics. Therefore, a converter and its control should be designed based on both modes of operation. We assume continuous current mode in all cases.

### Types of DC-DC Converters:

There are different types of DC-DC converters. Among these following are the common,

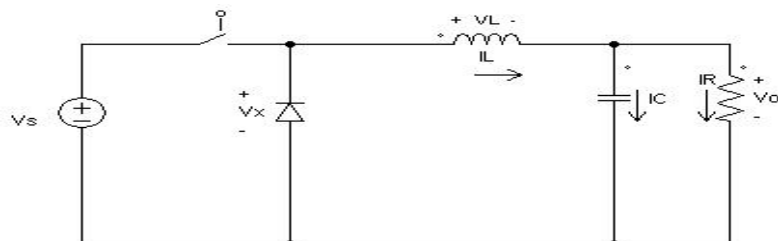
- Buck Converter,
- Boost Converter,
- Buck-Boost Converter
- Ćuk Converter,
- SEPIC Converter and
- Inverse SEPIC Converter.

Of these six converters, only the buck (step-down) and the boost (step-up) are the basic converter topologies. Buck-Boost, Ćuk, SEPIC and Inverse SEPIC are different combination of these two basic topologies.

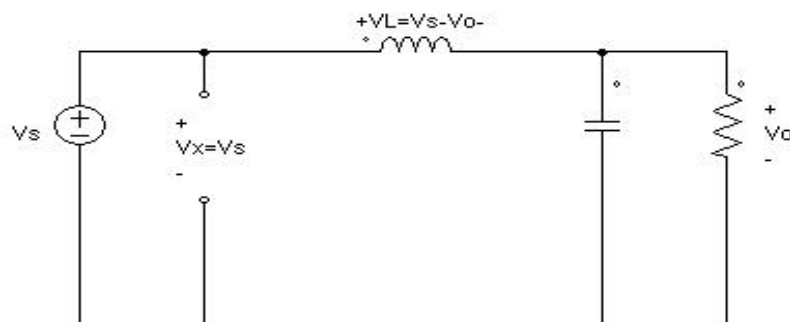
### Buck Converter:

As the name implies, a step-down converter produces a lower average output voltage,  $V_o$  than the dc input voltage  $V_{in}$ . The ideal input-output voltage and current relationships with the duty cycle are given by:

$$V_o/V_{in} = D = I_{in}/I_o$$



Equivalent for switch closed:



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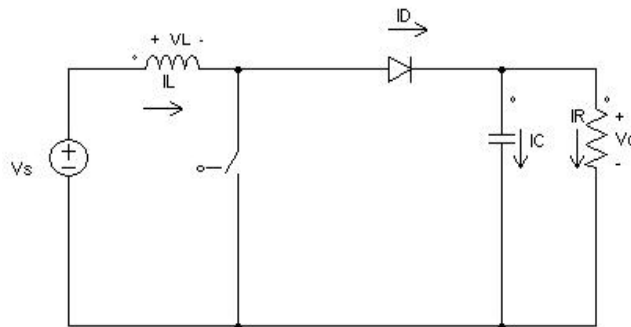
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**Buck converter of the circuit switch ON**

**Boost Converter:**

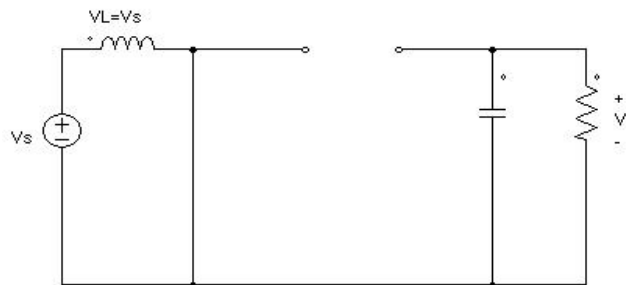


As the name implies, the output voltage is always greater than the input voltage. When the switch is on, the diode is reversed biased, thus isolating the output stage. The input supplies energy to the inductor. When the switch is off, the output stage receives energy from the inductor as well as from the input. In steady-state analysis, the output filter capacitor is assumed to be very large to ensure a constant output voltage,  $V_o$ . The ideal input-output relation is given by:

$$V_o/V_{in} = 1/(1-D) = I_{in}/I_o$$

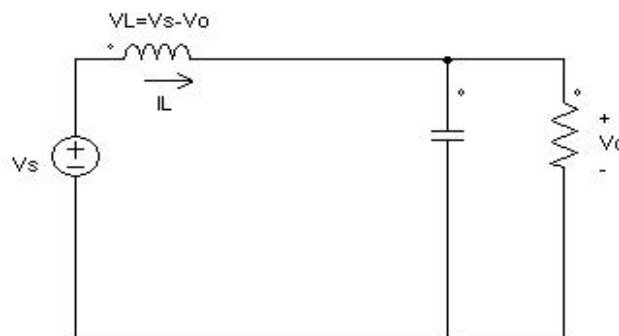
Boost converters are the most commonly used DC-DC converters in PFC techniques.

Equivalent for switch closed:



**Boost converter of the circuit with switch ON**

Equivalent for switch open:





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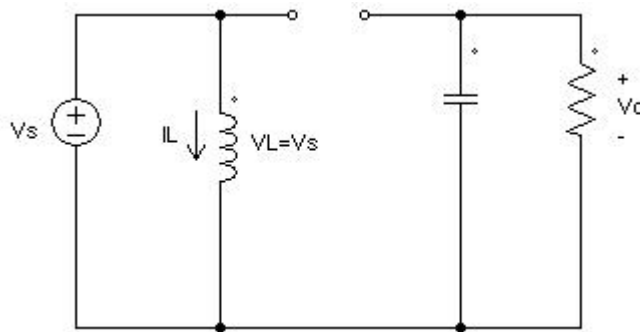
### Boost converter of the circuit with switch OFF

#### Buck-Boost Converter:

A buck-boost converter can be obtained by the cascaded connection of the two basic converters: the step-down and the step-up converter. It inherits pulsating input current of buck and pulsating output current of boost. The ideal output-to-input voltage conversion ratio is given by:

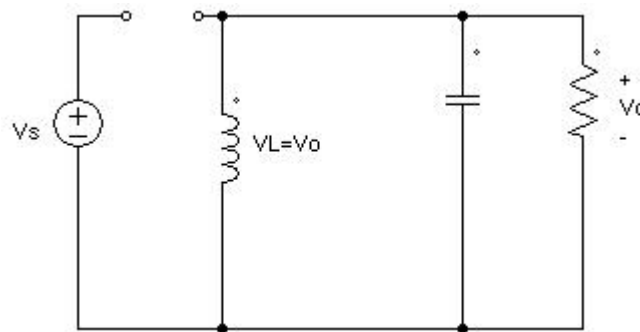
$$V_o/V_{in} = D/(1-D) = I_{in}/I_o$$

This allows the output voltage to be higher or lower than the input voltage, based on the duty ratio,  $D$ .  $D < 0.5$  ensures buck operation and  $D > 0.5$  ensures boost operation.



#### Buck-Boost DC-DC Converter

Equivalent for switch closed:



### Buck-Boost converter of the circuit with switch ON

#### Ćuk Converter:

Named after its inventor, the Ćuk converter is shown in Fig.3.15. This converter is obtained by using the duality principle on the circuit of a buck-boost converter, discussed in the previous section. Like buck-boost converter, output voltage is inverted with respect to the input voltage. It has the same ideal voltage and current gain relationship as the Buck-Boost DC-DC converter.

#### SEPIC Converter:

Single-ended primary-inductor converter (SEPIC) is a type of DC-DC converter allowing the electrical potential (voltage) at its output to be greater than, less than, or equal to that at its input. The output of the SEPIC is controlled by the duty cycle of the control transistor. A SEPIC is similar to a traditional buck-boost converter, but has advantages of having non-inverted output (the output voltage is of the same polarity as the input voltage), the isolation

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between its input and output (provided by a capacitor in series). On the other hand, power factor correction converters are extensively used in the industrial life. These converters aim at increasing the power factor and decreasing the total harmonic distortion of the supply current.

Power factor correction and minimization of total harmonic distortion find great interest from researchers [19-21]. The international standards such IEC 61000-3-2 [10] restrict the maximum allowable total harmonic distortion for the current drained from the electric system. A typical SEPIC converter is shown in Fig.3.19. It is a boost incorporated dc-dc converter.

### Inverse SEPIC Converter:

The ZETA converter (also known as the inverted SEPIC) offers certain advantages over the classical SEPIC. „Inverse“ comes from the fact that if the SEPIC converter is rotated around Y-axis it transforms to this topology. This topology has the same buck-boost functionality as the SEPIC, but the output current is continuous, providing a clean, low-ripple output voltage. This low-noise output converter can be used to power certain types of loads, such as LEDs, which are sensitive to the voltage ripple. The ZETA converter offers the same DC isolation between the input and output as the SEPIC converter, and can be used in high-reliability systems. This topology can offer high efficiency, especially if the synchronous rectification is used. The synchronous rectification can be easily implemented here, because this topology, unlike the SEPIC converter, uses a low-side rectifier. Besides, direct DC-DC converters briefly described, transformer coupled fly back and forward DC-DC converters, and other modified DC-DC converters to suit certain applications are also available in literature.

**Topology Based Rectifier Configuration 1 for Load Variation:**

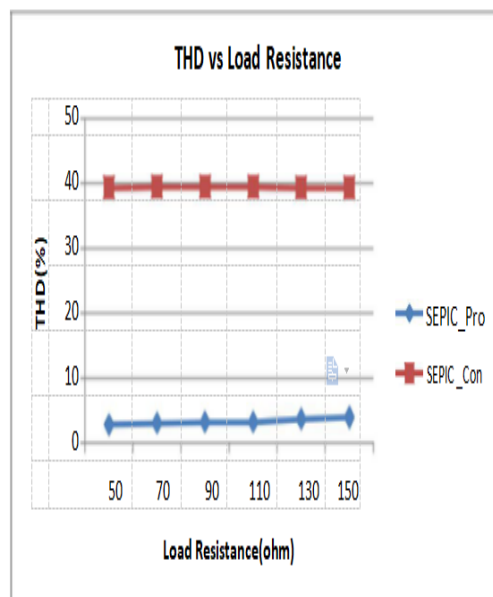
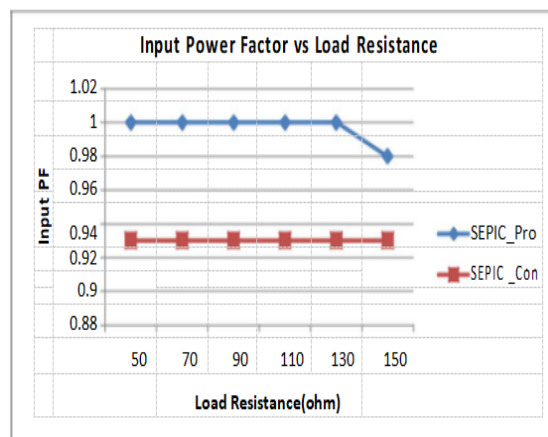
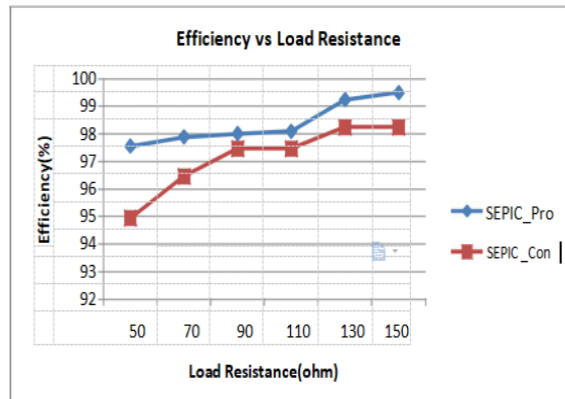
Load Resistance, RL (Ω)	Efficiency, η(%)		Input Power Factor (PF)		THD (%)	
	Proposed	Conventional	Proposed	Conventional	Proposed	Conventional
	SEPIC Topology	SEPIC Topology	SEPIC Topology	SEPIC Topology	SEPIC Topology	SEPIC Topology
50	97.55	94.94	1.00	0.93	2.83	39.3
70	97.89	96.46	1.00	0.93	3.08	39.4
90	98.01	97.46	1.00	0.93	3.23	39.4
110	98.10	97.46	1.00	0.93	3.28	39.4
130	99.24	98.25	1.00	0.93	3.70	39.3
150	99.50	98.25	0.98	0.93	3.99	39.3

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Efficiency, Input PF and THD vs. Load Resistance of input switched SEPIC AC-DC converter

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## III. CONCLUSION

### Summary of the thesis:

A single phase full wave diode rectifier has been studied. The input current was found non sinusoidal pulsating and the THD was high. A passive output filter has been employed to make the input current sinusoidal. The THD and efficiency was found at the desired levels. But the filter was large. The output voltage was not controllable.

Output regulated DC-DC converters have been investigated by researchers with small input filter. It was observed that the input current had low THD and high efficiency. The output voltage was also controllable. The study was repeated in this thesis. The switching frequency was kept constant at 5 kHz. It was found from the analysis that the THD has improved wide range of duty cycles, but the overall efficiency of the regulator was not acceptable in the open loop control at all duty cycles. It was also observed that efficiency and THD cannot be kept at the desired level simultaneously with change in duty cycle.

In this thesis, input switched single phase AC-DC converter circuits have been studied and presented. The topologies used are Buck, Boost, Buck-Boost, Ćuk, SEPIC and Inverse SEPIC. Each type studied has multiple configurations, where, the last configuration in each type is the newly reported configuration (Buck, Boost Configuration-2, Buck-Boost Configuration-3, Ćuk Configuration-2, SEPIC configuration-2, and Inverse SEPIC configuration-2). Newly proposed Buck and Buck-Boost topologies have one Buck/Buck-Boost inductor, whereas, the previously reported circuits had two inductors. In Ćuk, SEPIC and Inverse SEPIC configuration also, the output stage have less number of inductors than previously reported circuits. All the newly proposed input switched single phase AC-DC converters are easier to implement than previously reported circuits. The circuits without any feedback exhibit improved performance than their counter part of output regulated single phase AC-DC converters.

Newly proposed Boost (configuration 2) based input switched rectifier have been studied as an example of feedback controlled rectifier. Some controller circuit has been used for input and output switched single phase Boost AC-DC converter and the result in the form of typical waveforms are presented in this thesis. This illustrates that input switched single phase AC-DC converter topologies can also be successfully used in input current shaping, input power factor improvement and efficiency improvement

Input switched configurations have more diodes in the circuits than the output regulated circuits. However, the voltage stress across the switch of the input switched rectifiers is less than their output regulated counterparts. Further the study without feedback revealed that the input switched circuits have less input current THD than the output regulated circuits, hence it is expected that input regulated single phase AC-DC converters will require small input current filter for some input current ripple over sinusoidal shape. The same observation is applicable for output voltage filters of the two types of rectifiers.

## IV. FUTURE WORK

The contributions of this thesis indicate the opportunities of extending this work in future to meet other goals.

- Only simulation study is performed in this study. The proposed input switched AC-DC converter schemes may be implemented practically to investigate their actual potential. Such practical implementation would give further insight regarding the cost effectiveness of the proposed schemes compared to conventional PFC techniques of the similar types.
- Investigation can be made to improve quality of the gating signals at different duty cycle.
- Switching losses and EMI interference were not considered here. These can be investigated in future works.
- During the change of the output voltage by varying the duty cycle, it has been observed that the power factor also changes and becomes very low in some cases. To maintain the power factor unity at all duty cycle and output voltage, feedback control may be used as shown in the example of Boost PFC rectifier which will keep the power factor close to the unity and keep the THD and efficiency at acceptable levels.

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- Concept of hybrid AC-DC converter technology may be studied using input switching technology to attain good performance at very low and at very high voltage attenuations/gains where component non-idealities play a major role.

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