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Input switched closed-loop single phase ĈUK AC to DC converter with improved power quality

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ABSTRACT

A new closed loop AC to DC ĈUK converter is presented in this paper. The conventional ĈUK AC to DC converter has no feedback circuit. Thereby, the output voltage of the converter changes while changing the load. The proposed closed loop converter can regulate voltage with the variation of load over a wide range. Moreover, the power factor and Total Harmonic Distortion (THD) of the supply side current found quite satisfactory from this closed loop ĈUK converter. The converter operates in four steps with a different combination of voltage polarities and switching states. The feedback path consists of a voltage control loop and a current control loop. The closed loop ĈUK converter in this study is compared with the open loop version. Additionally, the comparison is made with the conventional converter of the same topology. The effectiveness in terms of power factor and THD of the proposed converter is verified using simulation results.

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1. INTRODUCTION

Utilization of DC switching power supplies in computer and telecom industries are flourishing day by day. Additionally, use of DC power supply in the electric transportation is becoming popular instead of conventional engine driven vehicles. Additionally, the DC power supplies are the driven force in aviation and power station sectors throughout the world [1–3]. Usually, rectifiers are used to convert alternating supply to direct supply [4–6]. However, these rectifiers inject non-sinusoidal current at grid side which contains harmonics. Due to the presence of harmonics, some of the problems like harmonic losses and core saturation in power transformers frequently take place. Thereby, removing harmonics is a significant concern for industries as well as the power supply authorities to keep the system robust [4, 5, 7, 8].

Passive and active filtering are two commonly used methods to remove harmonics. The Passive filter needs bulky indictors and capacitors which is costly and imposes a restriction on the mobility of the converter [7, 9–13]. The active filter usually consists of a switch of high frequency and reduced sized inductors and capacitors. Using the active filter has become a significant issue for modern industries to reduce harmonics from the power line.

Usually switching is performed at the output side of the converter. These types of conventional circuits are consists of a rectifier cascaded with a DC-DC converter. Newer circuits have also been designed using the single switch at the input side of power converters [5, 7, 10, 11, 14–16]. These converters give improved performances in terms of Total Harmonic Distortion (THD) and power factor at AC side. However, most of the input switched converters reported so far are open loop [5, 7, 10, 11, 14–16]. Hence, such a converter cannot regulate voltage and also cannot maintain good power factor under load variation. In the best of the authors' knowledge, no significant works have been done on closed loop input switched AC-DC converter.

In recent years, some research has been done on the reduction of THD of currents in the converters as well as in the power line. The multistage converter is widely used for THD reduction [17–20]. These converters consist of 6, 12, 24 pulse system, which is, however, challenging to implement and control. Moreover cost also increases while maintaining the multiple-pulse system. Additionally, matrix-based topologies are also used to achieve reduced THD [21–23]. However, it is difficult to maintain a lot of switches used in the converter which increases switching losses [24].

Some of the recent works incorporate quad-active-bridge AC–DC converter, automatic-power-decoupling controlled single-phase AC-to-DC converters, five-level packed U-cell converter, neural network based reference current generation schemes and so forth [25–28]. However, the primary challenge is implementation due to technical complexity.

In this regard, input switched close loop ĈUK topology based converter is investigated. The ĈUK topology has significant benefits over other topologies like buck and buck-boost. The principle benefit is that the input current and the output current of the ĈUK converter is continuous. Thereby, the converter can provide energy to the load both on and off states of the switch [5]. This proposed ĈUK converter has four operating states which ensure the switching of the alternating input current at high frequency [5, 7]. Furthermore, the converter has two loops at the feedback path, namely voltage control and current control loops. These loops can regulate the output voltage with satisfactory power quality.

The rest of the paper is organized as follows. In section II, the structure and working principles of the voltage and current control loops are discussed briefly. In section III, the structure of closed loop converter is discussed. Section IV discusses the working principle of the proposed circuit. Section V presents the simulation results and discussion, followed by a conclusion in section VI at the end.

2. THE VOLTAGE AND CURRENT CONTROL LOOPS

The controller circuit consists of a voltage control loop and a current control loop. Figure 1 shows a typical structure of the controller. The voltage loop consists of a voltage sensor, a summer and a PI controller. The current loop consists of the voltage sensor, a summer, a multiplier and a PI controller. The output voltage sample is given to the input of the fed back controller circuit. The output voltage sample is compared with the reference signal and generates an error voltage. Generated error voltage goes to the input of the PI controller and produces the reference signal. The reference signal goes to the input of the current control loop for the comparison with a reference current signal. After comparison, the error current signal is generated, which has been sent to the input of another PI controller. After being processed in the current control loop, the message signal is generated. This signal has been compared further with a high-frequency carrier signal. Further, the comparison is made in a comparator and the gate pulse is obtained which is used to control the switch of the converter [29, 30].

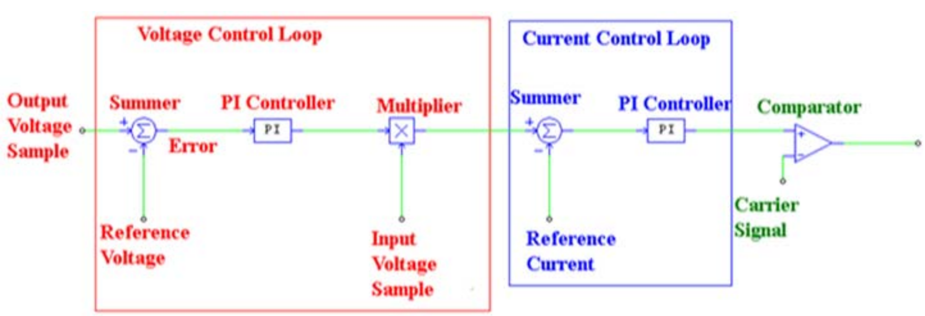


Figure 1. The typical structure of the voltage and current control loops

3. STRUCTURE OF PROPOSED CIRCUIT

Figure 2 shows the circuit structure of the proposed closed loop ĈUK AC-DC converter. The converter is assembled with inductors (Ll, L2), capacitors (Cl, C2), a semiconductor switching device (Sl) and the diodes. The Ll and Cl remain active when the source polarity is positive. On the contrary, the L2 and C2 are active when the source polarity is negative. However, the inductors labeled as L_Filter_1, L_Filter_2, L_Filter_3, L_Filter_4 and the capacitors C_Filter_1, C_Filter_2 are used to construct the input filter. The Co and Ro are the output capacitor and load respectively.

Additionally, the feedback path comprises two loops. The voltage control loop consists of a voltage sensor, a summer and a PI controller. On the other hand, the current control loop is formed by sensors, a multiplier, a summer and a PI controller. The voltage control loop helps to regulate the output voltage and the current loop helps to maintain quality power factor at the AC side by adjusting the duty cycle of the switch (S1).

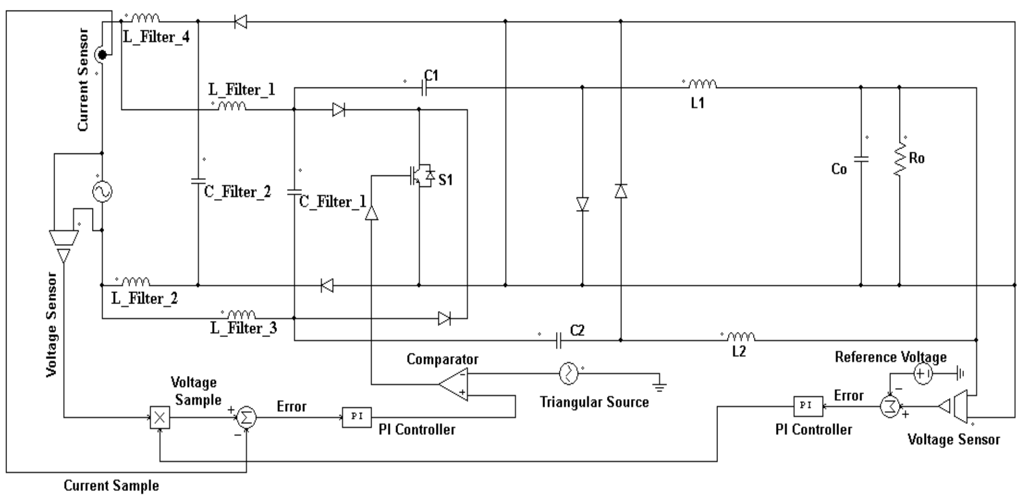
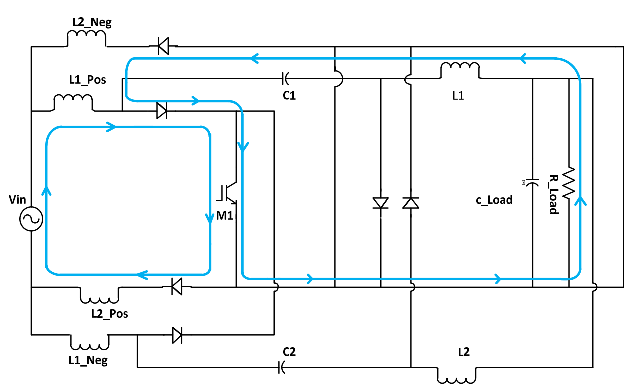


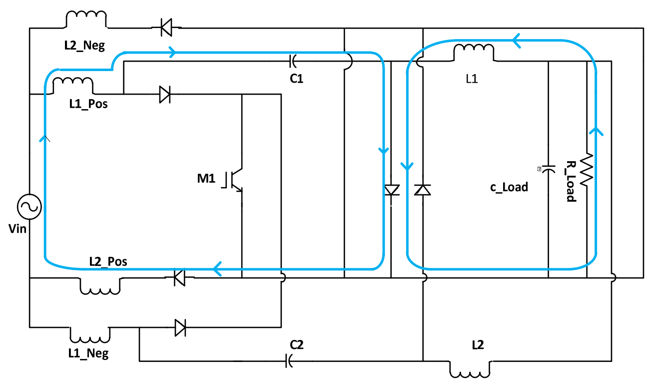
Figure 2. The proposed closed loop ĈUK AC-DC converter

4. WORKING PRINCIPLE

The line current at supply side is alternating (AC) in nature. In the proposed converter, this alternating input current is sampled at high frequency. Thereby, a small-size filter is required to make the current almost sinusoidal. Hence, the THD of the current reduces and the power factor at the supply side improves. Furthermore, the proposed ĈUK AC to DC converter works in four steps, which is presented in Figure 3. At step 1 and 2, the supply voltage polarity is positive and the switch is in the close and open state respectively. Similarly, states 3 and 4 correspond to the other two steps of operation when the supply voltage polarity is negative. The energy flow is accompanying with a capacitor and inductor Cl and L1 for the first two steps. Similarly, the capacitor and inductor C2, L2 remains active at last two steps.



(a)



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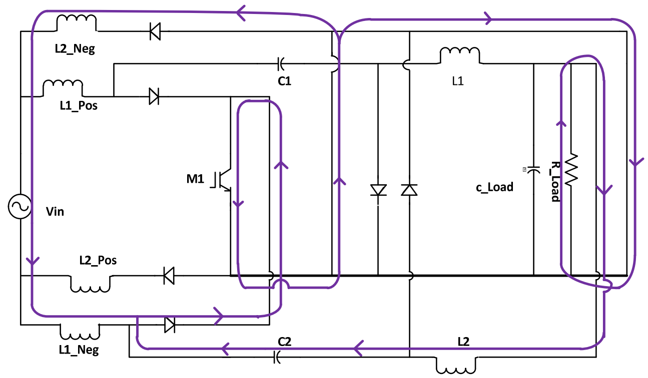

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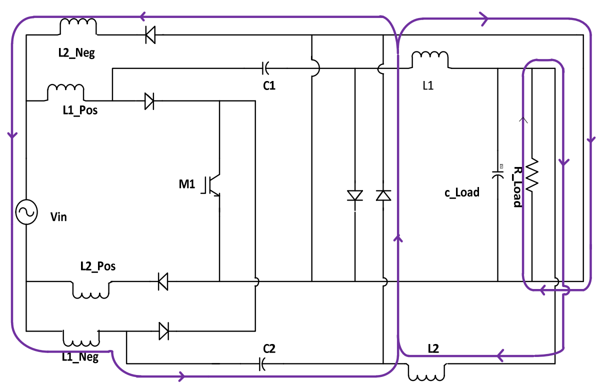

(d)

Figure 3. The operating steps of the proposed ĈUK AC-DC converter (A) Step 1, when switch is closed and supply voltage polarity is positive (B) Step 2, when switch is open and supply voltage polarity is positive (C) Step 3, when switch is closed and supply voltage polarity is negative (D) Step 4, when switch is open and supply voltage polarity is negative. [5]

5. SIMULATION RESULTS AND DISCUSSION

5.1. Circuit parameters

The proposed closed loop ĈUK converter configuration is simulated using PSIM professional version 9.0.3.400. An AC voltage source of 300V amplitude with a frequency of 50 Hz is employed. An Insulated Gate Bipolar Transistor (IGBT) acts as a switching device for the converter. For the ĈUK configuration, the energy transferring inductors (L1and L2) have their inductance of 1.5mH each. On the contrary; the inductors used in filtering (L_Filter_1, L_Filter_2, L_Filter_3 and L_Filter_4) have their inductance of 10 mH each. Similarly, the capacitors used for energy transfer (C1and C2) have their capacitance of 0.5μF each. Additionally, the filter capacitors (C_Filter_1 and C_Filter_2) have their capacitance of 1 μF each. The output capacitor Co has the capacitance of 470 μF. The load (Ro) is entirely resistive, which is varied to observe and analyze the performances of the converter. The proposed closed loop ĈUK converter is compared with the open loop ĈUK AC-DC configuration and the conventional one with consists of a rectifier cascaded with a DC-DC ĈUK converter.

5.2. Results and discussions

The simulated waveforms of the current at the input side and the terminal voltage of the proposed closed loop ĈUK AC to DC converter are presented in figure 4 to figure 6. The switching frequency (fs) used for simulation is of 4 kHz. Observing these figures, it can be concluded that the current at the input side is approximately sinusoidal with a regulated output voltage of 400V. Figure 7 to figure 9 represents the spectrums of the corresponding input side current. Analyzing these spectrums, it is observed that, the input currents have their peak value at 50 Hz for all the load values. This signifies the input current being near sinusoidal.

The corresponding results in terms of supply-side power factor and the THD of the input current of the closed loop converter are presented in Table 1. The input current THD values for a wide range of load resistance are recorded. According to the IEC 61000-3-2 and IEC 61000-3-4, the THD should be below 10%. From this table, it is observed that the THD values in most of the cases are pretty below the threshold. Satisfactory results are obtained when the load resistance is varied from 30Ω to 120Ω. For a few limiting cases, such as when the load resistance is in between 150Ω and 200Ω, the THD slightly exceeds. After crossing the 200Ω load value, the THD returns again within the threshold limit. Thereby, the closed loop converter shows satisfactory performances in terms of input current THD. Thus, the converter is applicable to a wide range of load values. In terms of supply-side power factor, the converter exhibits satisfactory performances as well. For the load values of 50 Ω, the supply side power factor is found above 90%. Thereby, considering the overall performances, it can be concluded that the proposed closed loop converter is applicable for the load values of 30Ω to 250Ω.

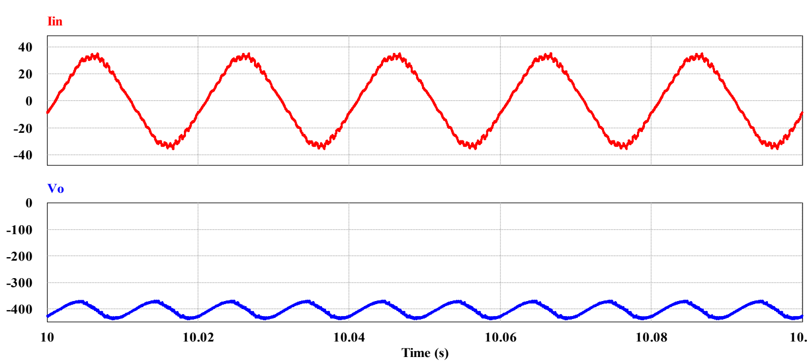

Figure 4. The waveform of the current at input side (Iin) and the terminal voltage (Vo) of the close loop ĈUK converter for load resistance of 50 Ω

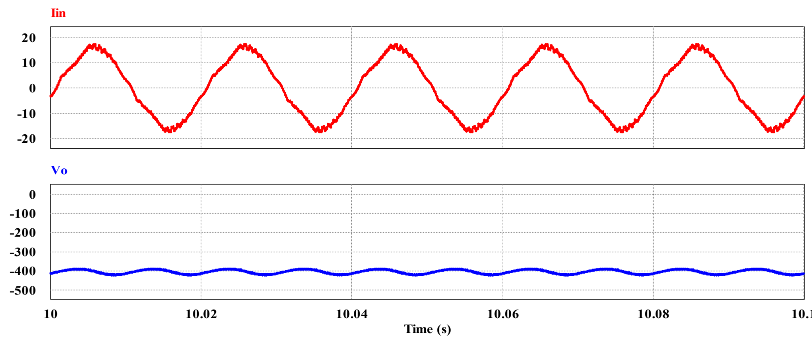

Figure 5. The waveform of the current at the input side (Iin) and the terminal voltage (Vo) of the closed loop ĈUK converter for a load resistance of 100 Ω

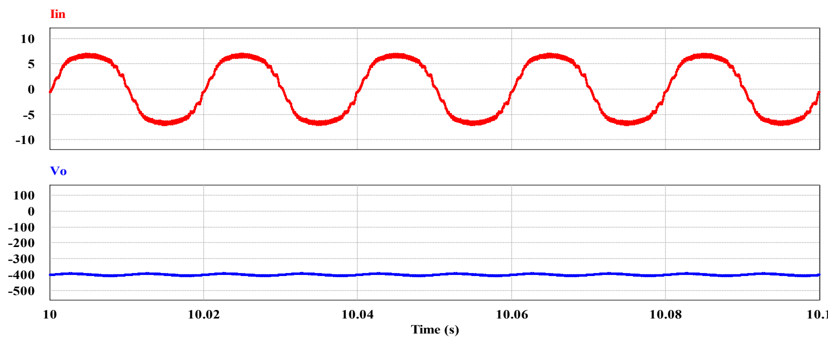

Figure 6. The waveform of the current at the input side (Iin) and the terminal voltage (Vo) of the closed loop ĈUK converter for a load resistance of 200 Ω

Figure 7. The input current spectrum of the closed loop ĈUK converter for load resistance of 50 Ω

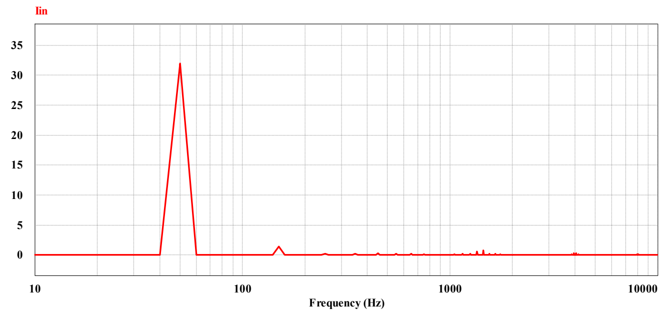

Figure 8. The input current spectrum of the closed loop ĈUK converter for load resistance 100 Ω

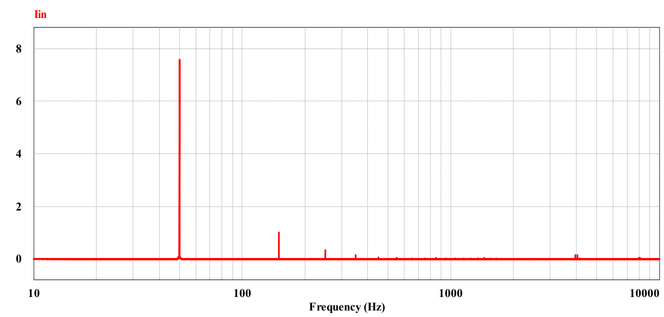

Figure 9. The input current spectrum of the closed loop ĈUK converter for load resistance 200 Ω.

Table 1. Numerical data for proposed ĈUK converter after introducing feedback controller

Load Value (Ω)	THD (%)	Power Factor
30	8.95	0.863
50	5.47	0.933
70	6.10	0.943
100	7.02	0.967
120	6.01	0.977
150	11.91	0.982
170	11.91	0.986
200	12.33	0.990
210	9.99	0.993
230	9.97	0.989
250	12.1	0.983

5.3. Comparative studies of power quality

The improvement in power quality of the proposed closed loop ĈUK configuration has been studied by comparing with the open loop version of the converter scheme, i.e. without having the feedback configuration. The comparison is also made with the conventional one having a rectifier cascaded with a DC to DC ĈUK converter circuit. Thereby, comparative scenarios are prepared in terms of THD (%) of the AC input side current and power factor at the input side. The results of the comparative studies are shown in Figure 10 to 11.

The bar chart displayed in Figure 13 specifies that the input current THD (%) of the closed loop converter is lower than that of both the open loop converter and conventional converters for most of the load values. The closed loop configuration has high input power factor at all load compared to the conventional one as illustrates in Figure 14. From the same figure, it is concluded that the input power factor of the closed loop configuration is above 90% for all the load values greater than 50 Ω. Additionally, the input power factor of the closed loop configuration is higher compared to the conventional one. In summary, considering the power qualities, it can be concluded that, the proposed closed loop ĈUK AC to DC converter is highly applicable to a wide range of load values.

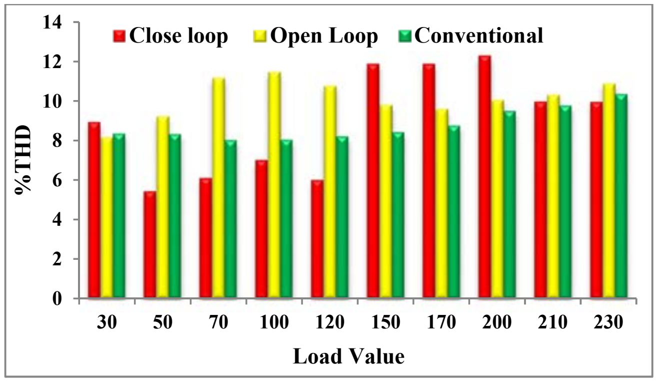

Figure 10. Comparison of %THD of the input current among different configurations

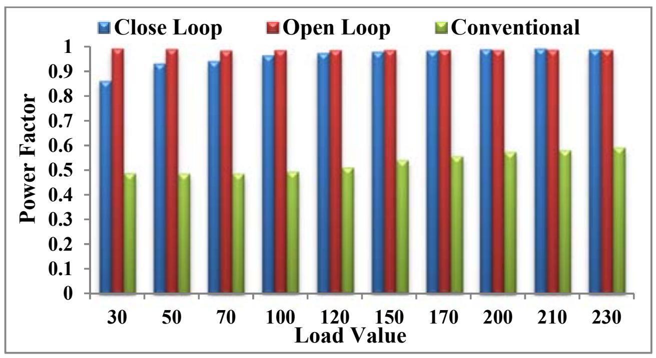

Figure 11. Comparison of power factor at the input side among different configurations

6. CONCLUSION

The performances of a single phase close loop ĈUK AC to DC converter is discussed in this paper. The difference between the proposed converter and the conventional one is that, the proposed circuit chops the input side current, which is AC. On the other hand, the conventional scheme chops the output current, which is DC by nature. Thereby, satisfactory performances regarding THD of the input side current and input power factor are achieved for the configuration. However, the main advantage is that the proposed configuration provides a regulated output voltage as well as maintains high power factor at the same time. Moreover, only one switch makes the control scheme simpler. Additionally, due to having a single switch, the switching loss is reduced, and the efficiency is increased. The closed loop ĈUK AC to DC converter is appropriate for a broader range of load value and switching frequency.

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