Two Stages Voltage Control Strategy using Cûk Topology with Three Phase Rectifier

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ABSTRACT

A two stage rectifier using Cûk topology is proposed to supply variable output voltage having amplitude higher and lower than input voltage in high frequency applications. The main purpose of this work is to achieve a wide variation of output voltage using two stages at the same circuit for same and different load situation. For this reason in this work single stage circuit is modified to a two stage topology for getting better regulation. The principal features of the circuit include bidirectional power flow with low harmonics and improved power factor. The proposed rectifier also able to draw sinusoidal input current with power factor nearly unity where different single stages is operated from a single three phase balance source and a simple control circuit is introduced to generate the switching pulses. The analysis has been carried out to control the output voltage more widely compared to single stage Cûk regulated rectifier. This rectifier contains two active switches and simple fixed frequency PWM technique is used to control it. The operating principle, circuit diagram and experimental results are presented in this paper.

1. INTRODUCTION

A variable dc power supply is the most important equipment in various electrical and electronics utilities. Traditionally dc is converted from ac sources through single phase or three phase diode bridge rectifier circuit. Because, they have some advantages of being simple, robust and low in cost [1-3]. But nonlinear operation, constant output voltage, unidirectional power flow, low power factor and harmonic pollution in the input side current are the major drawbacks of these rectifiers. The variable dc output voltage with improved power factor is practical requirements [4-7]. The output voltage can be made variable using a transformer in the output of a rectifier circuit. But the converter circuit becomes large and bulky in this case. Here a large filter is required to make sinusoidal input current with unity power factor. An effective way to design a light weight power converter is to reduce the volume and weight of passive bulky inductance and capacitance [8-12]. To solve the above problems rectifiers are analyzed using switch mode operation. The switch mode power supplies are much lighter than that of transformer power supplies. For this purpose Buck, Boost, Buck-boost topologies are commonly used. In most cases Boost topology has been used to overcome the following problems. Boost rectifiers are suffering from high voltage and current stresses. Another drawback of this topology is that they provide only greater output voltage than input voltage. But in practice many applications require both greater and lower output voltage than input voltage. The Buck-boost has the ability to step/down the output voltage. But they are not popular for their low efficiency and low power factor. In this case Cûk topology may be a good solution. Because, Cûk rectifier has the ability to step up or step down the output voltage than input voltage which is required for many applications. The input current is also almost sinusoidal with low harmonics and power factor is also near to unity in Cûk topology. But few works have been reported based on Cûk regulated rectifier. In [13] a three phase rectifier based on Cûk topology has been developed to solve these problems. It was a single stage single switch Cûk regulated rectifier requiring small sized input filter having the facility of stepping up and stepping down the output voltage and also capable of solving the problems of conventional Boost regulated rectifier with a good performance. But by using single stage voltage regulation it leads to poor switch utilization and single voltage variation opportunity. The main drawback is that the wide variation of output voltage has not been achieved. By using proposed two stage Cûk rectifiers it is possible to achieve two different variable voltages with a wide range of voltage regulation. For this reason in this work single stage circuit is modified to a two stage topology for getting better regulation than previous works.

2. OPERATING PRINCIPLE OF THE PROPOSED CIRCUIT

The most commonly used approach in ac to dc voltage conversion is the single stage approach. In many research works single stage Buck, Boost, Cûk converter has been analyzed to regulate ac to dc output voltage. But in most cases there are some problems, as high input current harmonics, low power factor etc. In practice many utilities require both higher and lower output voltage than input voltage. The above problem can be solved using Cûk regulator. In [13] a single stage Cûk regulator has been analyzed with three phase rectifier which is able to draw both lower and higher output voltage than input voltage. In this circuit, output voltage has been regulated some what lower than input voltage. In this respect two stage approaches may be a good solution. In single stage approach, voltage regulation and power factor correction control are performed in single step with good efficiency. Two stage approaches are relatively simple, mature and viable for a wide range of applications. But the two stage approaches suffer from several drawbacks. Due to two stages, power processing conversion efficiency is reduced and complexity increases and consequently increases the cost. In an effort to reduce the complexity, cost and improve the range of voltage regulation two stages has been made in this paper by introducing two separate single stages with a single source.

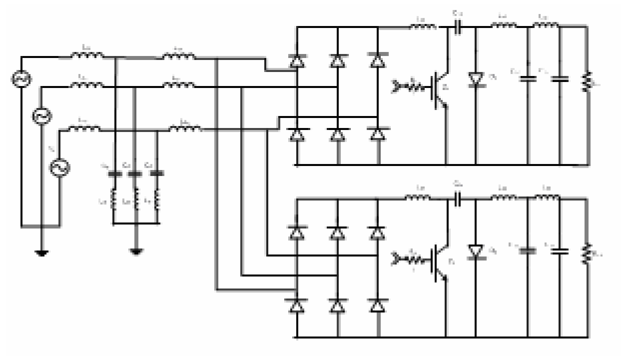


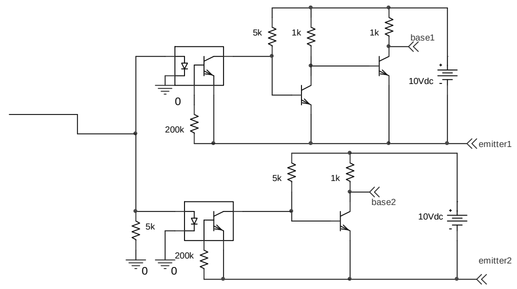
Fig. 1: The schematic circuit diagram of the proposed two stages Cûk regulated three phase rectifier.

The circuit diagram of the proposed regulated rectifier is shown in Fig. 1. The input current waveform with different duty cycle is illustrated in Fig. 2. Stage-1 consists of inductors L_{11}, L_{12}, an energy storage capacitor C_{11} and a Cûk switching element Z_1. The capacitor C_{11} is used to transfer energy and is connected alternately to the input and to the output of the converter. IGBT Z_1 is controlled in the same manner as single stage Cûk regulator. Two separate switching pulses are generated by control circuit to operate two different switches. One is operated with positive switching pulses and the other is operated with negative switching pulses. Z_1 is controlled with positive switching pulses.

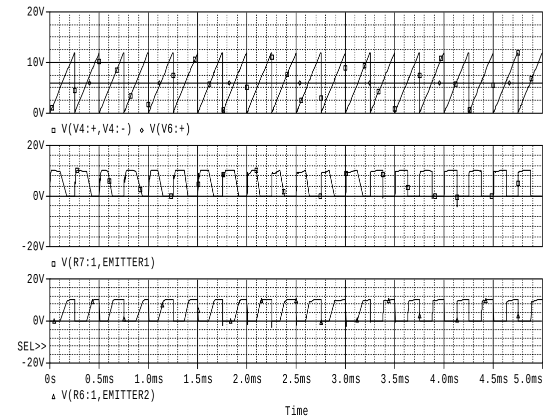
The two inductors L_{11} and L_{12} are used to convert the input voltage source and the output voltage source respectively into the current sources. Indeed, on a short time scale an inductor can be considered as a current source as it maintains a constant current. This conversion is necessary because the capacitor is connected directly to the voltage source. At the end of the switch Z_1 conduction period, the inductor current reaches peak values and diode D_1 is forward biased at this time. When Z_1 is turned off the energy of inductor L_{11} transfers to the energy storage capacitor C_{11} then it discharges its energy through inductor L_{12} and load R_{L1}. The resulting output polarity is inversely related to the input.

Similarly, Stage-2 consists of inductors L_{21}, L_{22}, an energy storage capacitor C_{21} and a Cûk switching element Z_2. During negative switching pulses Z_2 is switched on, the inductor current reaches peak values and diode D_2 is forward biased at this time. When Z_2 is turned off the energy of inductor L_{21} transfers to the energy storage capacitor C_{21} then it discharges its energy through inductor L_{22} and load R_{L1}. For charging and discharging process of C_{11} and C_{21}, the output voltage appears across the load R_{L1} and R_{L2}. Two different voltage levels can be obtained in this approach during a single period of switching pulses using the same load in two different stages. So this facilitates a wide variation of output voltage control strategy using the same source and rectifier. Here, these two stages can also be operated using different loads. When using two different loads, a more wide variation of output voltage can be achieved. But this has detrimental effect on the conversion efficiency and it requires a large filter with a large inductor and capacitor. Consequently, the cost and loss will increase.

3. CONTROL CIRCUIT DESIGN



(a)



(b)

Fig. 2: (a) The circuit diagram of control circuit and (b) Generation of switching pulses of the proposed circuit by the control circuit.

The voltage regulation in a converter is primarily a measure of the performance of the output voltage control. Various controlling techniques are available in switch mode regulator to control their switching element. Among these PWM technique is simple and popular. The method in which the control circuit regulates the output voltage of a switching device by constantly adjusting the conduction period or duty cycle of the power switching device is called PWM. In this method a triangular wave of fixed frequency is used as a reference signal and a variable dc voltage source is used as a carrier signal. An error signal is produced by applying both signals at the input of a comparator. Then a square wave switching pulse is generated which is used to drive the switching element IGBT Z_1 and Z_2. The control circuit should generate two switching pulses such that two switches are never on simultaneously. So isolation is necessary to control switches and to avoid the input virtually short circuit problem. In Fig. 2, the high frequency transistor is used after the opto-isolator to isolate the two switching pulses. The switching voltage is taken from the collector of the transistor and it is limited by using a fixed dc voltage source across the transistor. The magnitude of output voltage is controlled by controlling the duration of the switching pulses. The duty cycle is controlled by changing the dc level of the carrier voltage.

4. SIMULATED RESULTS

Since the voltage of energy storage capacitor C_{11} and C_{21} is loosely regulated and diode has some losses for reverse recovery activities, R_{L1} and R_{l2} provide output voltage which contains some ripple. A passive filter (L = 1mH and C = 200uF) is used to reduce ripple content from the output voltage. The output voltage can be regulated from 70V to 750V (when both loads are 50 Ω) with small ripple, while in a single stage rectifier it is varied from 250V to 520V. The harmonic pollution in input current is a common problem in diode rectifier.

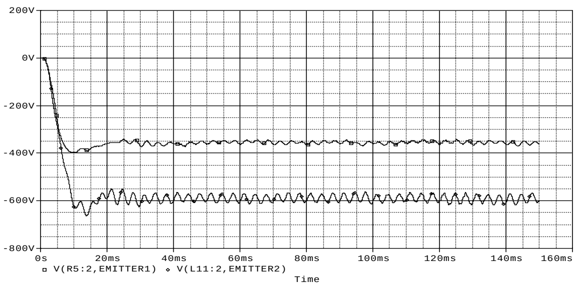


Fig. 3: Output voltage wave shape of stage-1 and stage-2 respectively of the proposed rectifier circuit with resonating filter (D = 0.4) When R_{11} = 50Ω and R_{12} = 50 Ω.

The resonant inductance is used in series with each phase to reduce harmonic components. Still 5^{th} and 7^{th} harmonics are observed in input current. This requires a resonance input filter having parameter 10mH and 50uF to reduce the above high frequency components of the pulsating input current waveform. Then input current of each phase becomes almost sinusoidal pulses, having peak amplitude proportional to the applied line to neutral voltage. The amount of THD is also reduced to less than 10%.

The output voltage wave shape of both stage-1 and stage-2 of the proposed circuit is shown in Figs. 3, 4 and 5 respectively. It is seen that the level of output voltage of stage-1 and stage-2 is changed with variation of duty cycle. The input current wave shape of proposed circuit with resonating filter is shown in Figs. 6, 7 and 8 respectively. It is observed that input current is almost sinusoidal with low harmonics.

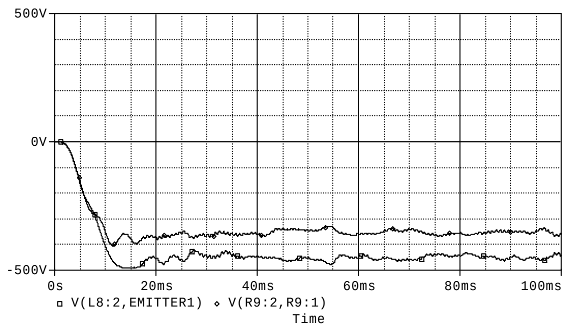


Fig. 4: Output voltage wave shape of stage-2 and stage-1 respectively of the proposed rectifier circuit with resonating filter (D = 0.5) When R_{11} = 50Ω and R_{12} = 50 Ω.

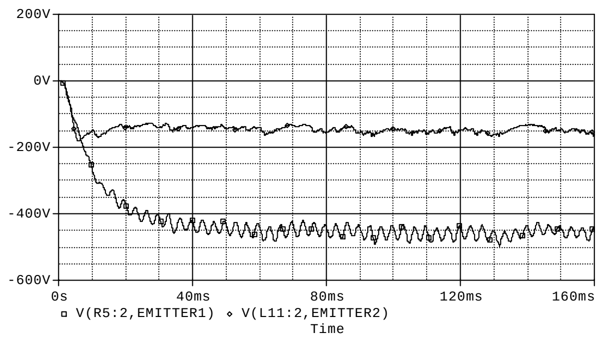


Fig. 5: Output voltage wave shape of stage-2 and stage-1 respectively of the proposed rectifier circuit with resonating filter (D = 0.8) When R_{11} = 50Ω and R_{12} = 50 Ω.

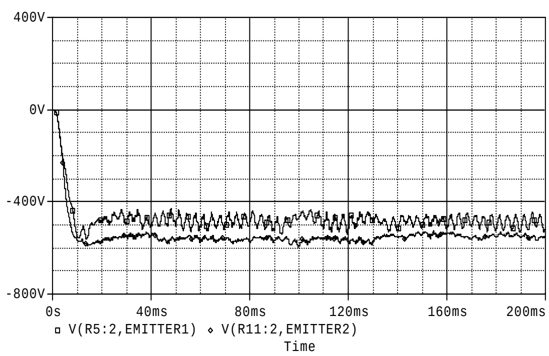


Fig. 6: Output voltage wave shape of stage-2 and stage-1 respectively of the proposed rectifier circuit with resonating filter (D = 0.5) When R_{11} = 50Ω and R_{12} = 100 Ω.

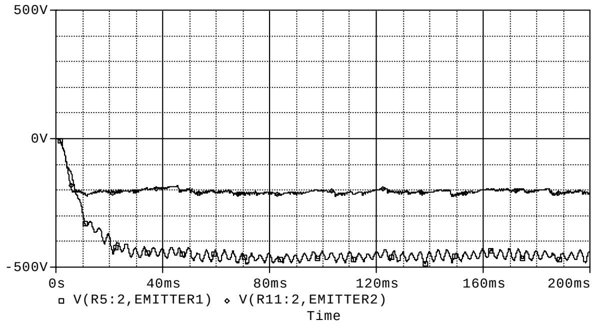


Fig. 7: Output voltage wave shape of stage-2 and stage-1 respectively of the proposed rectifier circuit with resonating filter (D = 0.8) When R_{11} = 50Ω and R_{12} = 100 Ω.

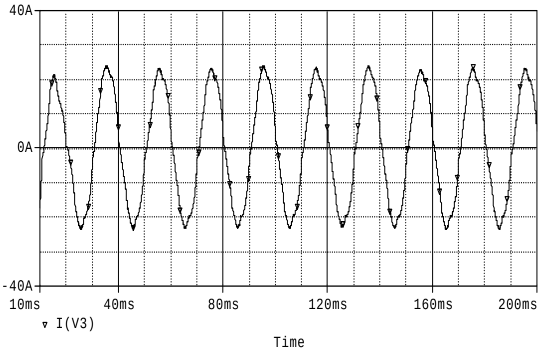


Fig. 8: Input current wave shape of the proposed rectifier circuit with resonating filter (D = 0.4).

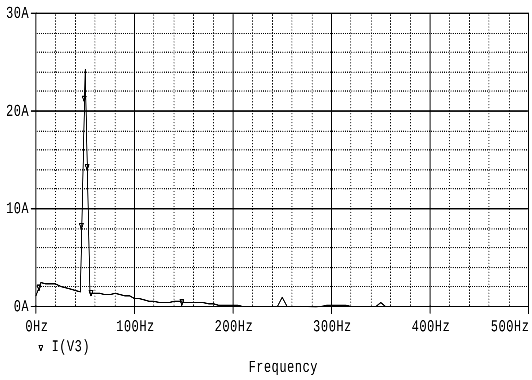


Fig. 9: Frequency spectrum of proposed rectifier circuit with harmonic filter (D = 0.4).

The comparative experimental results of the proposed circuit and the previous single stage Cûk rectifier are presented in table 1. The graphical representation of these output voltage with various duty cycle is shown in Figs. 9, 10 and 11 respectively. When both loads R_{L1} and R_{L2} are 50Ω, the output voltage of stage-1 increases gradually from 140V to 620V and then decreases slowly up to 200V at D = 0.95. While in stage-2 it rapidly rises from 440V to 700V and after that it starts to decrease steadily up to 70V at D = 0.95.

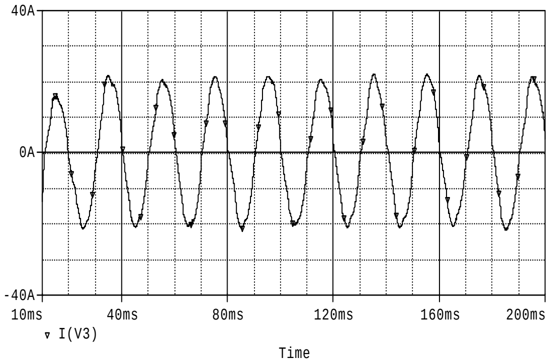


Fig. 10: Input current wave shape of the proposed rectifier circuit with resonating filter (D = 0.5).

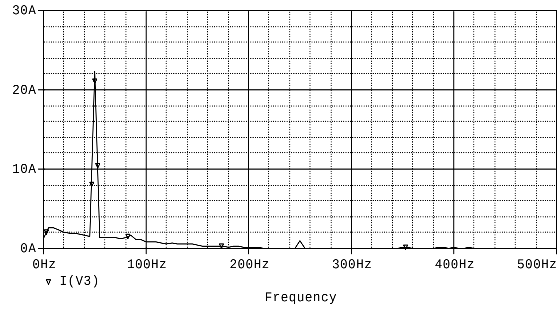


Fig. 11: Frequency spectrum of proposed rectifier circuit with harmonic filter (D = 0.5).

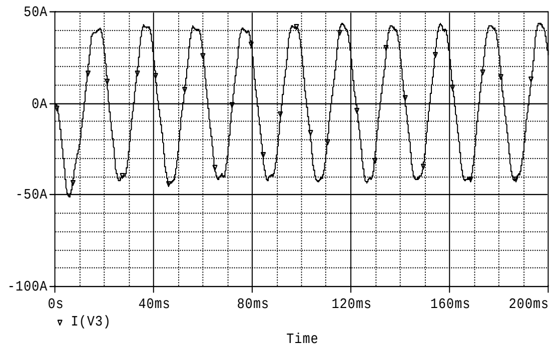


Fig. 12: Input current wave shape of the proposed rectifier circuit with resonating filter (D = 0.8).

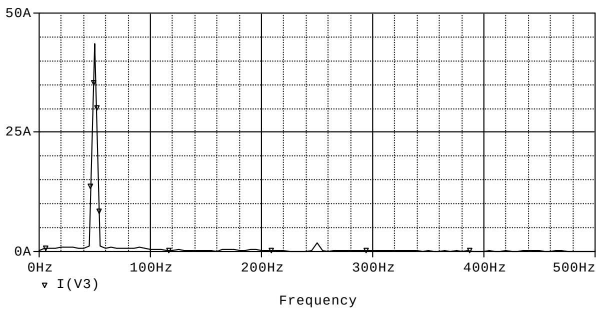


Fig. 13: Frequency spectrum of proposed rectifier circuit with harmonic filter (D = 0.8).

Table 1: Experimental results of proposed model and single stage Cûk regulated three phase rectifier

Duty cycle (D)	Output voltage in volts				
	For two Stage when R_{L1}=50Ω, R_{L2}=50Ω		For two Stage when R_{L1}=50Ω,R_{L2}=100Ω		For single stage when R_L=50Ω
	Stage-1	Stage-2	Stage-1	Stage-2	
0.1	140	440	250	890	430
0.2	220	700	300	1000	492
0.3	300	650	370	810	520
0.4	350	560	400	750	570
0.5	470	420	480	550	560
0.6	600	320	600	480	520
0.7	620	220	580	350	430
0.8	400	140	480	180	380
0.9	230	90	240	120	320
0.95	200	70	200	90	250

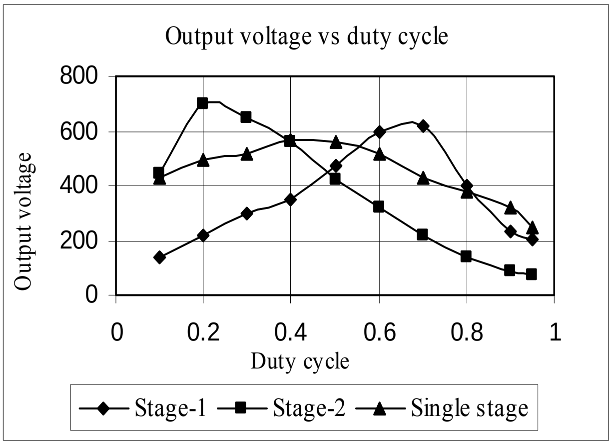


Fig. 14: Output voltage vs duty cycle with the proposed model (when R_{11} = 50Ω and R_{21} = 50Ω) and single stage Cûk rectifier.

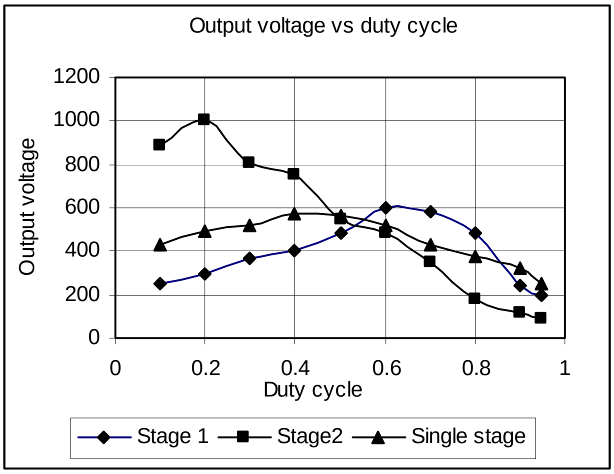


Fig. 15: Output voltage vs duty cycle with the proposed model (when R_{11} = 50Ω and R_{21} = 100Ω) and single stage Cûk rectifier.

When the load R_{L2} is changed to 100Ω, the maximum value of output voltage is found to be 600V in stage-1 and 1000V in stage-2, where the minimum voltage is 200V in stage-1 and 90V in stage-2. Fig 10 indicates the output voltage variation of single stage Cûk rectifier where output voltage is varied from 250V to 570V.

The variation of power factor of the proposed model with various duty cycles is shown in Fig. 12. It is seen that power factor varies from 0.78 to 0.99.

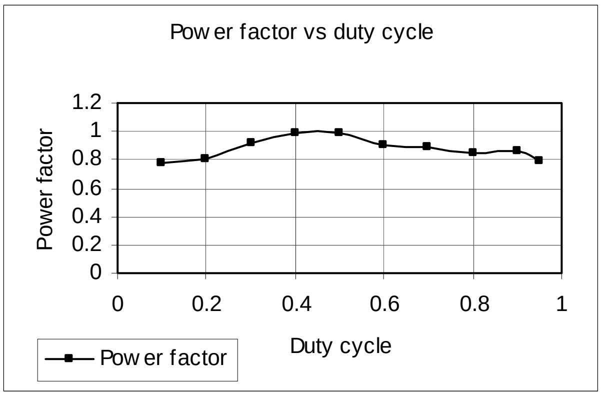


Fig. 16: Power factor vs duty cycle with the proposed rectifier circuit.

5. CONCLUSION

A two stage Cûk based three phase rectifier has been presented in this paper. This rectifier is low cost, robust and light weight because simulation is carried out using small parameters. It is observed that, a wide variation of output voltage is achieved by this proposed circuit than a single stage single switch Cûk based three phase rectifier. The input current is also achieved almost sinusoidal having low harmonics using small size input filter and power factor is also nearly unity. Two different regulations of output voltage at different operating point have been obtained across two loads at the same period of switching pulses. It is concluded from the above discussion that the lower output voltage than the input voltage has been achieved in eight operating points for using both loads equal and in six operating points by using two different loads whereas higher output voltage has been achieved in eleven operating points for using both loads equal and in thirteen operating points by using two different loads. In single stage Cûk rectifier it was only in nine operating points. Finally, it may be concluded that the limitation of voltage control strategy of single stage Cûk regulated rectifier has been solved with the proposed two stage Cûk regulated rectifier providing better regulation of output voltage at different levels in wide range. So it will be helpful for wide variation of output voltage required in many applications. This can be used to control the variable speed motor, drives and induction heating where the wide variation of output voltage is required.

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