Ćuk Topology Based High Performance Three Phase to Single Phase Switch Mode Cycloconverter with V/f motor control

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Abstract **- In this paper, a high performance Switch Mode Power Supply (SMPS) using a three-phase to single-phase AC cycloconverter is proposed. The proposed SMPS based cycloconverter is implemented using the Ćuk topology, which has higher reliability, low switching losses and thereby increased efficiency as the number of switches is reduced. It also provides means to have high input power factor and low input current Total Harmonic Distortion (THD) with use of simple input and output filter. Incorporation of SMPS topology enables the proposed circuit to operate in either buck or boost voltage mode. The proposed topology ensures high performance by maintaining reduced input current THD (below 10%), improved input power factor (above 0.85), and better efficiency (greater than 85%) as the duty cycle of the PWM control signal is varied for resistive load while the voltage gain is varied between 50% to 150%. The improvement in converter performance is compared with the conventional 12-SCR three to single phase AC cycloconverter. Furthermore, a closed loop control circuit is designed to provide V/f control while the cycloconverter is employed to drive machines with constant flux at low speed. The integration of control circuit provides enhanced reliability and better grip over the output voltage and frequency of the cycloconverter.**

Index Term- **Switch Mode Power Supply (SMPS), Cycloconverter, Three phase to single phase conversion, V/f control and High efficiency.**

I. INTRODUCTION

A cycloconverter is a static frequency changer (SFC) designed to convert AC voltage with constant magnitude and frequency to an AC supply of variable voltage and variable frequency without any DC link. Cycloconverters are vastly used for controlling ac motors at low speed, especially in high power application [1]. Cycloconverters are also used in solid state industries for ac-ac conversion to get output frequency lower than the supply- frequency. They are now being used in heavy industries like cement industries [2], rolling mills, electric traction and ship propellers [3] . Traditional three-phase to single-phase cycloconverters require at least 12 switches. Additional switches are required to obtain better input current shaping. In conventional cycloconverters, input current is distorted and contains higher order harmonics and Substantial amount of development and researches have been carried out in the analysis and the application aspects of cycloconverter drives. The control strategies have been developed so far includes cosine-wave control [4] and current feedback method [5] etc. A few publications have appeared in recent years documenting the configuration of SMPS topology based cycloconverters. In [6], the authors proposed a three to single phase Cycloconverter regulated and controlled by Buck-Boost converters. However, in this scheme, input current THD is above 20% and efficiency is less than 80% for buck mode operation with resistive load that demonstrates the limitation of the circuit to maintain satisfactory performance in terms of power quality. The output for resistive, R-L and motor load is demonstrated for a three to single phase Ĉuk topology based cycloconverter by the authors in [8]. Though the power quality parameters are selected to be in satisfactory range but comparison between the conventional and proposed converter is not shown in that work. Additionally, no control circuit is designed for controlling output parameters. A buck–boost topology based three phase to single phase conversion is implemented in [7] that can operate in four quadrant mode at voltage–frequency plane. Fuzzy logic control is incorporated in the design to provide better stable output voltage and frequency and microcontroller is used to drive the switches. However, closed loop control of the converter is overlooked in the design.

Therefore, in this paper a three-phase to single-phase AC cycloconverter is proposed using Ćuk converter based SMPS topology. A conventional three-phase AC to single-phase AC SCR cycloconverter requires at least 12 SCR switches, whereas only four switches are needed in the proposed topology. The reduction of the number of switches minimizes the switching losses and thereby increases the converter efficiency. The number of gate/base drive is reduced and the proposed topology has higher reliability as the number of switch is reduced. It also provides means to have high input power factor and low input current THD incorporating small input and output filters. The performance of the proposed topology is evaluated in terms of THD, input power factor, output voltage, output frequency and efficiency as the duty cycle of the control signal is varied. For controlling purpose, the output to input voltage ratio is selected for 5 different values (50%, 75%, 100%, 125% and 150%). The control approach is selected as open loop sliding mode control. A V/f control circuit is also designed for the proposed cycloconverter based single phase induction motor drive. The constant V/f ratio at the cycloconverter output guarantees constant rotating magnetic field vector for single phase induction motor operated even in low speed.

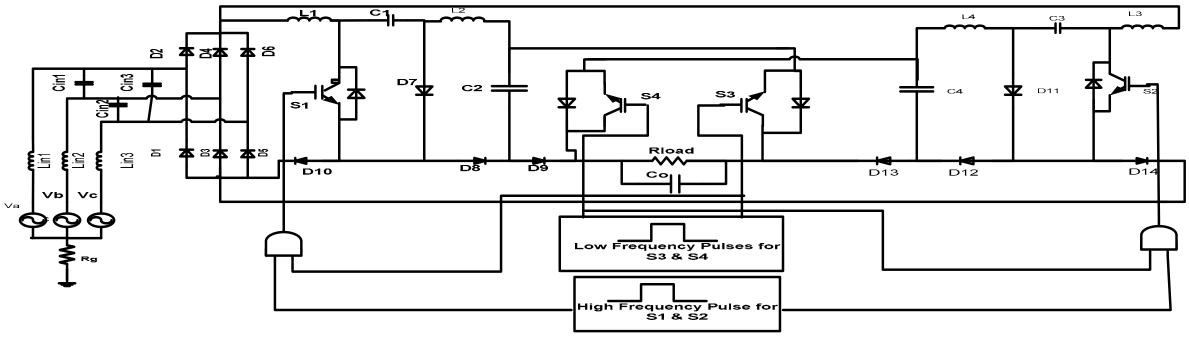


Fig. 1: Proposed Ćuk topology based three phase to single phase AC cycloconverter.

II. Proposed Circuit Configuration

Fig. 1 shows the proposed scheme of the Ćuk topology based 3-phase to 1-phase AC cycloconverter. It changes the voltage and the frequency of input AC signal. Because of high frequency switching, small input filter is sufficient to reduce the low frequency harmonic components with improved input current shaping.

A full-bridge three-phase uncontrolled rectifier circuit is used for three-phase AC to DC conversion. For three phase input voltage supply, 300V amplitude and 50 Hz frequency supply is chosen. For input filter, inductor and capacitor values are chosen as 40mH and 12μF. IGBT modules are employed as switches S1, S2, S3 and S4 to provide paths for the corresponding P and N-converters having 0.001 Ω on state resistance and 1V forward voltage drop.

III. Circuit Operation

A Ćuk converter basically operates by charging and discharging of capacitor during switch ON and OFF state while inductor maintains unidirectional flow of current in both states. Combining these two topologies Ćuk topology based cycloconverter operates in four different states:

1. P converter-S1 ON, S3 ON state
2. P converter- S1 OFF, S3 ON state
3. N converter- S2 ON, S4 ON state
4. N converter- S2 OFF, S4 ON state

Only operation of state 1 and 4 is explained with circuit configuration in following section.

A. P-Converter Switches S1 and S3 ON State

Fig. 2 shows the direction of current flow during ON state of Ćuk P-converter switches S1 and S3. Current from inductor L1 and L2 flow through switches as shown in this figure. The capacitor C1 discharges (which was charged during earlier state when S1 was OFF and S3 was ON) and capacitor C2 is charges. At the same current flows through load, R_{load}, which also charges the capacitor C_o.

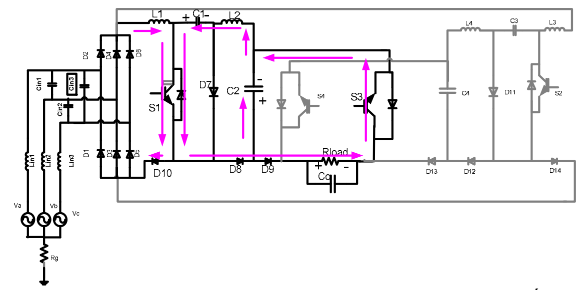


Fig. 2: Direction of current flow path during ON state of Ćuk P-converter switches S1 and S3.

B. *N-Converter Switches S2 OFF, S4 ON State*

When the switch S2 is turned OFF with S4 ON, the switch off state of the N converter occurs. The changed current directions are shown in Fig. 3. For this, L3 and L4 will continue to carry current in the previous directions. The polarity of C3 changes as it starts charging up. C_o keeps the output voltage constant.

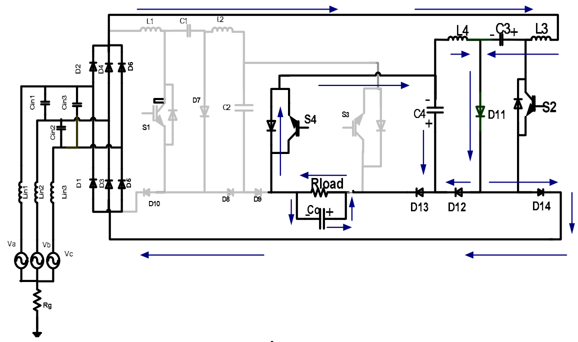


Fig. 3: Current flow path for Ćuk topology based N-converter switches S2 OFF, and S4 ON state.

Both positive and negative converters can generate voltages at either polarity, but the positive and negative converter can only supply positive and negative current individually. Thus, the cycloconverter can operate in four quadrants: (+v, +i) and (-v, -i) rectification modes and (+v, -i), and (-v, +i) inversion modes.

IV. Simulation Results

The simulation for open loop sliding mode control of the cycloconverter has been performed using PSIM and Orcad Pspice software. The closed loop control circuit is simulated using MATLAB-Simulink software.

Switch mode cycloconverters show good performance at variable frequency operation by providing non-integer frequency division at output in terms of input frequency. In the proposed Ćuk topology based cycloconverter, 33.33 Hz, 25 Hz, 20 Hz, 16.66 Hz ,14.28 Hz, 12.5 Hz, 11.11 Hz, 10 Hz or any fraction to 50 Hz conversion of waveform from input side to output side is achievable. Non-integer multiple of supply cycle at the output are obtained without any significant change in supply input current.

As the switching frequency increases the duty cycle of the switching pulses should be kept lower to regulate the performance of the converter within the acceptable limit. Considering this analysis as the basis, open loop variable switching frequency control has been proposed in the paper. For a given load, the performance of the proposed cycloconverter is examined for a varied range of duty cycles and switching frequencies. As Ćuk cycloconverter can produce variable output voltages with amplitude higher or lower than the input rms value. Five different points have been selected for output voltage with values 64%, 75%, 100%, 125% and 150% of the input voltage. To produce these output voltages, the frequency and the duty cycle have been varied. As the objective is to design a high performance cycloconverter, the operating points are selected in such a way that the input power factor remains higher than 0.85, input current THD is confined below 10% and the efficiency of the cycloconverter is maintained higher than 85%.Table-I depicts the performance of the converter for both buck and boost mode operations at different voltage gains.

Figs. 4 (a)-(c) depicts the phase-a input voltage and input current, input current spectrum and output voltage respectively for 150% voltage gain (Boost mode). It is found from Fig. 4 that for boost mode the input current THD is 9 %, and input power factor is 0.91, which are within the acceptable limits. Figs. 5 (a)-(c) depicts the phase-a input voltage and input current, input current spectrum and output voltage respectively for 75% voltage gain (buck mode). It is found from Fig. 5 that for buck mode operation the input current THD (8%,) and input power factor (0.85) are also within the acceptable limits.

Table II shows the performance of the proposed Ćuk cycloconverter with variable resistive load at different switching frequency. The corresponding optimum duty cycle at each frequency is obtained by trial and error to achieve high performance (i.e., low input current THD, high input PF and high efficiency) of the proposed converter.

TABLE I
SWITCHING CHARACTERISTICS OF THE CONVERTER FOR HIGH PERFORMANCE

Load		R_L=50 Ω			R_L=100 Ω			R_L=200 Ω		
D	Switching frequency f(Hz)	Input PF	%THD	%η	Input PF	%THD	% η	Input PF	%THD	% η
0.41	6000	0.75	0.05	93.74	0.91	0.09	90.36	0.91	0.09	83.52
0.48	4500	0.94	0.07	94.42	0.95	0.08	88.39	0.95	0.08	86.40
0.60	4000	0.93	0.09	88.01	0.92	0.10	87.46	0.91	0.10	84.85
0.70	3510	0.86	0.08	85.43	0.86	0.08	85.12	0.84	0.09	84.49
0.80	3100	0.65	0.07	79.16	0.65	0.07	73.51	0.64	0.07	70.39

TABLE-II
PERFORMANCE OF THE PROPOSED CYCLOCONVERTER AT VARIABLE RESISTIVE LOAD

Switching Freq, f(Hz)	**Duty cycle**	**Input pf**	**Input current THD**	**Output rms Voltage**	**Vout/ Vin**	**Efficiency (%)**
6000	0.4	0.91	0.09	772.56	150%	90.35
4500	0.47	0.94	0.07	730.82	125%	88.39
4000	0.6	0.92	0.09	629.69	100%	87.46
3510	0.7	0.85	0.08	507.62	75%	85.12
670	0.87	0.87	0.09	487.47	64%	86.60

V. COMPARISON WITH CONVENTIONAL CYCLOCONVERTER

The conventional 12-SCR cycloconverter is simulated with gating pulses having different phase angles. The results are obtained for a resistive load of 100 Ohm. The maximum input voltage in all three-phase is 300 volt with a supply frequency of 50 Hz. The proposed Ćuk topology based cycloconverter is selected to be operated at definite duty cycle with corresponding determined switching frequency to provide high performance. Figs. 6 (a) and (b) show the performance comparison between the conventional SCR and proposed Ćuk topology based 3-phase to 1-phase cycloconverter on the basis of same output voltage for input power factor and input current THD.

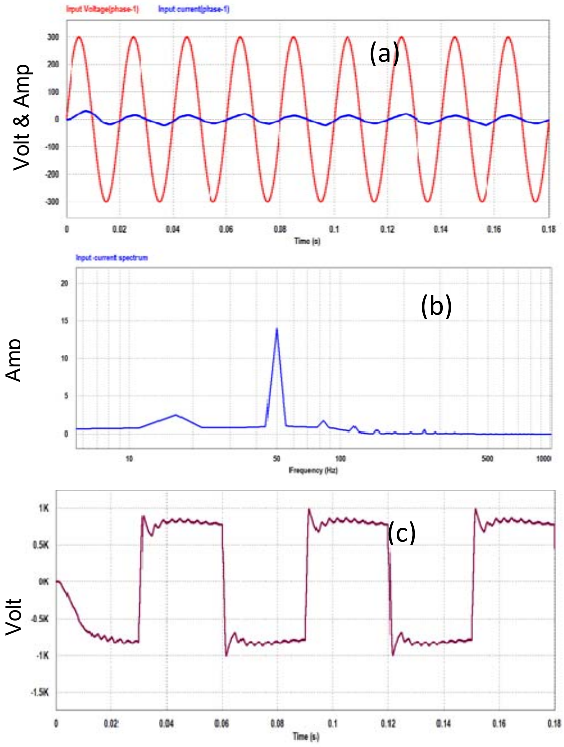


Fig. 4: (a) Input current and input voltage, (b) Input current frequency spectrum and, (c) Output voltage waveform for 150% converter voltage gain

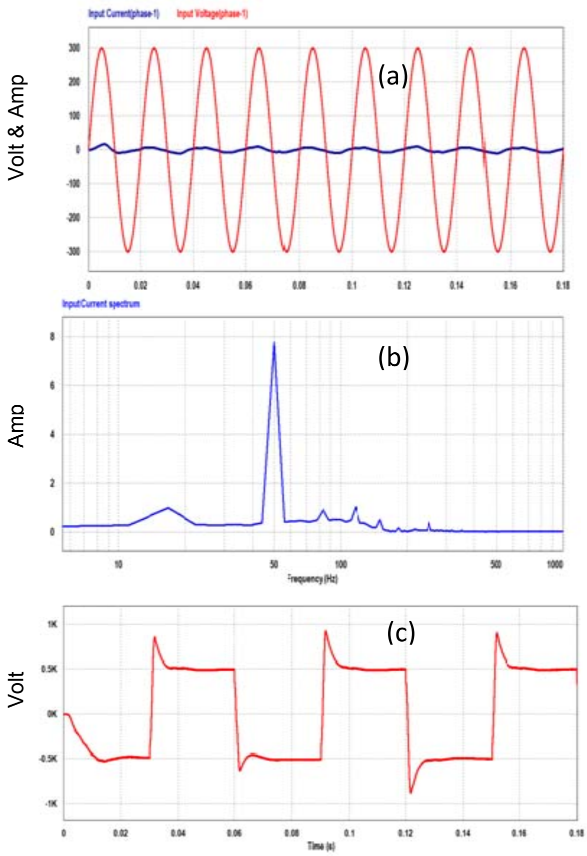
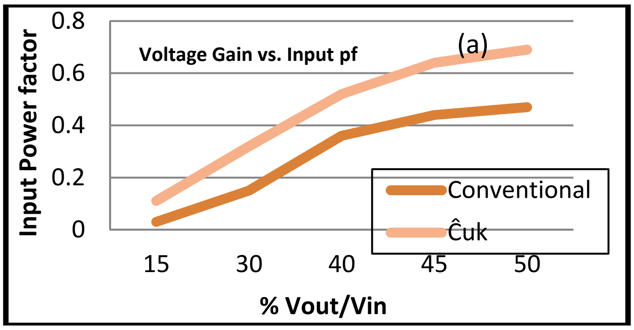


Fig. 5: (a) Input current and input voltage, (b) Input current frequency spectrum and, (c) Output voltage waveform for 75% converter voltage gain

The comparison reveals that the input power factor for the proposed Ćuk topology based 3-phase to 1-phase than that of conventional 3-phase to 1-phase SCR based cycloconverter.

The SMPS topology based converter provides the facility of controlling output voltage through the duty ratio of the high frequency switching pulse and the number of switches of these converters are less as compared to the conventional twelve SCR based 3-phase to 1-phase AC cycloconverters. From all the figures and charts it can be stated that the proposed Ćuk topology based cycloconverter shows superior performance in terms of number of switches, efficiency, input PF and input current THD to the conventional cycloconverter.



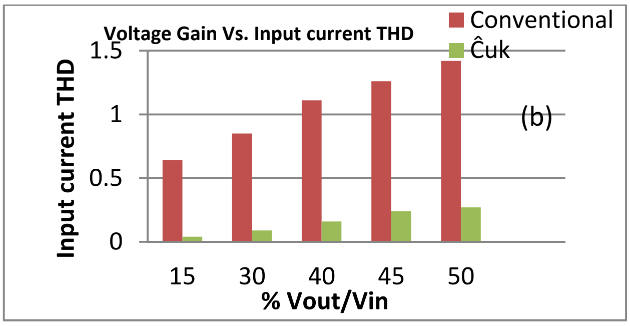


Fig. 6: Comparison between the proposed and conventional cycloconverters in terms of: (a) input Pf (b) input current THD.

Operation of a cycloconverter is best at high input frequency to low output frequency ratios, when a high quality signal can be obtained. In this paper, a controller circuit is designed to serve this goal. The constant V/f principle is achieved through regulation of slip speed to obtain accuracy in control [9]. Fig. 7 depicts the control circuit for adjustable speed operation of the motor. PI control is utilized to regulate the slip speed of the motor to keep the motor speed at its set value determined by output voltage. Since square waves with variable frequency and controlled duty cycle are required to drive the IGBTs, two Voltage Controlled Oscillator (VCO) blocks are designed where PI control is utilized to regulate the slip speed of the motor to keep the motor speed at its set value determined by output voltage. The VCOs generate variable frequency fine-tuned sawtooth waves. In final stage, comparator blocks are employed to yield pulses for converter switches by comparing between sawtooth wave and variable dc signal obtained from modified controller input signals. Table III shows the control block output for different motor torque.

TABLE III
PERFORMANCE DATA OF V/F CONTROL CIRCUIT

Applied Torque(N-m)	Converter Output Freq(Hz)	Converter RMS Output Voltage(Volt)	V/f ratio
2	31	160	5.16
4	29	154	5.31
8	27	141	5.22
10	24	128	5.33

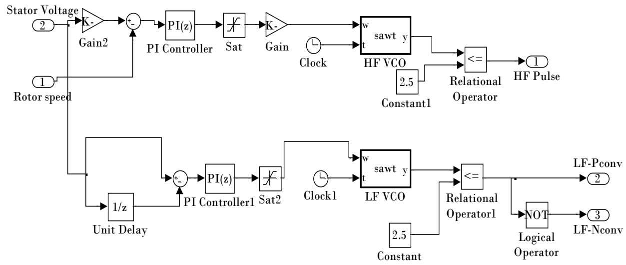


Fig. 7: Detail of control circuit for pulse generation of constant V-f control

VI. CONCLUSION

A high performance switch mode three-phase to single-phase AC cycloconverter using Ćuk topology has been proposed in this paper. The performance of the proposed cycloconverter circuit has been evaluated in terms of power quality parameters, namely, power factor, total harmonic distortion and efficiency. The proposed circuit exhibited satisfactory performance having near sinusoidal input current with low THD (less than 10%), high input power factor (higher than 0.85), better control of voltage and frequency and high efficiency (greater than 85%) for both buck and boost mode operations with voltage gain of 50%-150%. The performance of the proposed Ćuk topology based cycloconverter has also been found superior to the conventional 12-SCR 3-phase to 1-phase cycloconverter in terms of power quality and also used less number of switches. A closed loop control circuit has also been designed to serve the purpose of controlling output voltage and output frequency of the proposed cycloconverter to maintain V/f operation of a single-phase IM load. It has been found that the proposed control of cycloconverter can maintain satisfactory performance to maintain the constant flux operation of 1-phase IM drive.

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