ENVELPPE CYCLOCONVERTER BASED ON INTEGRAL HALF CYCLE SELECTION AND HALF CYCLE OMISSION TECHNIQUE

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Abstract *This paper proposes a new three-phase envelope cycloconverter based on integral half cycle selection with selected half cycle omission (HCO) technique. The advantage of using this technique is to eliminate completely the dominant supply frequency harmonic component and other undesirable harmonic components that may present in the conventional frequency division cycloconverter output voltage waveforms. Total harmonic distortion is drastically reduced and the possible risk of supply short-circuit is effectively minimized. The output voltage and current of this converter are smooth compared with corresponding waveforms obtained by conventional converters.*

Keyword:*powerelectronics,a.c.converters,cycloconverters,frequency changers*

1. INTRODUCTION

In conventional cycloconverters, the alternating voltage at supply frequency is converted directly to a lower frequency voltage without any intermediate DC stage. Two types of cycloconverters are commonly used in industry, namely, the phase angle controlled and the envelope cycloconverters [1]. The operating principles of these types of frequency changers are well known and their circuits are well developed in the last five decays due to the invention of the thyristor and other power semiconductor devices. The microprocessor and microcomputer -based circuitry have led to a revival of interest in the cycloconverter principle. Sophisticated control circuits permit the conversion of a fixed input frequency to a variable output frequency at variable voltage, and such schemes are attractive for AC motor drives [1,2].

Some new conversion methods from ac to ac have also been reported such as matrix converter and integrated PWM converter/inverter systems [3,4] These methods have gained considerable acceptance as schemes in the field of power frequency changers and speed control of induction motors..

The envelope cycloconverter proposed in this paper, is based on half cycle selection technique which is considered as a form of integral cycle control [2]. The output voltage at the desired level and frequency is produced by sequentially triggering chosen bidirectional MOSFET's connected directly across the input a.c. voltages without using input transformer.

The main circuit diagram of the proposed single-phase to single-phase cycloconverter is shown in Fig. 1. The two single-phase P and N converters are operated as bridge rectifiers; their delay angles are such that the output voltage of one converter is equal and opposite to that of the other converter. If converter P is operating alone, the average output voltage is positive and if converter

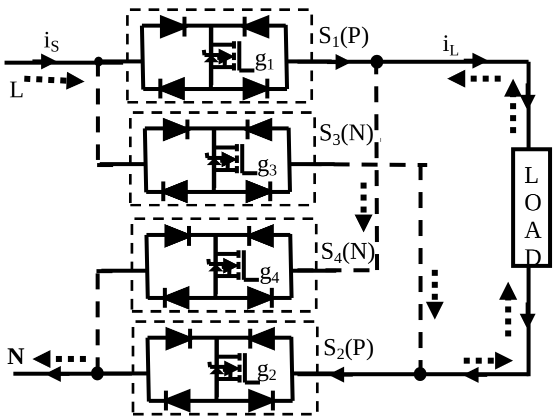

Fig.1 Single-phase to single-phase circuit diagram of the proposed cycloconverter.

N is operating, the output voltage is negative. The output waveform will result in (T) number of positive supply half cycles driven by the P – converter and the same number of the negative supply half cycles driven by the N-converter to form a periodic output sinusoidal load voltage with frequency f_o equal to f_{supply} / T as shown in Fig.2.

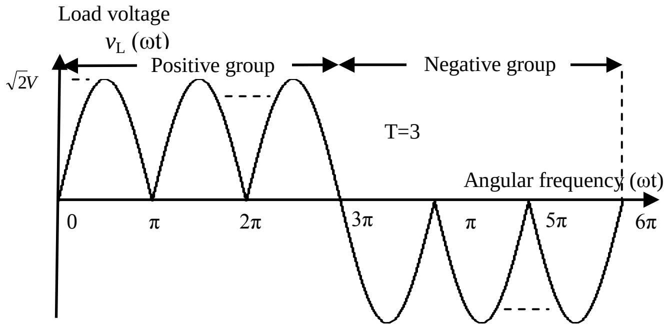

Fig.2. Typical load voltage waveform for the cycloconverter (T=3).

According to this principle of operation, the cycloconverter can be viewed as a frequency divider (down converter), that is, it is possible to divide the supply frequency by any positive integer number (T). Suitable switching timing of the two groups of bidirectional MOSFET's, from the assigned control circuits with pre-specified T number of cycles (division factor) will result in a desired cycloconverter output waveform with frequency f_o.

2. HALF CYCLE OMISSION TECHNIQUE

When the output voltage of the envelope cycloconverter with a waveform shown in Fig. 2 is controlled by omitting appropriate half cycles completely or partially from the positive as well as the negative half cycles, the harmonic content of the resulting waveform will be greatly affected. This technique may be called half cycle omission (HCO).

As one interesting feature of HCO is to omit the last half cycle of the positive half cycle bank as well as the last one from the negative bank of half cycles to avoid any possible short circuit between the P- and N-converters in conventional envelope cycloconverter. This will lead to avoid using the expensive intergroup reactors as well as solve the circulating current problem.

The application of HCO technique to the cycloconverter output waveforms will offer two very important advantages. First, is the effective total harmonic distortion reduction, and the second is the phase balancing improvement in a three-phase cycloconverter. These two techniques will be discussed in the following subsections.

2.1 Harmonic Reduction Using HCO Technique

Consider the T=3 cycloconverter output waveform shown in Fig. 3, where the last half cycle of both the

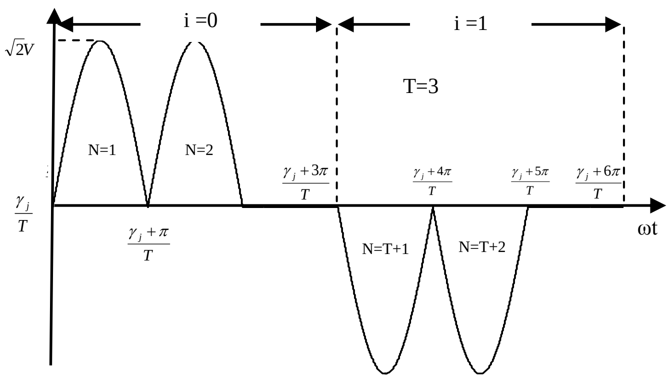

Fig. 3 Typical load voltage waveform for single-phase integral-cycle based cycloconverter with half cycle omission (T=3).

positive and negative bank of half cycles are omitted completely. The Fourier series coefficients for this waveform will be derived to investigate the effect of applying the HCO technique on the harmonic content of the waveform. However, this waveform can be expressed in terms of summation of half cycles of the original sine waveform as follows;

For the jth phase of a multi-phase system, the output voltage waveform can be expressed as:-

$$v_{L\,j}(\omega t)=\sum_{i=0}^{i=1}\sum_{N=1+iT}^{N=((1+i)T)-1}(-1)^{N+1-i}\sqrt{2}V\sin(\omega T\,t-\gamma_j)\Big|_{\frac{\gamma_j+(N-1)\pi}{T}}^{\frac{\gamma_j+N\pi}{T}} \quad (1)$$

and the Fourier coefficients are

$$a_{0\,j}=\frac{1}{\pi}\int_{\gamma_j}^{\gamma_j+2\pi}v_L(\omega t)\,d\omega t=0 \quad (2)$$

For $n\neq T$ (3)

$$a_{n\,j}=\frac{1}{\pi}\int_{\gamma_j}^{\gamma_j+2\pi}v_L(\omega t)\cos n\omega t\,d\omega t$$

$$=\frac{\sqrt{2}V\,T}{\pi(T^2-n^2)}\sum_{i=0}^{i=1}\sum_{N=1+iT}^{N=((1+i)T)-1}(-1)^{2N+2-i}\left(\cos\frac{n}{T}(\gamma_j+N\pi)+\cos\frac{n}{T}(\gamma_j+(N-1)\pi)\right)$$

$$b_{n\,\mathrm{j}} = \frac{1}{\pi}\int_{\gamma_j}^{\gamma_j+2\pi} v_L(\omega t)\sin n\omega t \, d\omega t$$

$$= \frac{\sqrt{2}V\,T}{\pi(T^2-n^2)}\sum_{i=0}^{i=1}\sum_{N=1+iT}^{N=((1+i)T)-1}(-1)^{2N+2-i}\left(\sin\frac{n}{T}(\gamma_j+N\pi)+\sin\frac{n}{T}(\gamma_j+(N-1)\pi)\right) \quad (4)$$

and the Fourier coefficients of the supply frequency component, where $n = T$ are

$$a_{T\,\mathrm{j}} = \frac{\sqrt{2}V}{4\pi\,T}\sum_{i=0}^{i=1}\sum_{N=1+iT}^{N=((1+i)T)-1}(-1)^{N+1-i}\left(-2\pi\sin\gamma_j\right) \quad (5)$$

$$b_{T\,\mathrm{j}} = \frac{\sqrt{2}V}{4\pi\,T}\sum_{i=0}^{i=1}\sum_{N=1+iT}^{N=((1+i)T)-1}(-1)^{N+1-i}\left(-2\pi\cos\gamma_j\right) \quad (6)$$

The amplitude C_n of the nth harmonic component and the angle ψ_n for the jth phase can be found as;

$$c_{n\,j} = \sqrt{a_{n\,\mathrm{j}}^2 + b_{n\,\mathrm{j}}^2} \quad (7)$$

and,

$$\psi_{n\,\mathrm{j}} = \tan^{-1}\frac{a_{n\,\mathrm{j}}}{b_{n\,\mathrm{j}}} \quad (8)$$

for n=1,2,3, ………

Using eqs. (2)-(6) for the HCO waveforms and eq. (7) describing C_n , the effect of half cycle omission on the frequency spectrum can be obtained and compared to the spectrum of the cycloconverter output waveforms without HCO. Fig.4 shows two converted frequencies with and without HCO application for j=1.

It is clear from Fig. 4 that the major effect of half cycle omission is to reduce the amplitudes of the dominant harmonic components. In addition, it results in cancellation of some undesirable harmonic frequency components that leads to reduce THD. Moreover, the application of HCO will result in reduced r.m.s. value of the output voltage as it is clear in each case.

Without using HCO, the supply frequency component is generated with significant amplitude for odd values of (T). One of the most important advantage resulted from using symmetrical half cycle omission is the complete elimination of the supply frequency component.

The r.m.s. voltage value of the half cycle omitted cycloconverter output waveform of T cycles can be simply derived using eq. (1). From which the load r.m.s. output voltage is

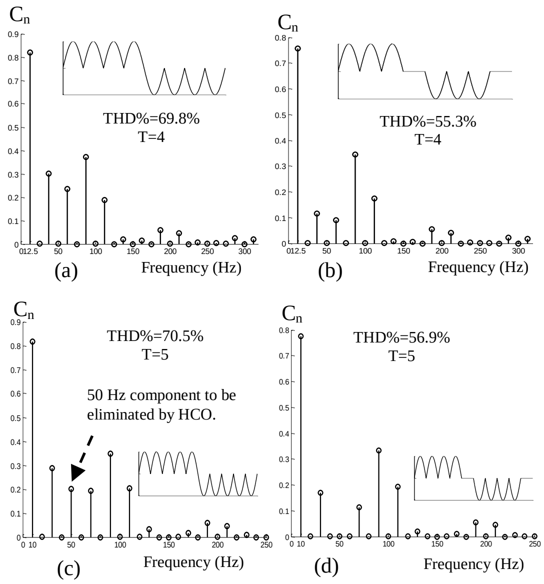

Fig. 4 Frequency spectrum of cycloconverter output waveforms (a) (50 to 12.5)Hz (b) (50 to12.5)Hz with HCO, (c) (50 to10) Hz, and (d) (50 to10) Hz with HCO.

$$V_{Lrms} = \sqrt{\frac{1}{2T\pi}\int_0^{2\pi(T-1)}\left(\sqrt{2}V\sin(\omega t)\right)^2 d\omega t} \quad (9)$$

with further simplification, the resultant load r.m.s. voltage is found to be

$$V_{Lrms} = \sqrt{1-\frac{1}{T}}\;V \quad (10)$$

From eq. (10), it is clear that V_{Lrms} is a function of T. The reduction in harmonic content due to HCO can be seen clearly by comparing the THD% before and after application of HCO curves given in Fig. 5.

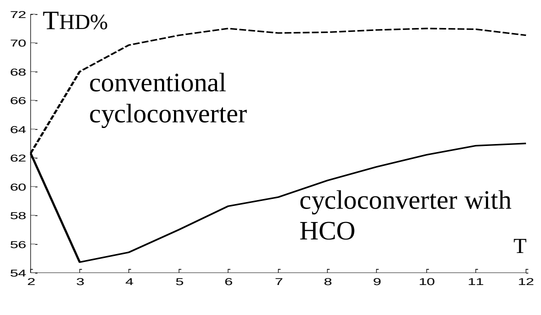

Fig. 5 Effect of varying cycloconverter number of cycles T on the THD% of outputs with and without the application of HCO.

2.2 Three-Phase Balancing Improvement Using HCO

In the three-phase systems, it is not adequately sufficient to generate a desired output waveform with desired output frequency, but also to ensure that the three generated phases have balanced phase displacement relations of the operating frequency component.Unfortunately, in all types of conventional envelope three-phase cycloconverters the fundamental desired frequency as well as the harmonic components is generated with random unbalanced phase relationships with phase angle displacement depends on the values of T. This fact is also appears in conventional 3-phase integral cycle –based frequency changers, although little attempts had been made to improve the phase relationships. [5,6,7].However, using the proposed HCO technique, phase balancing improvement for the fundamental and other certain harmonic components could be achieved.

If we consider the T=3 (16.6 Hz) cycloconverter output waveform shown in Fig. 6, where the application of HCO is experienced through the testing of the three possible waveforms resulted from omitting the first, second, or the third half cycle. The original output waveform as well as its phase displacement angle is shown in Fig. 6(a) with the resulted THD%. Now, if a comparison is made between waveforms depicted in Figs. 6 (b), (c), and (d) with that for the original waveform in Fig. 6 (a), it is clear that HCO can be used to change the phase angle displacement of the fundamental harmonic component by a phase angle Φ_o with reduced THD.

For any output waveform defined by the value of (T), the modification phase angle is found to be

$$\phi_o = \frac{\pi}{2T} \qquad \text{(radian)} \qquad (11)$$

The location of the omitted half cycle will be defined by N_o, where N_o will range from 1 (first half cycle) to T (last half cycle) as shown in Fig. 6. In other words, N_o must take two convenient values (1 and T) only for obtaining both reduced THD% and phase displacement modification.

In order to clarify the application of HCO for three-phase cycloconverter, Fig. 7 (a) depicts the phase relations for the first four harmonic components for T=3 (16.6 Hz) output waveform, which is to be improved for the 16.6 Hz fundamental frequency component.

If HCO is applied such that v_A is shifted by +30^o (N_o=T=3) and v_C by -30^o (N_o=1), the resultant phase relation for the fundamental component will still

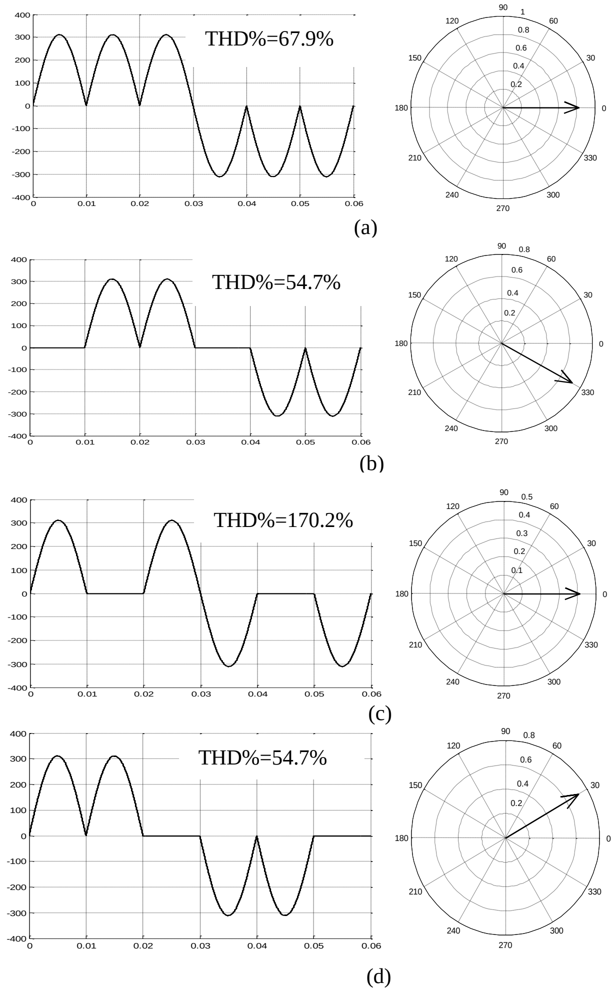

Fig. 6 Single phase waveform and fundamental component (16.6Hz) phase angle displacement for T=3 cycloconverter (a) without HCO (b) 1st cycle omission N_o=1 (c) 2nd cycle omission N_o=2 (d) last (3rd) cycle omission N_o=T=3.

have significant unbalanced displacement angles between the three phases. A more acceptable phase relation improvement can be obtained by shifting v_A by +30^o and v_B with -30^o, while inverting and then shifting v_C by +30^o as shown in Fig. 7(b). It is also possible to reverse the direction of rotation for the fundamental component by simply reversing v_B and shifting v_C by -30^o. The phase improvement offered by half cycle omission shown for the T=3 cycloconverter output, can also be applied for all values of T.

Another advantage of using HCO for phase balancing is that it eliminates completely the harmful tripplen harmonics, which are usually associated with waveforms generated by the conventional envelope cycloconverters for odd values of T. This can be clearly shown from Fig. 7(b).

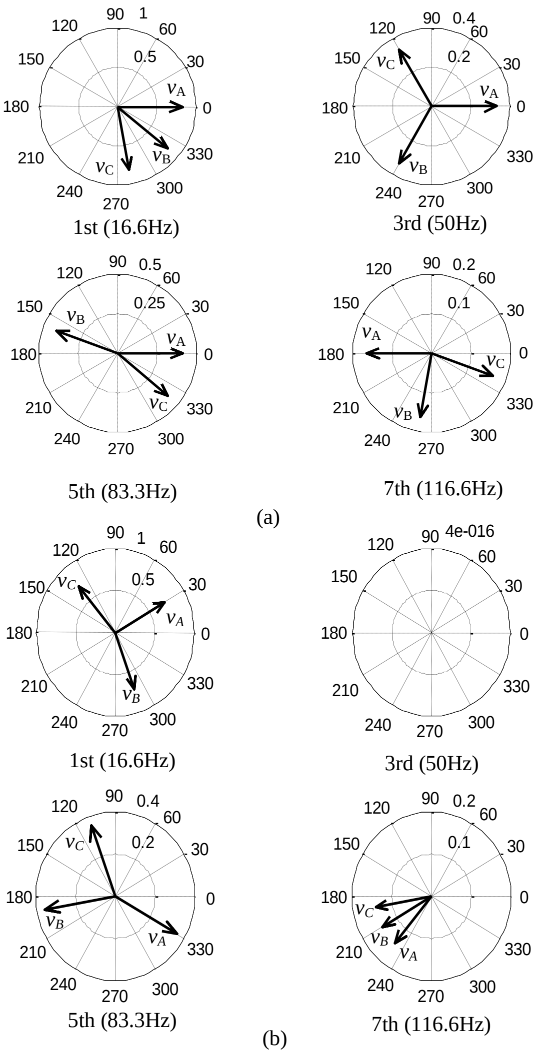

Fig.7 Harmonic phase relationships for T=3 cycloconverter output showing the 1st, 3rd, 5th, and 7th harmonic component for (a) ordinary cycloconverter (b) Improved phase displacement by HCO applied to v_A with N_o=T and v_B with N_o=1, while v_C is inverted and then applied with HCO of N_o=T.

2.3 Partial HCO Technique

Half cycle omission may not only be introduced by omitting complete half cycles from both the positive and negative bank of half cycles, but partial half cycle omission is also possible. Partial half cycle omission (PHCO) will offer a fractional modification of the phase displacement relation of a certain frequency component by offering phase deviation between 0 and 90^o/T by means of phase angle control of the half cycle to be partially omitted.

Fig. 8 shows the output waveform of partial half cycle omission (PHCO) with ψ as phase control angle, that ranges from 0 (complete HCO) to 180^o (no HCO). The bold line shown in this waveform represents only the partially introduced part of the previously omitted half cycle. The Fourier coefficients of the dashed line for HCO waveform shown in Fig. 3 are given in eqs. (2) to (6), and the overall Fourier series coefficients will be the summation of that of the bold line in Fig. 7 with that previously obtained for the dashed line (Fig. 3).

Now the load voltage expression of the bold line waveform is

$$v_{L\,j}(\omega t)=\sum_{i=0}^{i=1}(-1)^{N+1-i}\sqrt{2}V\sin(\omega T\,t-\gamma_j)\Big|_{\frac{\gamma_j+(N-1)\pi}{T}}^{\frac{\gamma_j+(N-1)\pi+\psi}{T}} \qquad (12)$$

where N=(1+i)T, and the Fourier coefficients are

$$a_{0\,j}=\frac{1}{\pi}\int_{\gamma_j}^{\gamma_j+2\pi}v_{Lj}(\omega t)\,d\omega t=0 \qquad (13)$$

For $n\neq T$

$$a_{n\,j}=\frac{1}{\pi}\int_{\gamma_j}^{\gamma_j+2\pi}v_{Lj}(\omega t)\cos n\omega\,t\,d\omega t$$

$$=\frac{\sqrt{2}V\,\mathrm{T}}{\pi(T^2-n^2)}\sum_{i=0}^{i=1}(-1)^{2N-i}\begin{pmatrix}-\cos(\gamma_j+\psi)\cos((\frac{n}{T}+1)\gamma_j+\frac{n}{T}((N-1)\pi+\psi))\\-\frac{n}{T}\sin(\gamma_j+\psi)\sin((\frac{n}{T}+1)\gamma_j+\frac{n}{T}((N-1)\pi+\psi))\\+\cos(\gamma_j)\cos((\frac{n}{T}+1)\gamma_j+\frac{n}{T}((N-1)\pi))\\+\frac{n}{T}\sin(\gamma_j)\sin((\frac{n}{T}+1)\gamma_j+\frac{n}{T}((N-1)\pi))\end{pmatrix} \qquad (14)$$

$$b_{n\,j}=\frac{1}{\pi}\int_{\gamma_j}^{\gamma_j+2\pi}v_{Lj}(\omega t)\sin n\omega\,t\,d\omega t$$

$$=\frac{\sqrt{2}V\,T}{\pi(T^2-n^2)}\sum_{i=0}^{i=1}(-1)^{2N-i}\begin{pmatrix}-\cos(\psi)\sin\frac{n}{T}(\gamma_j+(N-1)\pi+\psi)\\+\frac{n}{T}\sin(\psi)\cos\frac{n}{T}(\gamma_j+(N-1)\pi+\psi)\\+\sin\frac{n}{T}(\gamma_j+(N-1)\pi)\end{pmatrix} \qquad (15)$$

and the supply frequency component, where $n=T$ is

$$a_{T\,j}=\frac{\sqrt{2}V}{4\pi\,T}\sum_{i=0}^{i=1}(-1)^{N+1-i}\left(\cos\gamma_j-\cos(\gamma_j+2\psi)-2\psi\sin\gamma_j\right) \qquad (16)$$

$$b_{T\,j}=\frac{\sqrt{2}V}{4\pi\,T}\sum_{i=0}^{i=1}(-1)^{N+1-i}\left(-\sin\gamma_j-\sin(\gamma_j+2\psi)+2\psi\cos\gamma_j\right) \qquad (17)$$

The frequency spectrum and the phase angle displacement relations, which are investigated by means of Fourier series coefficients for PHCO, show that, in addition to the fractional change in phase displacement from 0 to 90°/T, obtained by varying ψ, a further reduction in THD% is also achieved. The effect of varying ψ on both, the THD% and the phase displacement obtained by PHCO, can be shown in Fig. 9.

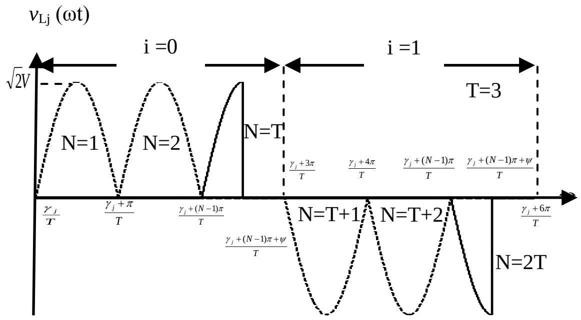

Fig. 8 Typical load voltage waveform for single-phase integral-cycle based cycloconverter with partial half cycle omission (T=3).

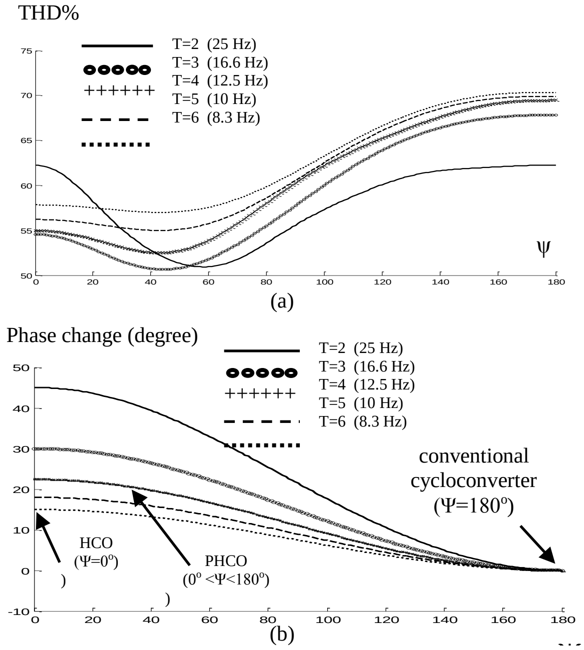

Fig. 9 Effect of PHCO control phase angle ψ, for different output frequencies, on (a) THD%, and (b) resultant phase change.

3. EXPERIMENTAL WORK AND RESULTS

The proposed cycloconverter based on half cycle selection and HCO techniques is built and tested in the laboratory with various types of loads. The results confirm both the principles and the theoretically predicted characteristics.

3.1 Resistive load: Harmonic reduction and phase balancing effect of using HCO technique is tested with three-phase resistive load for 1:2 (25 Hz) output cycloconverter voltage. Phase voltages and neutral current for conventional envelope cycloconverter output are monitored and shown in Fig. 10. The neutral current is found to have a d.c. component. This is due to the unbalance phase relations of the generated voltage harmonic components.

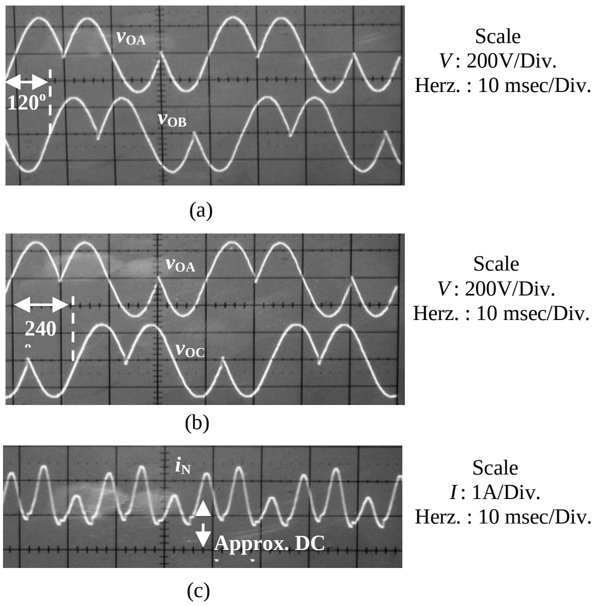

Fig.10. Voltage and current oscillograms of a 1:2 (25 Hz) frequency division cycloconverter 3-phase waveforms (a) v_{OA} and v_{OB} (b) v_{OA} and v_{OC} (c) Neutral Current .

When the HCO technique is used to make the phase displacement balanced, the neutral current is found to have less estimated d.c. component as shown in Fig.11 (c) and it has more smooth waveform.

3.2 Performance with 3-Phase AC Motor Load:

The converter was tested with a 3-phase, 500W, 220 V, 50 Hz, Y-connected, 2-pole induction motor. Each generated waveform is evaluated according to the shaft speed that the motor will run at, and how it is close to the corresponding frequency designed to cause such a rotating speed. The synchronous speed n_s of the induction motor with ignored slip factor is given by the following well known fundamental equation : $n_S=120* f / p$, where p = number of poles and f = supply frequency. This indicates that n_s can be varied by changing the frequency f.

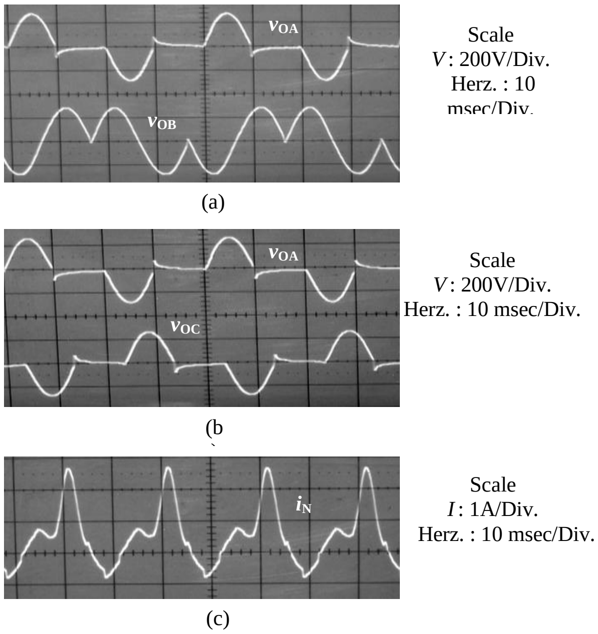

Fig. 11 1:2 (25 Hz) frequency division cycloconverter 3-phase waveforms phase balanced and quality improvement using HCO (a) v_{OA} and v_{OB} (b) v_{OA} and v_{OC} (c) Neutral Current .

The motor is tested first with the conventional envelope cycloconverter generating 3-phase 25 Hz output voltage. Oscillograms for the stator voltage and currents are shown in Fig.12 (a) and (b) respectively. Frequency spectrum and three-phase displacement angles of the fundamental 25 Hz component are also shown in Figs. 12(c) and (d) respectively. The motor is supposed to run at half of the synchronous speed (1468 r.p.m.) corresponding to 25 Hz component. The measured speed is found to be 485 r.p.m. and according to eq. (18) this speed corresponds to 8.25 Hz component, which is not even appears in the frequency spectrum as shown in Fig. 12(d). However, unsmooth and unstable rotation of the motor is observed in this case.

Now, when HCO technique is applied to obtain a phase balance to the three-phase output voltage waveforms by omitting the last half cycle of phase A, first half cycle of phase C, and leaving phase B unchanged as shown by Fig. 13. Phase balancing improvement achieved results in motor shaft speed of 1467 r.p.m. corresponding to 24.97 Hz with smooth rotation. The application of HCO results in slight voltage amplitude unbalance as shown theoretically in Fig. 14(e). However, this will have no significant effect on the motor performance.

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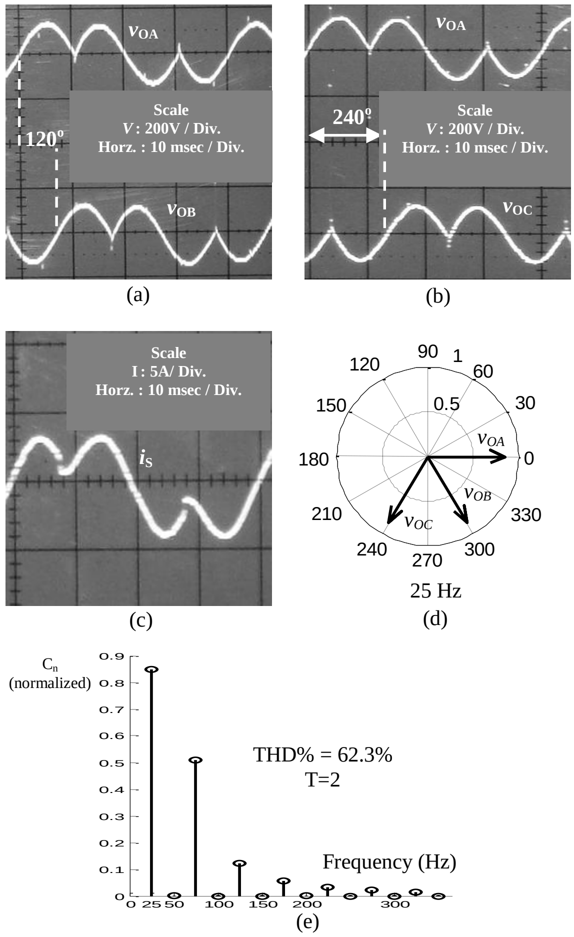

Fig.12 25 Hz unbalanced 3-phase waveform generation causing motor to run at speed of n_r=485 r.p.m. (a) v_{OA} and v_{OB} (b) v_{OA} and v_{OC} (c) stator current (d) 25 Hz component phase relations (e) theoretical phase voltage frequency spectrum.

However, when HCO technique is applied to obtain a phase balance to the three-phase output voltage waveforms by omitting the last half cycle of phase A, first half cycle of phase C, and leaving phase B unchanged as shown by Fig. 13. Phase balancing improvement achieved results in motor shaft speed of 1467 r.p.m. corresponding to 24.97 Hz with smooth rotation. The application of HCO results in slight voltage amplitude unbalance as shown theoretically in Fig. 13(e). However, this will have no significant effect on the motor performance.

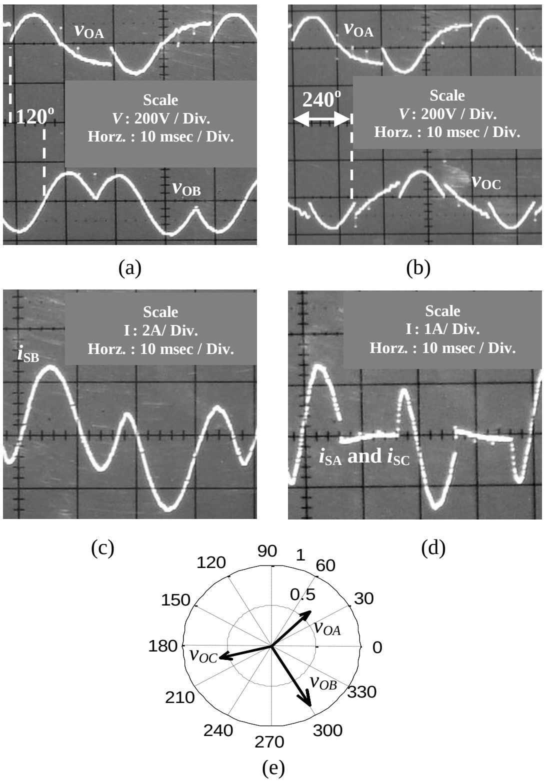

Fig. 13 25 Hz balanced 3-phase waveform generation using HCO technique causing motor to run at speed of n_r=1467 r.p.m. (a) v_{OA} and v_{OB} (b) v_{OA} and v_{OC} (c) phase B stator Current (d) phase A and C stator Current (e) 25 Hz component phase relations

CONCLUSION

Theoretical and practical behavior characteristics of a proposed three-phase variable frequency cycloconverter have been presented. This cycloconverter is based on half cycle selection and half cycle omission (HCO) technique. It is found that using HCO technique solves the inherent problems associated with conventional envelope cycloconverters of similar type. With HCO significant reductions in harmonics, elimination of the supply frequency component, and balancing the output voltage waveforms in the three phases are easily achieved. Experimental results found to agree well with the theoretical investigations. The suggested frequency changer proves to have many advantages over conventional types , such as inverters and cycloconverters , in that it is more simple, requires no complex triggering circuits due to the few MOSFETs used , need no input transformers and need no filter because the output voltage and current waveforms are smooth and largely free from spikes and undesirable discontinuities. As an a.c. drive, this cycloconverter has many advantages over PWM inverter drives since it imposes no problems on the a.c. machine windings due to the high frequency switching associated with PWM techniques [8]. Moreover, it is almost free of switching losses; therefore, its conversion efficiency is relatively high.

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