A POWER FREQUENCY CHANGER USING BI- PHASE INTEGRAL CYCLE CONTROL TECHNIQUE

Mohammed T.LAZIM , ,Mahmoud A. ZEIDAN
Electrical Engineering Department –Philadelphia University –Jordan
drmohamadtofik@yahoo.com Mobile: +962788343005, mzeidan@philadelphia.edu.jo ,mobile :+09627953326595

ABSTRACT *This paper proposes a three – phase ac –to- ac power frequency changer employing a bi-phase integral cycle control technique. The advantage of using bi-phase integral cycle control is that it is simple in theory and circuitry compared with conventional ac-to-ac power frequency changers such as cycloconverters and cycloinverters. With bi-phase integral cycle control, the supply frequency component is eliminated, and the power associated with this component is completely transferred to the other desirable frequency components in the generated frequency spectrum. This means that a process of frequency changing with high power is achieved.*

The output voltage and current waves of this converter are smooth compared with corresponding waveforms obtained by conventional converters and the number of switching devices employed is small. The functionality of the proposed frequency changer is analyzed theoretically and proven by experiments.

Key words: *Power electronics, ac converter, a.c. drive, motor control*

I. INTRODUCTION

With the development of modern power semiconductor technology a number of solid-state power frequency changer schemes have been introduced and gained considerable industrial interest. The currently available methods of obtaining a variable-frequency power output from 50 Hz public supply can be divided into two main classes. In the first, the power is converted in two stages, with an intermediate d.c. link, using inverter circuits. In the second, the power is converted directly in one stage using cycloconverters circuits [1,2]. The control circuits of these traditional frequency changers are complex owing to the relatively involved logic functions that need to be performed and the large number of power switching devices such as thyristors that require gate signals [3].

Alternatively, another method of achieving power frequency changing is by employing modulation techniques. This method has gained considerable acceptance as schemes in the field of power frequency changers and speed control of induction motors. Some works have been reported based on the principle of modulating a sine wave of power frequency by a rectangular modulating function produced by the switching action of thyristor elements to form a discrete modulation [4,5]. In general, the load voltage waveforms corresponding to symmetrical phase-angle triggering and integral-cycle triggering in single and three-phase thyristor circuits are all shown to be discrete forms of amplitude modulation at power frequency [6]. Integral-cycle triggering in which the thyristor is used to permit complete cycles of load current followed by complete cycles of extinction is considered as amplitude modulation of discrete form. Integral cycle control often results in considerable power loss but it is preferably used type of control in many industrial applications such as temperature control and DC motor drives [7, 8].

As a frequency changer, this type of control proves to be inefficient because the supply frequency component often exists as an effective component in the output voltage. Complete removal of the supply frequency component from the output waveform is considerably difficult due to the necessary use of physically large adding, subtracting, and phase-shifting components because the signals are at high level of power. This means that ,suppression of the supply frequency component using these techniques results in high losses and implementing expensive equipment On the other hand, ICC has many advantages over phase angle control as it generates less number of harmonics, reduces the electromagnetic interference and possesses all the advantages of zero voltage switching techniques.

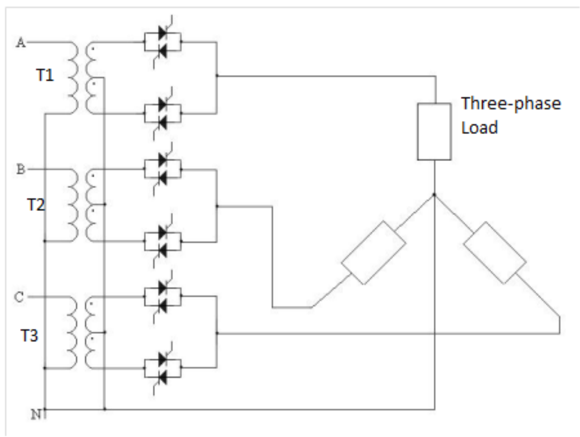
It was also shown elsewhere that ICC in its conventional form is not feasible for ac drives application [9]. The reason for that is the three-phase waveforms produced are rich of subharmonics of the supply frequency which are unbalanced neither in phases nor in amplitudes. The effects of these subharmonics on the motor causes vibration, noise, and temperature rise in the motor windings.

In the present work, an attempt is made to improve ICC performance by using two anti-phase ICC waves triggered alternatively to produce phase modulated like or bi-phase integral cycle controlled (BPICC) voltage or current waveforms. The technique uses bi-phase integral cycle controlled waveforms is called elsewhere angle or phase modulation of discrete form. Although little attempts had been made in the past to realize this form of control in three-phase systems, but these attempts were merely theoretical [10]. In the present paper, theoretical and practical works has been made to realize bi-phase integral cycle control (BPICC) for a three-phase system with an attempt to solve its inherent limitations.

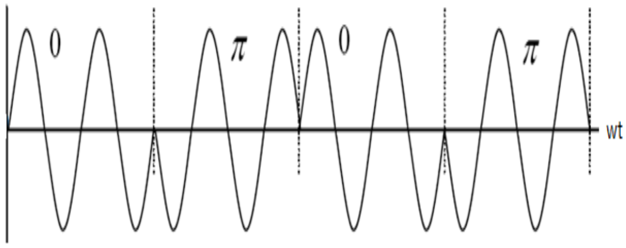
2. THREE-PHASE POWER FREQUENCY CHANGER USING BI-PHASE INTEGRAL CYCLE CONTROL TECHNIQUE

The strategy of bi-phase integral cycle control which is considered as phase modulation gained little attention in previous days for three-phase applications, although this type of control gives high efficiency of conversion as well as eliminates completely the supply frequency component. Most of the power associated with the supply frequency component is transferred to the desired frequency component, and the output voltage waveform contains little harmonics. Among the few papers published in this field nobody tried to investigate, why this important type of frequency changing technique is not feasible for the three-phase system applications. However, the following analysis will highlight theoretically, the main features of power frequency phase modulation of discrete form for such systems.

The proposed power converter is depicted in Fig.1 (b). The converter consists of three single-phase center – tapped transformers supplying three – phase load via groups of inverse parallel connected thyristors. If the in-phase and anti-phase supply voltage waveforms are switched ON at zero voltage instant alternatively in a control period of *T* supply cycles, then for the case of *R*- load, the output voltage waveform per phase will be as shown in Fig.1 (b).



(a)



(b)

Fig.1 Three-phase, 4-wire, star-connected load supplied by a three single -phase centre –power transformer to realize bi –phase ICC waveforms, (a) circuit diagram , (b) Output voltage waveform per phase.

For the case of *R-L* load, the current will not fall to zero after the end of the zero-phase ICC wave and the load voltage v_{Lj} of the j^{th} phase will be as shown in Fig. 2, and it may be defined by the following equation :

$$v_{Lj} = \sqrt{2}V \left[\begin{array}{l} \sin\left(\omega Tt - \gamma_j\right)\Big|_{\frac{\gamma_j}{T}}^{\frac{2\pi N_1 + x + \gamma_j}{T}} \\ -\sin\left(\omega Tt - \gamma_j\right)\Big|_{\frac{2\pi N_1 + \gamma_j}{T}}^{\frac{2\pi (N_1 + N_2) + x + \gamma_j}{T}} \end{array} \right] \quad (1)$$

where $N_1 = N_2 = 1, 2, \ldots, T/2$ and T= the control period.

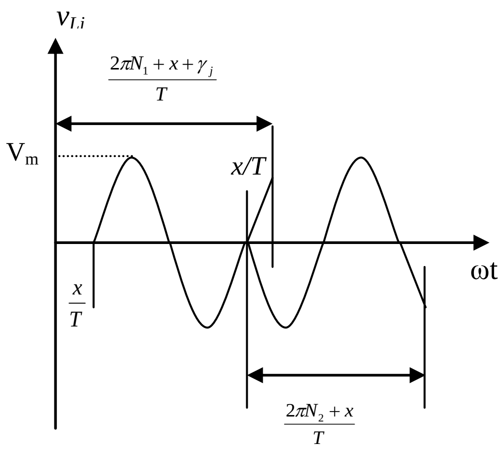


Fig. 2 Load voltage v_{Lj} of the j^{th} phase for the phase modulating circuit (*R-L* load).

Fourier expansion of eq. (1) gives the following results:

For $n \neq T$ and $x=\Phi$ (impedance angle), the amplitude C_n and the phase angle ψ_n of the n^{th} harmonic component for the j^{th} phase may be found as:

$$a_{oj}=0 \qquad (2)$$

$$a_{nj} = \frac{\sqrt{2}V}{\pi(T^2-n^2)}\left[T\left\{ \begin{array}{l} \cos\frac{n\gamma_j}{T} - \cos\frac{n}{T}(2\pi N_1+\gamma_j) \\ -\cos\phi\cos\frac{n}{T}(2\pi N_1+\phi+\gamma_j) \\ +\cos\phi\cos\frac{n}{T}(2\pi(N_1+N_2)+\phi+\gamma_j) \end{array} \right\} + n\left\{ \begin{array}{l} \sin\phi\sin\frac{n}{T}(2\pi(N_1+N_2)+\phi+\gamma_j) \\ -\sin\phi\sin\frac{n}{T}(2\pi N_1+\phi+\gamma_j) \end{array} \right\} \right] \qquad (3)$$

$$b_{nj} = \frac{\sqrt{2}V}{\pi(T^2-n^2)}\left[T\left\{ \begin{array}{l} \sin\frac{n\gamma_j}{T} - \sin\frac{n}{T}(2\pi N_1+\gamma_j) \\ -\cos\phi\sin\frac{n}{T}(2\pi N_1+\phi+\gamma_j) \\ +\cos\phi\sin\frac{n}{T}(2\pi(N_1+N_2)+\phi+\gamma_j) \end{array} \right\} + n\left\{ \begin{array}{l} \sin\phi\cos\frac{n}{T}(2\pi N_1+\phi+\gamma_j) \\ -\sin\phi\cos\frac{n}{T}(2\pi(N_1+N_2)+\phi+\gamma_j) \end{array} \right\} \right] \qquad (4)$$

$$c_{nj} = \sqrt{a_{nj}^{\ 2} + b_{nj}^{\ 2}} \qquad (5)$$

$$\psi_{nj} = \tan^{-1}(a_{nj}/b_{nj}) \qquad (6)$$

For $n = T$, which is the supply frequency component:

$a_{Tj} = 0$ (7)
$b_{Tj} = 0$ (8)
$C_{Tj} = 0$ (9)

$\psi_{Tj} = 0$ (11)

It is obvious from the above two equations that the amplitude of the supply frequency component (i.e. c_{Tj}) equals to zero. Plot of the harmonic amplitude spectrum of the BPICC wave shown in Fig.3(a) for different values of T, N_1, and N_2 for *R* - load shows that only odd harmonics are exist, i.e. for even harmonics , $c_{nj} = 0$.

Figure 3 shows a typical example for the harmonic amplitude spectrum and phase displacement angles of the load voltage waveform for the case where $N_1 = N_2 = 2$ and $T = 4$, for *R*-load. It is seen that the harmonic amplitude spectrum contains odd harmonics only and the amplitudes of the even harmonics as well as the supply frequency component are equal to zero. Also the harmonic spectrum for the three phases are found to be similar.

As it can be seen from Fig.3, the phase displacement angles for any individual harmonic are found to be unbalanced for the three-phase system. This problem may not be encountered in conventional three-phase inverters or cycloconverters. All higher order harmonics are found to be balanced in phase-angle displacements in these converters. The unbalanced phase harmonics in the present converter are found to create severe problem when it is used as an a.c. drive [9]. However, this problem can be solved by using phase-shifting technique. This technique, although it is simple, it has solved the similar problems associated with integral-cycle triggering for the three-phase systems. The phase-shifting technique involves shifting the load voltage v_{Lj} of phase B or phase C or both by multiples of 2π with respect to phase A which is taken as a reference phase[11,12}.

Figure 4 shows the resulting phase displacement angles after phase shifting. It is obvious that most of the important harmonic components become balanced in amplitude and phase displacement.

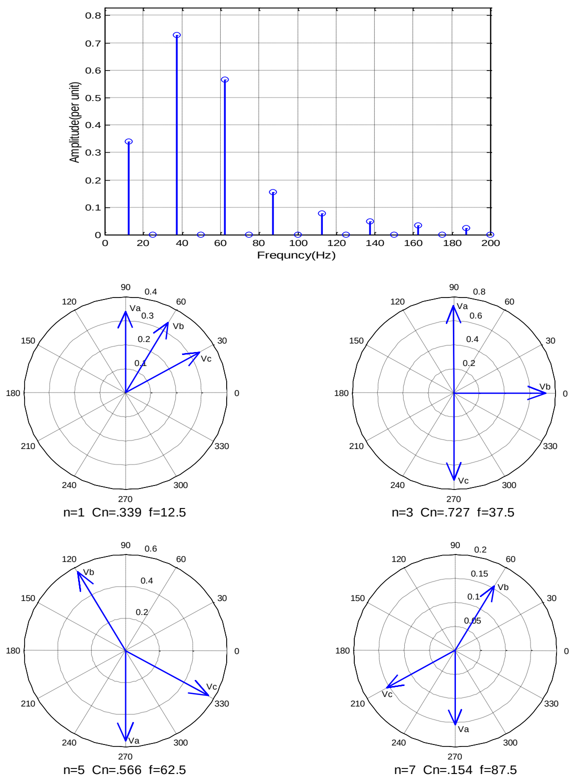


Fig. 3 Harmonic amplitude spectrum (of phase *A*, *B*, and *C*) and phase angle relationships for N_1 = N_2 = N= 2 and T = 4, *R*-load.

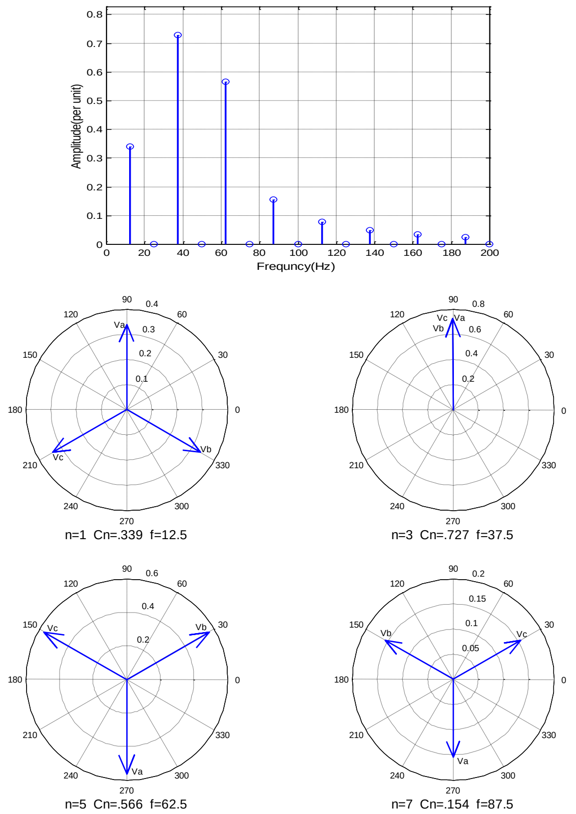


Fig. 4 Harmonic amplitude spectrum (of phase *A*, *B*, and *C*) and phase angle relationships for N_1 = N_2 = 2 and T = 4, *R*-load after phase correction.

Nevertheless, few of them becomes in-phase. In any case, the amplitude of an individual harmonic does not affected by the phase-shifting procedure.

3. HARDWARE DESCRIPTION FOR THE PROPOSED POWER FREQUENCY CHANGER

Figure 5 illustrates the three-phase design configuration of the proposed system. Step-down transformers are used to reduce the three-phase a.c. voltage. Zero crossing detectors are used to sense the positive going zero of the a.c. supply. The microprocessor now can sense the zero-instant of the a.c. supply, and then the conduction of the thyristors is started by sending pulses from the microprocessor to the gate drives.

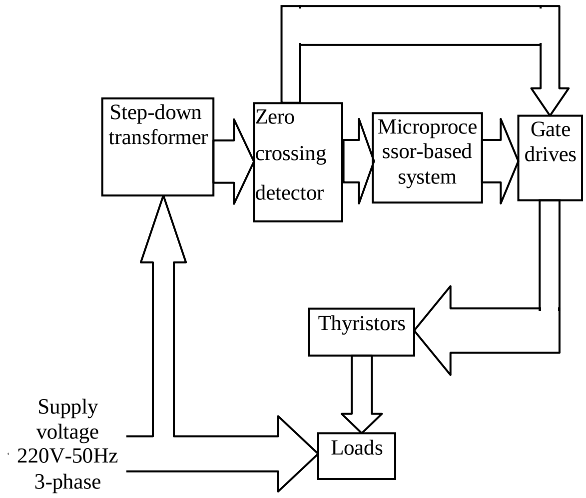
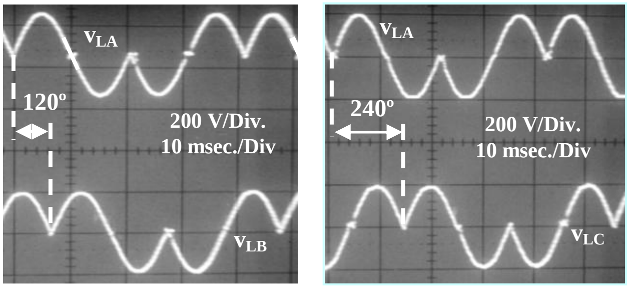


Fig. 5 System block diagram

4. EXPERIMENTAL RESULTS

The proposed frequency changer circuit shown in Fig. 5 was tested in the laboratory using a three-phase resistive load. Fig. 6 shows the theoretical and practical harmonic amplitude spectrum for v_{LA} for example. The practical results are obtained by using a digital wave analyzer. The phase displacement angles for the 1^{st} harmonic (25Hz) before and after shifting v_{LB} by 360º in time phase (theoretically) are shown in Fig. 7.

Another example is for the case when N_1=N_2= N = 2 and T = 4. Figs. 8 and 9 show oscillograms of the load voltage waveforms v_{LA}, v_{LB}, and v_{LC} before and after phase correction. Figs.10,11and 12 show the phase displacement angles for the 1^{st} harmonic (12.5 Hz) before and after phase correction for phase *B* and *C* respectively. Also, in this case, phase



(a) (b)

Fig. 6 Oscillograms for Load voltage waveforms for N=1, T=2, (a) v_{LA} & v_{LB} ,(b)v_{LA} & v_{LC} before phase correction.

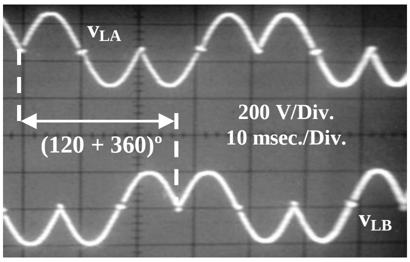
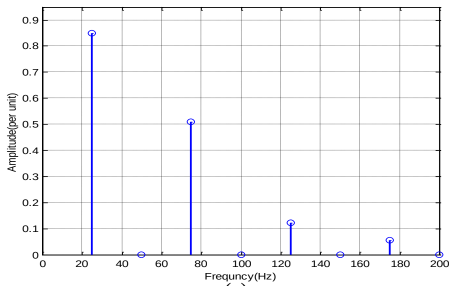
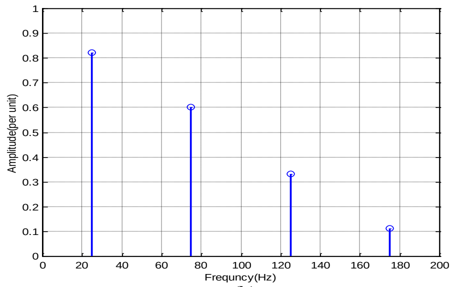


Fig. 7 Oscillograms for Load voltage waveforms for v_{LA} and v_{LB} after phase correction.

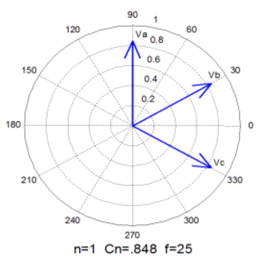


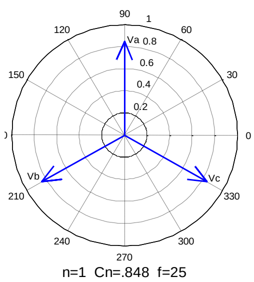
(a)



(b)

Fig. 8 Harmonic amplitude spectrum for the load voltage of phase A.





(a) Before phase correction (b) After phase correction

Fig. 9 Phase angle displacement of the load voltage.

phase B and C respectively. Also, in this case, phase correction affects only the phase relationships of a particular subharmonic or higher order harmonic, but it does not affect neither the wave shape of the load voltage nor the harmonic amplitudes.

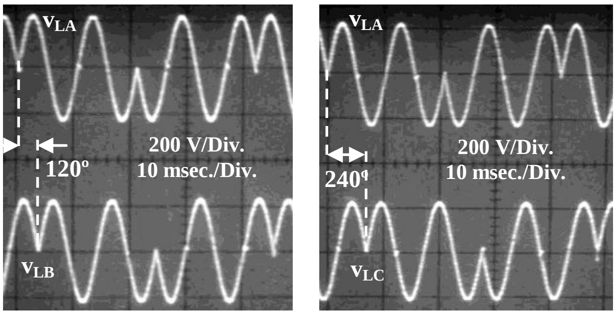
The frequency changer was also tested with a resistive-inductive load. It is commonly known that the waveform of the output load voltage depends largely on the ratio of the inductance to resistance. This comes from the load impedance angle, which is given by

$$\phi = \tan^{-1}\left(\frac{\omega L}{R}\right) \qquad (12)$$

However, ϕ affects the extinction angle of the load current, and force the current to reach zero value after the input voltage. Due to this delay, the output voltage waveform will no longer be integral multiples of the input voltage waveform. Therefore, the harmonic analysis of the output voltage waveform gives different harmonic amplitude spectrum from that of the output voltage waveform obtained from nearly pure resistive load. Nevertheless, the influence of small values of ϕ on the harmonic amplitude spectrum is found to be negligible , but for high values of ϕ (highly inductive load), the current may cause short circuit problems to the converter circuit. However this problem is solved by allowing a dead time of D cycles between the in – phase and ati- phase waves as shown in Fig.13.

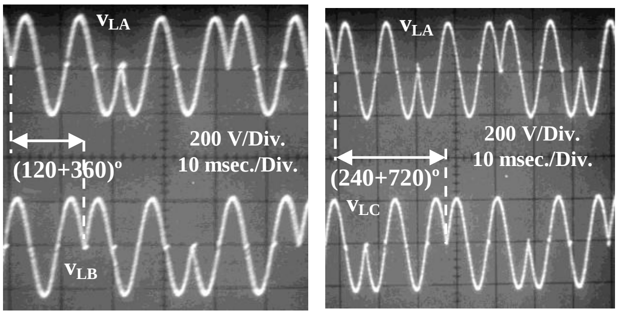
Fig.14 shows frequency spectrum for the case when N1=N2 ,D=1 and T=4. Also,Fig.15 shows the lowest order harmonics (12,5 Hz) phase relationship in a three-phase system before and after phase angle correction for this case.

The system was also tested with a three-phase, cage-type induction motor described in the Appendix. The stator windings were connected in 4-wire, star-connected form. Practically it is found that this technique produces some problems to the motor such as vibration and heat rising to the motor windings. These problems become severe especially at output frequencies near the supply frequency value. However, Table (1) gives the speed measurement values of the motor n_r at different values of N and T using a digital tachometer before and after the phase displacement angles correction in addition with the frequency of rotation for each case that is calculated using the basic equation of the three-phase induction motor speed with slip ignored, $n_r=120*f/p$ [13], where f=supply frequency and p=number of poles.



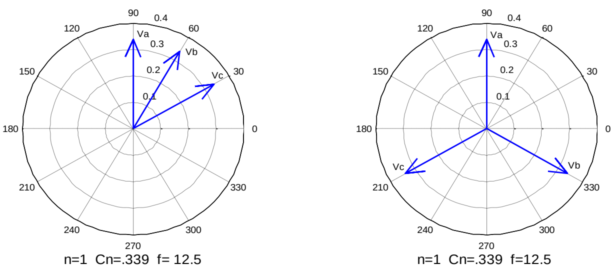
(a) (b)

Fig. 10 Oscillograms for Load voltage waveforms for N=2, T=4, (a) v_{LA} and v_{LB} (b) v_{LA} and v_{LC} before phase correction.



(a) (b)

Fig. 11 Oscillograms for Load voltage waveforms for (a) v_{LA} and v_{LB} (b) v_{LA} and v_{LC} after phase correction



(a) Before phase correction (b) After phase correction

Fig. 12 Phase angle displacement of the load voltage.

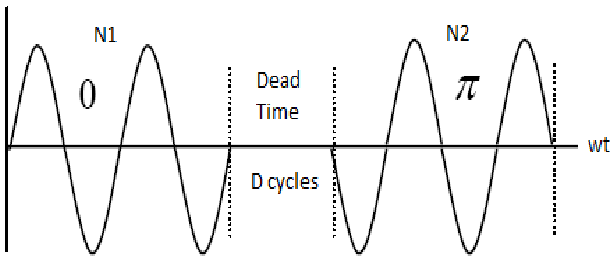


Fig. 13 Dead time of D cycles is allowed for highly inductive loads between the in-phase and anti-phase waves of the converter.

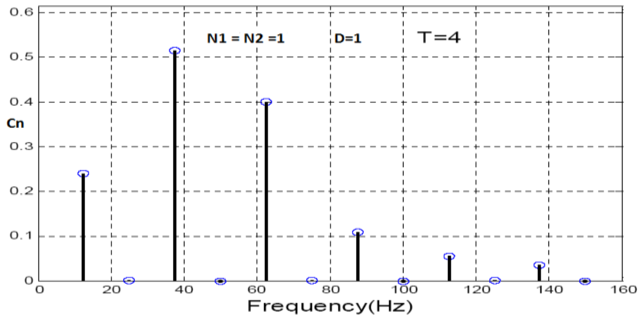
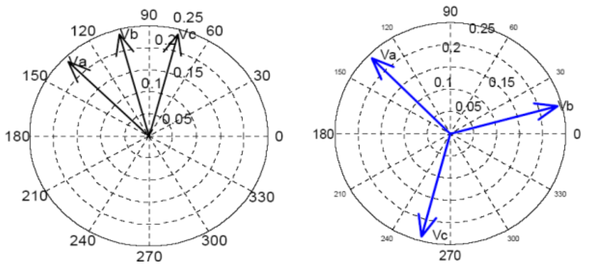


Fig. 14 Frequency spectrum for the case when D =1 cycle is allowed for highly inductive loads (N1=N2 =1 and T=4).



(a) Before phase correction (b) After phase correction

Fig. 15 Phase angle displacement of the load voltage for the case when D =1 cycle is allowed for highly inductive loads (N1=N2 =1 and T=4).

Oscillograms for Load voltage waveforms for v_{LA} and v_{LB} after phase angle correction for the case when a dead time of D =1 cycle is allowed for resistive loads when N1 = N2 =1 and T=4 is shown in Fig.16.

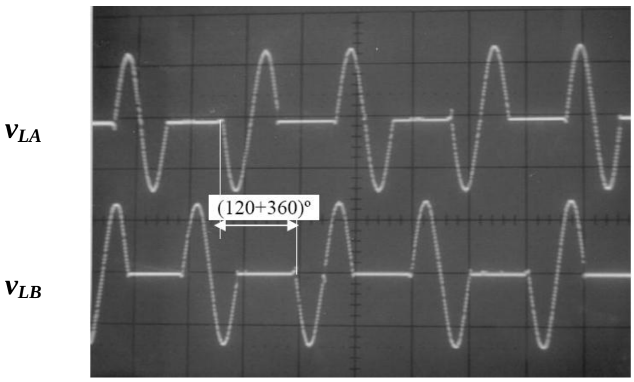


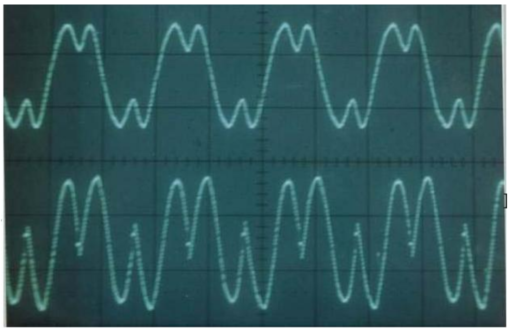
Fig.16 Oscillograms for Load voltage waveforms for v_{LA} and v_{LB} after phase correction when a dead time of D =1 cycle is allowed.

However, results of Table (1) show that, the motor speed n_r changed when the phase displacement is corrected. This is because the phase displacement angles of a certain harmonic component becomes dominant and balanced i.e. separated by 120° in time phase, so that its own speed is produced. This means that after the correction of the phase displacement angles of the lowest harmonic, the motor began to rotate at speed corresponding to this frequency.Oscillogram for the Stator current i_s and stator voltage v_s waveforms of the motor is shown in Fig.17 for the case when T=2,N_1=N_2=1.

Table (1) Motor performance with some desired frequencies produced by the proposed frequency changer

T	N	n_r (r.p.m.) before phase angle	Frequency of rotation (Hz) (Experimental)	n_r (r.p.m.) after phase angle correction	Frequency of rotation (Hz) (Experimental)	Frequency of the 1st harmonic (Hz) (Theoretical)
2	1	1263	21.5	1404	23.9	25
4	2	885	15.06	684	11.46	12.5
8	4	1455	24.77	368	6.26	6.25

i_s



v_s

Fig.17 Oscillogram for the Stator current i_s and stator voltage v_s waveforms of the motor is for the case when N_1=N_2=1, T=2.

5. CONCLUSION

Analytical results show that the principles of bi-phase integral cycle control of the supply voltage provide adequate theoretical as well as practical bases for power frequency changing schemes. bi-phase integral cycle control represents a powerful technique that yields high power, amplitude invariance and high efficiency of conversion. The supply frequency component can be completely eliminated, and the power associated with this component is transferred to the other desirable components in the frequency spectrum. As a frequency changer using bi-phase integral cycle control technique a single stage ac/ac converter with nearly sinusoidal output voltage and input current is achieved, and no filtering components are required. Moreover, it is a bi-directional power flow converter with no reactive elements (bulky dc-capacitors and large line inductors).

The suggested frequency changer proves to have many advantages over conventional types, such as iverters and cycloconverters, in that it is more simple , requires no complex triggering circuits due to few thyristors used and need no filtering equipment because the output voltage and current waveforms are smooth and largely free from spikes and undesirable high order harmonic components that produce electromagnetic interferences.

A laboratory prototype of the frequency changer using bi-phase integral cycle control technique has been built and successfully tested.

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APPENDIX

Induction Motor Parameters

The three-phase induction motor used to carry out the experimental investigation is a laboratory demonstrating set. Details of the motor are as follows:

P = 500W
V = 380 / 220V ⅄ / △ Connected .
I = 1.2A / 2.1A
n_r = 2850 r.p.m
frequency = 50 Hz
No. of poles = 2

NOMENCLATURE

a_0 Zero order Fourier coefficient.
a_n, b_n n^{th} order Fourier coefficients.
a_T, b_T $n = T$ order Fourier coefficients.
c_n Peak amplitude of n^{th} order harmonic .
n Order of harmonic.
n_r Rotor speed (rpm)
n_s Synchronous speed (rpm)
t Time, second.
x Extinction angle, rad.
v Instantaneous voltage, V.
v_{Lj} Load voltage at the j^{th} phase, V.
N, N_1, N_2, N_3, N_4 Number of conduction cycles.
L Inductance, H.
R Resistance, Ω.
T Control period (no. of cycles).
γ_j Phase displacement of the j^{th} phase,rad
ψ_{nj} Phase angle for n^{th} harmonic, rad.
ϕ Phase angle of load impedance, rad.
ω_t Angular frequency, rad /s.

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