2009 IEEE Symposium on Industrial Electronics and Applications (ISIEA 2009), October 4-6, 2009, Kuala Lumpur, Malaysia

PWM-Based Control Strategy for Forced Commutated Cycloconverters

Ebrahim Babaei
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran.
Email: e-babaei@tabrizu.ac.ir

Ali Aghabeigi Heris
Faculty of Electrical and Computer Engineering
University of Tabriz
Tabriz, Iran.
Email: hanibalslr@yahoo.com

Abstract- **This paper presents a new control method for three-phase to single-phase cycloconverters based on pulse width modulation (PWM) technique. Due to the proposed control method, the desired output voltage can be generated even with unbalanced input voltages. The proposed control method can easily be extend to three-phase to n-phase cycloconverters. The theoretical analysis based on the proposed method is given for both of the conventional topologies of three-phase to single-phase cycloconverters. Using the proposed control method, the maximum output/input voltage transfer ratios for balanced operation are 0.5 and 1.5 for cycloconverters that consist of three and six bidirectional switches, respectively. It is important to note that the low voltage transfer ratio is an intrinsic limitation of the conventional control methods. This method has no limitation on frequency conversion and is independent of the load. In other words, using the proposed control method, the three-phase to single-phase cycloconverter can operate as a step-up voltage and frequency. The other advantage of this method is no low order harmonics in the input and output quantities. Therefore, the size of required filters is decreased. The operation and performance of the proposed control method has been verified by simulation and experimental results of a three-phase to single-phase cycloconverter.**

Keywords– Cycloconverter; Forced commutated; Matrix converter; Three-phase to single-phase converter; Bi-directional switch

I. Introduction

A forced commutated cycloconverter (FCC) is a power electronic converter that converts constant voltage constant frequency ac power such as the mains supply to adjustable voltage adjustable frequency ac power without an intermediate dc link. These types of converters also called matrix converters.

In [1], the first modulation strategy (in the following Alesina–Venturini (AV) method) allowing the full control of the output voltages and of the input power factor has been derived. The maximum voltage transfer ratio of the proposed algorithm is limited to 0.5 and the input power factor control requires knowledge of the output power factor.

The inclusion of third harmonics in the input and output voltage waveforms has been successfully adopted in [2] to increase the maximum voltage transfer ratio up to 0.866, a value which represents an intrinsic limitation of the three-phase to three-phase FCC, with balanced supply voltages and balanced output conditions.

A sensible increase of the maximum voltage transfer ratio up to 1.053 is a feature of the fictitious dc link algorithm, presented in [3]. This strategy considers the modulation as a two-step process, namely, rectification and inversion. The higher voltage transfer ratio is achieved in spite of low frequency distortion in the input and output variables.

The above modulation methods are the basic modulation techniques and the other presented methods are mostly tried to eliminate weak points of previous methods [4-6].

A cycloconverter can be constructed with a range of different configurations from the viewpoint of topology [7-11]. More complex cycloconverter designs have been proposed which use forced-commutated or load-commutated techniques to provide a much wider frequency range. However, the need for a load which has the correct characteristics for the load-commutated cycloconverter and the increased complexity and cost of FCCs make these circuits unattractive [12].

The main problem in the conventional control methods is low output/input voltage transfer ratio. Also, if the input voltages are significantly unbalanced then these methods can not produce the desired output voltage. It is important to note that the matrix converters are direct converters and any unbalance in input sides are immediately reflected to the output side. It is noticeable that the previous methods for solving this problem cause to generate low order harmonics in the input and output quantities which can not easily be eliminated.

This paper presents a new control method based on PWM technique for three-phase to single-phase cycloconverters. Using the proposed control method, the desired output voltage can be generated even with unbalanced input voltages. The proposed method is independent of the load and it is possible to generate the voltage transfer ratio of 1.5 without low order harmonics at input and output quantities. Also this method can easily be developed to n-phase systems.

In this paper, two topologies are introduced for direct conversion of three-phase to single-phase and then the mathematical base of the proposed method is given. The simulation and experimental results will admit accuracy of mathematical computation.

II. Three-phase to Single-phase Cycloconveters

FCC as a new race of power electronics converters is a kind of power supply with variable amplitude and frequency which converts m numbers of input voltages to n numbers of output voltages without using storage elements. It requires bidirectional switches with capability of blocking voltage and conducting current in both directions. There are several arrangements that can be used to create such a bidirectional switch [13]. In this paper the common emitter arrangement is used. A cycloconverter consists of n power switches and can create 2^n numbers of on and off states. The following two basic rules should be considered for the safe operation of the converter:

- Prevention of short-circuit among power supplies (over current constraint),
- Prevention of open circuit of the loads with inductive properties (over voltage constraint).

This paper focuses on the forced-commutated three-phase to single-phase cycloconverter. The input voltages of the converter are v_{i1}, v_{i2} and v_{i3}. Load is typically inductive and its voltage and current are v_o and i_o, respectively. The input voltages under balanced operation can be considered as below:

$$\begin{aligned} v_{i1}(t) &= V_{im}\sin(\omega_i t) \\ v_{i2}(t) &= V_{im}\sin(\omega_i t - 120^\circ) \\ v_{i3}(t) &= V_{im}\sin(\omega_i t + 120^\circ) \end{aligned} \tag{1}$$

Which V_{im} and ω_i denote amplitude and angular frequency of the input voltages, respectively. The fundamental component of the desired output voltage is assumed as follows:

$$v_o(t) = V_{om}\sin(\omega_o t) \tag{2}$$

Where V_{om} and ω_o denote amplitude and angular frequency of the desired output voltage, respectively. It is noticeable that any phase can be considered for the output voltage in general. The relation between V_{im} and V_{om} can be expressed as output/input voltage transfer ratio (q) as below:

$$q = \frac{V_{om}}{V_{im}} \tag{3}$$

Considering (2), the fundamental component of the output current for the inductive load $(R-L)$ can be calculated as follows:

$$i_o(t) = \frac{V_{om}}{\sqrt{(L\omega_o)^2 + R^2}}\sin\left(\omega_o t - \tan^{-1}\left(\frac{L\omega_o}{R}\right)\right) \tag{4}$$

There are two different topologies for the three-phase to single-phase cycloconverters. Theses topologies are introduced briefly as follows.

A. Three-phase to Single-phase Cycloconverter with Three Bidirectional Power Switches

Fig. 1 shows the three-phase to single-phase cycloconverter with 3 bidirectional power switches [6]. This topology is capable of creating $2^3 = 8$ different mods which is confined to three mods, due to the two mentioned restrictions. The permitted modes for this topology is summarized in Table I.

B. Three-phase to Single-phase Cycloconverter with Six Bidirectional Power Switches

The power circuit of three-phase to single-phase cycloconverter with six bidirectional power switches is shown in Fig. 2 [6]. This topology generates $2^6 = 64$ switching states. These states are decreased to 7 states due to the two mentioned restrictions. The permitted modes for this topology is summarized in Table II.

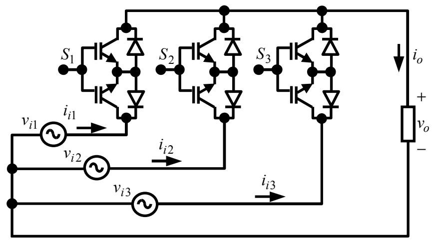

Figure 1. Three-phase to single-phase cycloconverter with three switches

TABLE I.
PERMITTED MODES FOR THREE-PHASE TO SINGLE-PHASE CYCLOCONVERTER WITH 3 SWITCHES

Mode	*On Switch*	v_o	i_o
1	S_1	v_{i1}	i_{i1}
2	S_2	v_{i2}	i_{i2}
3	S_3	v_{i3}	i_{i3}

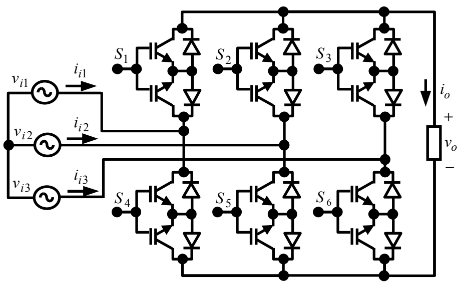

Figure 2. Three-phase to single-phase cycloconverter with six switches

TABLE II.
PERMITTED MODES FOR THREE-PHASE TO SINGLE-PHASE CYCLOCONVERTER WITH 6 SWITCHES

Mode	*On Switches*	v_o	i_o
1	S_1 & S_5	$v_{i1} - v_{i2}$	$i_{i1} = -i_{i2}$
2	S_1 & S_6	$v_{i1} - v_{i3}$	$i_{i1} = -i_{i3}$
3	S_2 & S_6	$v_{i2} - v_{i3}$	$i_{i2} = -i_{i3}$
4	S_2 & S_4	$v_{i2} - v_{i1}$	$i_{i2} = -i_{i1}$
5	S_3 & S_4	$v_{i3} - v_{i1}$	$i_{i3} = -i_{i1}$
6	S_3 & S_5	$v_{i3} - v_{i2}$	$i_{i3} = -i_{i2}$
7	(S_1 & S_4) or (S_2 & S_5) or (S_3 & S_6)	0	i_o

III. THE PROPOSED CONTROL METHOD

One of the control methods which can be used for controlling the waveform of the output voltage is PWM technique which alters the duty cycle of switches at the high switching frequency for attaining output voltage and current at the low frequency. In other words, the PWM modulation technique can control output voltage with suitable switching among the legal states in such a way that the average value of the output voltage becomes equal to desired waveform. Using this, the desired sinusoidal voltage is generated by sampled pieces of the input waveforms.

This paper presents a new control method based on PWM modulation technique for three-phase to single-phase cycloconverters. In the proposed control method each cycle of the input voltage are divided to six equal areas (each area with 60 degree). It is noticeable that the reason of choosing each area equal to 60° is that the peak equation of voltages is constant and also has large instantaneous values. In each area according to Tables I and II the switching application is run between modes which generate maximum voltage at the output. The reason of choosing modes which can generate maximum output voltage at the output is attaining the maximum voltage transfer ratio $(q_{\max})$ for the cycloconverter.

In the proposed modulation method, the switching frequency in each area is assumed as $f_s = 1/T_s$. During the $j-th$ sampling period $(T_s^j;\ j=1,2,3,\cdots)$, every sampling period is divided to two time intervals $t_{\max}^j$ and $t_{\min}^j$ as follows:

$$T_s^j = t_{\max}^j + t_{\min}^j \quad (5)$$

During the time interval $t_{\max}^j$, the voltage of $v_{\max}(t)$ will be transferred to the output and during the time interval $t_{\min}^j$, the voltage of $v_{\min}(t)$ will be transferred to the output and this process will be iterated for the rest of sampling periods.

According to the Tables I and II the relations of the $v_{\max}(t)$ and $v_{\min}(t)$ for the both mentioned converters can be defined as follows:

$$\begin{aligned} v_{\max}(t) &= V_{\max}\sin(\omega_i t + \phi_{\max}) \\ v_{\min}(t) &= V_{\max}\sin(\omega_i t + \phi_{\min}) \end{aligned} \quad (6)$$

Where $V_{\max}$, $\phi_{\max}$ and $\phi_{\min}$ denote the amplitude and phases of the $v_{\max}(t)$ and $v_{\min}(t)$, respectively. It is noticeable that in the both three-phase to single-phase converters, the peak value of the $v_{\max}(t)$ and $v_{\min}(t)$ is equivalent.

During the $j-th$ sampling period, the time intervals of $t_{\max}^j$ and $t_{\min}^j$ should be chosen in such a manner that the fundamental component of the generated output voltage follows the waveform of the desired output voltage. Assuming high switching frequency $(f_s >> f_i$ and $f_s >> f_o)$ the average of the output voltage can be written as below:

$$v_o(t) = \frac{1}{T_s}[t_{\max}^j v_{\max}(t) + t_{\min}^j v_{\min}(t)] \quad (7)$$

As shown in (7), the combination of $v_{\max}(t)$ and $v_{\min}(t)$ during time intervals $t_{\max}^j$ and $t_{\min}^j$ can generate suitable output voltage. Considering (2), (5), (6) and (7), the time intervals $t_{\max}$ and $t_{\min}$ are attained as follows:

$$\begin{aligned} t_{\max} &= T_s \frac{q\sin\omega_o t - x\sin(\omega_i t + \phi_{\min})}{x\sin(\omega_i t + \phi_{\max}) - x\sin(\omega_i t + \phi_{\min})} \\ t_{\min} &= T_s - t_{\max} \end{aligned} \quad (8)$$

Which x denotes the relation between $V_{\max}$ and V_{im} and it is expressed as follows:

$$x = \frac{V_{\max}}{V_{im}} \quad (9)$$

It is important to note that $t_{\max}$ and $t_{\min}$ are determined in a manner which the average of output voltage per modulation cycle follows the desired output voltage. It can be seen that this method is independent of the load and even for unbalanced input voltages, the desired output voltage can be acceptably produced.

During the $j-th$ sampling period, $t_{\max}^j$ and $t_{\min}^j$ must be adapted to (5) and below inequations:

$$\begin{aligned} 0 \le t_{\max}^j \le T_s^j \\ 0 \le t_{\min}^j \le T_s^j \end{aligned} \qquad for\ \ j = 1, 2, 3, \cdots \quad (10)$$

The following sections show the results of the proposed method for the mentioned three-phase to single-phase cycloconverters in details.

A. Results for Three-phase to Single-phase Cycloconcerter with Three Switches

According to the proposed control method, the generation of the typical desired output voltage under balanced input voltages operation is shown in Fig. 3. As this figure shows each period of the input voltages is divided to six equal areas. The desired output voltage is generated using sampled pieces from maximum instantaneous values of the input voltages. Table III summarizes the equations of the maximum and minimum voltages and switching functions of $t_{\max}$ in different areas.

B. Results for Three-phase to Single-phase Cycloconcerter with Six Switches

Fig. 4 shows the typical output voltage waveform for this topology under balanced input voltages operation. It can be seen, the output voltage is generated with sampled pieces from maximum instantaneous values of the input line voltages. Table IV summarizes the equations of maximum and minimum line voltages and switching functions of $t_{\max}$.

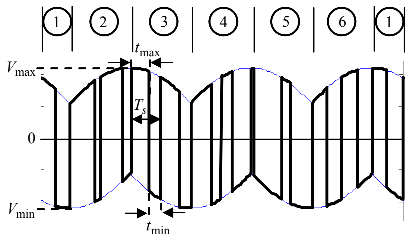

Figure 3. Proposed control method for three-phase to single-phase cycloconverter with three switches

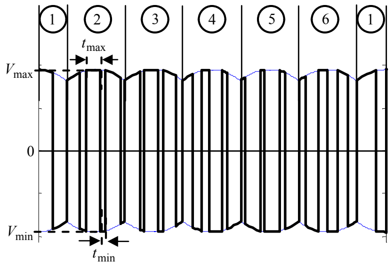

Figure 4. Proposed control method for three-phase to single-phase cycloconverter with six switches

TABLE III.
EQUATIONS OF $v_{\max}(t)$, $v_{\min}(t)$ AND $t_{\max}$ IN DIFFERENT AREAS FOR CIRCUIT SHOWN IN FIG. 1 (BALANCED OPERATION)

Area	$v_{\max}(t)$ and $v_{\min}(t)$	$t_{\max}$
1	$v_{\max} = V_{im}\sin(\omega_i t + 120^\circ)$ $v_{\min} = V_{im}\sin(\omega_i t - 120^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sin(\omega_i t - 120^\circ)}{\sqrt{3}\sin(\omega_i t + 90^\circ)}$
2	$v_{\max} = V_{im}\sin(\omega_i t)$ $v_{\min} = V_{im}\sin(\omega_i t - 120^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sin(\omega_i t - 120^\circ)}{\sqrt{3}\sin(\omega_i t + 30^\circ)}$
3	$v_{\max} = V_{im}\sin(\omega_i t)$ $v_{\min} = V_{im}\sin(\omega_i t + 120^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sin(\omega_i t + 120^\circ)}{\sqrt{3}\sin(\omega_i t - 30^\circ)}$
4	$v_{\max} = V_{im}\sin(\omega_i t - 120^\circ)$ $v_{\min} = V_{im}\sin(\omega_i t + 120^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sin(\omega_i t + 120^\circ)}{\sqrt{3}\sin(\omega_i t - 90^\circ)}$
5	$v_{\max} = V_{im}\sin(\omega_i t - 120^\circ)$ $v_{\min} = V_{im}\sin(\omega_i t)$	$T_s \dfrac{q\sin(\omega_o t) - \sin(\omega_i t)}{\sqrt{3}\sin(\omega_i t - 150^\circ)}$
6	$v_{\max} = V_{im}\sin(\omega_i t + 120^\circ)$ $v_{\min} = V_{im}\sin(\omega_i t)$	$T_s \dfrac{q\sin(\omega_o t) - \sin(\omega_i t)}{\sqrt{3}\sin(\omega_i t + 150^\circ)}$

TABLE IV.
EQUATIONS OF $v_{\max}(t)$, $v_{\min}(t)$ AND $t_{\max}$ IN DIFFERENT AREAS FOR CIRCUIT SHOWN IN FIG. 2 (BALANCED OPERATION)

	$v_{\max}(t)$ and $v_{\min}(t)$	$t_{\max}$
1	$v_{\max} = \sqrt{3}V_{im}\sin(\omega_i t + 90^\circ)$ $v_{\min} = \sqrt{3}V_{im}\sin(\omega_i t - 90^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sqrt{3}\sin(\omega_i t - 90^\circ)}{2\sqrt{3}\sin(\omega_i t + 90^\circ)}$
2	$v_{\max} = \sqrt{3}V_{im}\sin(\omega_i t + 30^\circ)$ $v_{\min} = \sqrt{3}V_{im}\sin(\omega_i t - 150^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sqrt{3}\sin(\omega_i t - 150^\circ)}{2\sqrt{3}\sin(\omega_i t + 30^\circ)}$
3	$v_{\max} = \sqrt{3}V_{im}\sin(\omega_i t - 30^\circ)$ $v_{\min} = \sqrt{3}V_{im}\sin(\omega_i t + 150^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sqrt{3}\sin(\omega_i t + 150^\circ)}{2\sqrt{3}\sin(\omega_i t - 30^\circ)}$
4	$v_{\max} = \sqrt{3}V_{im}\sin(\omega_i t - 90^\circ)$ $v_{\min} = \sqrt{3}V_{im}\sin(\omega_i t + 90^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sqrt{3}\sin(\omega_i t + 90^\circ)}{2\sqrt{3}\sin(\omega_i t - 90^\circ)}$
5	$v_{\max} = \sqrt{3}V_{im}\sin(\omega_i t - 150^\circ)$ $v_{\min} = \sqrt{3}V_{im}\sin(\omega_i t + 30^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sqrt{3}\sin(\omega_i t + 30^\circ)}{2\sqrt{3}\sin(\omega_i t - 150^\circ)}$
6	$v_{\max} = \sqrt{3}V_{im}\sin(\omega_i t + 150^\circ)$ $v_{\min} = \sqrt{3}V_{im}\sin(\omega_i t - 30^\circ)$	$T_s \dfrac{q\sin(\omega_o t) - \sqrt{3}\sin(\omega_i t - 30^\circ)}{2\sqrt{3}\sin(\omega_i t + 150^\circ)}$

IV. DETERMINATION OF THE MAXIMUM VOLTAGE TRANSFER RATIO

According to mentioned algorithm, the output voltage waveform is generated by the sampled pieces of the input voltage waveforms. In order to avoid the generation of low order harmonics, the modulation frequency must be chosen considerably greater than the input and output frequencies. Considering (7) and (10), it is clear:

$$\min[v_k(t)] \le v_o(t) \le \max[v_k(t)] \quad for\ k = \min,\ \max \quad (11)$$

It is important t to note that $\min[v_k(t)]$ and $\max[v_k(t)]$ denote the input voltage lower and upper bands, respectively. For all times, every generated output waveform must be set in confine of the input waveforms. This means that for all times the minimum input voltage upper band must be greater than the maximum voltage upper band. Therefore, this restriction for a three-phase to single-phase cycloconverter with three switches under balanced input voltages operation is as follows:

$$V_{om} \le 0.5V_{im} \qquad or \qquad q \le 0.5 \qquad (12)$$

This restriction for a three-phase to single-phase cycloconverter with six switches under balanced input voltages operation is as follows:

$$V_{om} \le 1.5V_{im} \qquad or \qquad q \le 1.5 \qquad (13)$$

V. DEVELOPMENT OF THE PROPOSED CONTROL METHOD TO THREE-PHASE TO N-PHASE CYCLOCONVERTER

The mentioned topologies and proposed control method can easily be developed to more phases. For example, extension of the three-phase to single-phase cycloconverter to three-phase to three-phase cycloconverter. This topology consists of three units. Each unit can have topologies as Figs. 1 and 2. Using topology of Fig. 2 it can generate the desired output voltage with maximum voltage transfer ratio equal $q = 1.5$. It is important to note that the lower output/input voltage transfer ratio is the main problem of the conventional methods. Also regarding to independent control of the different units, it is possible to generate unbalanced output voltages (not only in amplitude but also in phase). By choosing high switching frequency in this method low order harmonics are not generated. So, the size of the filter is extremely decreased.

VI. SIMULATION AND EXPERIMENTAL RESULTS

In order to exhibit the ability of the proposed control method in generation of desired output voltages, the operation of both mentioned FCCs are studied for the different outputs. Fig. 5 shows the block diagram of proposed control method for three-phase to single-phase FCC. According to Tables III and IV the functions of $v_{\max}$ and $v_{\min}$ are determined. Then, in each sampling period $t_{\max}$ and $t_{\min}$ are calculated in such a way that the fundamental component of the generated output voltage tracks the desired output voltage.

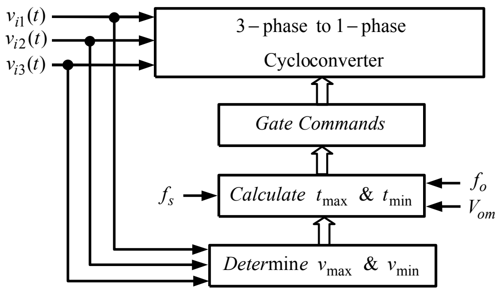

Figure 5. Block diagram of the proposed control method

In experimental set-up, the IGBTs of the prototypes are BUP306D with internal anti-parallel diodes. The 89C52 microcontroller by ATMEL Company has been used to generate the switching patterns according to the proposed control method.

The amplitude and frequency of the input voltages are $V_{im} = 110\mathbf{V}$ and $f_i = 50Hz$, respectively. Also, the load is considered as $R-L$ with $R = 65\Omega$ and $L = 55mH$. The output frequency and switching frequency are assumed $f_o = 60Hz$ and $f_s = 4\,kHz$, respectively. In cycloconverters with three and six switches the voltage transfer ratios are considered $q = 0.4$ and $q = 0.9$, respectively. In the unbalanced operation the input voltages are considered as follows:

$$v_{i1}(t) = V_{im}\sin(\omega_i t)$$
$$v_{i2}(t) = 0.8V_{im}\sin(\omega_i t - 120^\circ)$$
$$v_{i3}(t) = 1.3V_{im}\sin(\omega_i t + 120^\circ)$$

It is mentionable that the PSCAD/EMTDC software is used for simulation.

A. Simulation and Experimental Results for the Three-phase to Single-phase Cycloconverter with Three Switches

A1. Balanced Operation

Figs. 6 and 7 show the waveforms of the output voltage and current, respectively. The experimental results have good agreement with simulation results. As shown in Fig.6, the output voltage is generated from sampled pieces of the maximum values of the input voltages. So, the maximum instantaneous value of the output voltage is limited to the peak value of the input voltage and this exactly agrees with the results of Table I.

Figs. 8 and 9 show the spectrums of the output voltage and current, respectively. As these figures show, the spectrums of the output voltage and current have the fundamental component $(f_o = 60Hz)$ and $(Kf_s + \Delta f)$ harmonics, where K is an integer and Δf is a function of f_i and f_o. Since the load of the converters is almost a low pass filter $(R-L)$, then the output current contains less high order harmonics than the output voltage. The amplitude of the fundamental component of the output voltage is 44.444V that agrees with the amplitude of the desired output voltage. Also the amplitude of the fundamental component of the output current is 0.65A that adapts to the given value of (4). THDs of the output voltage and current are 2.5394 and 0.1236, respectively.

A2. Unbalanced Operation

Figs. 10-12 show the simulation and experimental resutls of the converter under unbalanced operation. It is very interesting to note that the proposed control method can generate desired output voltage from unbalanced input voltages. The amplitudes of the fundamental components of the output voltage and current are 42.62V and 0.625A, respectively. Also their THDs are 2.706 and 0.1227, respectively.

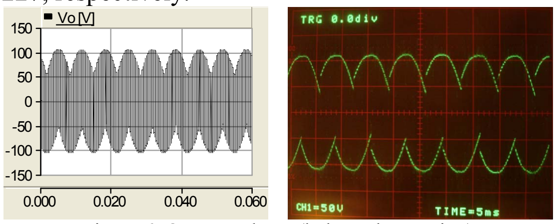

Figure 6. Output voltage (balanced operation)

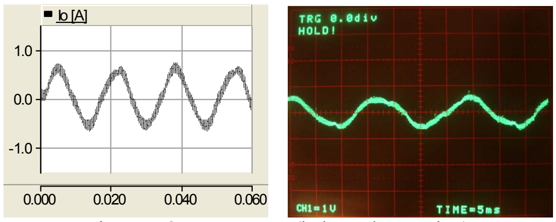

Figure7. Output current (balanced operation)

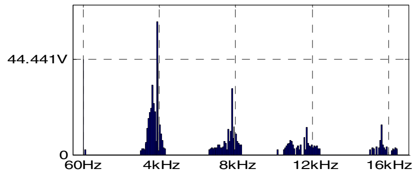

Figure 8. Spectrum of the output voltage (balanced operation)

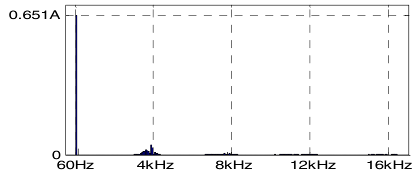

Figure 9. Spectrum of the output current (balanced operation)

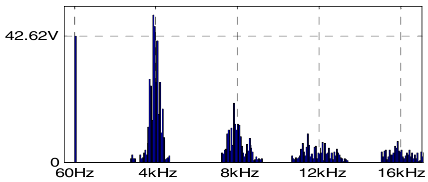

Figure 10. Spectrum of the output voltage (unbalanced operation)

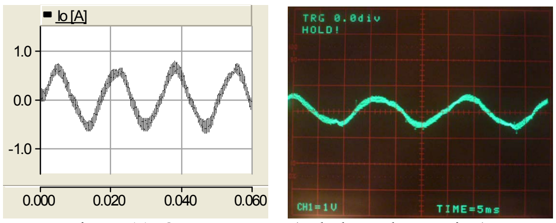

Figure 11. Output current (unbalanced operation)

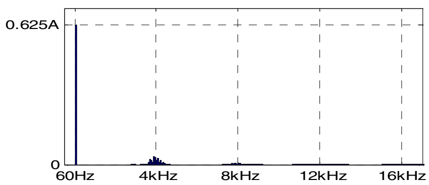

Figure 12. Spectrum of the output current (unbalanced operation)

B. Simulation and Experimental Results for the Three-phase to Single-phase Cycloconverter with Six Switches

B1. Balanced Operation

Figs. 13-15 show the waveforms of different quantities of the input and output sides and their spectrums. As mentioned in previous subsection, the spectrums of the output voltage and current have the fundamental component ($f_o = 60Hz$) and ($Kf_s + \Delta f$) harmonics. The amplitude of the fundamental component of the output voltage and current are 96.89V and 1.42A, respectively and their THDs are 2.3544 and 0.1097, respectively.

B2. Unbalanced Operation

Figs. 16-17 show the spectrums of the output voltage and current under unbalanced operation. The results show that the proposed control method can generate desired output voltage from unbalanced input voltages. The amplitudes of the fundamental components of the output voltage and current are 96.534V and 1.414A, respectively. Also their THDs are 2.484 and 0.1123, respectively.

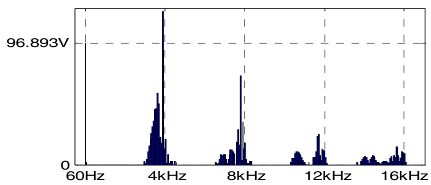

Figure 13. Spectrum of the output voltage (balanced operation)

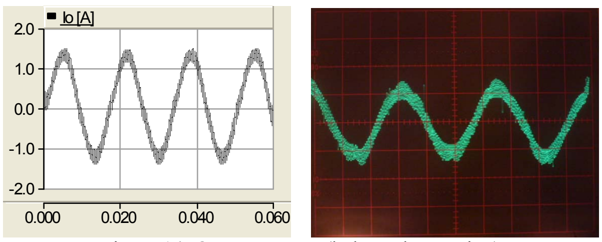

Figure 14. Output current (balanced operation)

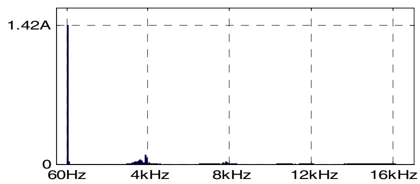

Figure. 15 Spectrum of the output current (balanced operation)

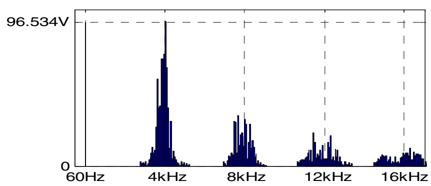

Figure. 16 Spectrum of the output voltage (unbalanced operation)

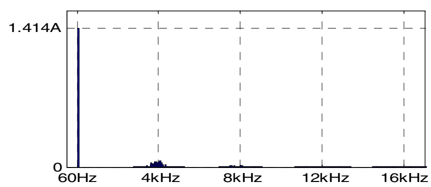

Figure 17. Spectrum of the output current (unbalanced operation)

VII. CONCLUSION

A new control method for three-phase to single-phase cycloconveters has been presented. By the proposed control method, the desired output voltage can be generated even with unbalanced input voltages. Using the proposed control method, the maximum value of the voltage transfer ratio under balanced input voltages operation for three-phase to single-phase cycloconverters with three and six switches are $q = 0.5$ and $q = 1.5$, respectively. There is no limitation on frequency conversion. Also, by proposed control method, the harmonics are generated environs of switching frequency that can easily be eliminated with using small filter. The topologies and proposed control method can easily be developed to three-phase to n-phase. Due to the independence of converters in different units, it is possible to generate unbalanced n-phase (not only in amplitude but also in phase). The proposed control method guarantees that there is no short circuit among input voltages and no open circuit for output current. This method is independent of the load.

REFERENCES

[1] A. Alesina and M. Venturini, “Solid-state power conversion: A Fourier analysis approach to generalized transformer synthesis,” *IEEE Trans. Circuits Syst.*, vol. CAS-28, pp. 319–330, Apr. 1981.

[2] M. J. Maytum and D. Colman, “The implementation and future potential of the Venturini converter,” in *Proc. Drives, Motors Controls*, 1983, pp. 108–117.

[3] P. D. Ziogas, S. I. Khan, and M. H. Rashid, “Analysis and design of forced commutated cycloconverter structures with improved transfer characteristics,” *IEEE Trans. Ind. Electron.*, vol. 1E-33, pp. 271–280, Aug. 1986.

[4] M. Imayavaramban, K. Latha, G. Uma, “Analysis of different schemes of matrix converter with maximum voltage conversion ratio,” *MELECON 2004*, vol. 3, pp. 1137-1140.

[5] S. Khanmohammadi, A. Aghagolzadeh, S.H. Hosseini, and E. Babaei, “A new algorithm for three-phase to single-phase ac/ac matrix converters,” *ICECS2003*, vol. III, pp. 1121-1124.

[6] E. Babaei, A. Aghagolzadeh, S.H. Hosseini, and S. Khanmohammadi, “A new structure for three-phase to single-phase ac/ac matrix converters,” *ICECS2003,* vol. I, pp. 36-39.

[7] L. Wei and T.A. Lipo, “A novel matrix converter topology with simple commutation,” *Proceedings of the IEEE-IAS Annual Meeting, vol. 3* (2001), pp. 1749–1754.

[8] J.W. Kolar, M. Baumann, F. Schafmeister and H. Ertl, “Novel three-phase AC–DC–AC sparse matrix converter,” *in Proc. IEEE APEC’02,* vol. 2, pp. 287–292.

[9] S. Kwak, “Design and analysis of modern three-phase AC/AC power converters for ac drives and utility interfaces,” *Ph.D. dissertation*, Texas A&M University, 2005.

[10] Fang Zheng Peng, Lihua Chen, Fang Zhang, “Simple Topologies of PWM AC-AC Converters,” *IEEE Power Electronics Letters,* vol. 1, no. 1, March 2003, pp. 10-13.

[11] Nguyen Minh Khai, Young-Gook Jung, and Young- Cheol Lim, “A single-phase Z-source cycloconverter (SPZC) based on single-phase matrix converter (SPMC) topology with safe-commutation strategy,” *International Symposium on Electrical & Electronics Engineering,* 2007, Vietnam, pp. 205-211.

[12] Sedat Sunter, “A vector controlled matrix converter induction motor drive,” *Ph.D. Thesis*, University of Nottingham, July 1995.

[13] C. Klumpner and F. Blaabjerg, “Using reverse blocking IGBTs in power converters for adjustable speed drives,” *IEEE Trans. Ind. Appl.*, vol. 42, no. 3, pp. 807-816, May/Jun. 2006.