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Modified Single Stage AC-AC Converter

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ABSTRACT

The paper describes the single stage AC-AC converter. This converter is a good alternative to quasi direct back to back converter. This single stage converter is called Matrix Converter. Matrix converter is an array of controlled semiconductor switches that connects three phase source to the three phase load. This converter provides bidirectional power flow, sinusoidal input and output waveforms and they have no dc link storage elements. Simulation model and results presented showing Venturini control method of matrix converter.

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1. INTRODUCTION

The transformation and control of energy is one of the most important processes in electrical engineering. In recent years, this work has been done with the use of power semiconductors and energy storage elements such as capacitors and inductances. Several converter families have been developed: rectifiers, inverters, choppers, cycloconverters, etc. Each of these families has its own advantages and limitations. The main advantage of all static converters over other energy processors is the high efficiency that can be achieved. One of the most interesting families of converters is that of the so-called matrix converters (MCs). It is hoped that the AC-AC matrix converter topology will replace the work of standard AC-DC-AC converters since standard converters are bulky and costly. This converter topology will play a large role in the application of an industrial AC drives and wind energy power generation. This topology can for instance be used in the following areas: in wind energy power generation, in an industrial AC motor drives, in a marine application, in a military application especially for military vehicles, in an aerospace application.

2. LITERATURE REVIEW

The first study of direct AC/AC frequency converters was presented in 1976 by [1]. In a general sense, an AC/AC power frequency conversion is the processes of transforming AC power of one frequency to AC power of another frequency. In addition to the capability of providing continuous control of the output frequency relative to the input frequency the power frequency converter provide a continuous control of the amplitude of the output voltage. Theseconverters have inherent bidirectional power flow capability. Static power frequency converters can be divided in to two main categories. The first type is a two stage power converter with an intermediate DC link called indirect AC/DC/AC power frequency converter. The second type is called a direct AC/AC power frequency converter. This latter type is a one stage power converter which consists basically of an array of semiconductor switches connected directly between the input and output terminals.

2.1. Indirect AC/DC/AC Power Converter

The most traditional topology for AC/AC power converter is a diode rectifier based pulse width modulated voltage source inverter (PWM-VSI) which is shown in Figure 1. This consists of two power stages and an intermediate energy storage element. In the first stage the AC power is converted to uncontrolled DC power by the means of a diode rectifier circuit. The converted DC power is then stored in DC link capacitor. In the second stage a high frequency switching operated PWM-VSI generates AC signals with arbitrary amplitude and frequency [2].

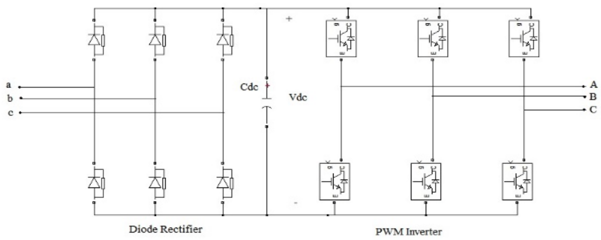

Figure 1. Diode rectifier-PWM VSI converter

2.2. Direct AC/AC Converter

The direct AC/AC converter provides a direct connection between the input and output terminals without an intermediate energy storage element through an array of semiconductor switches as shown in Figure 2.

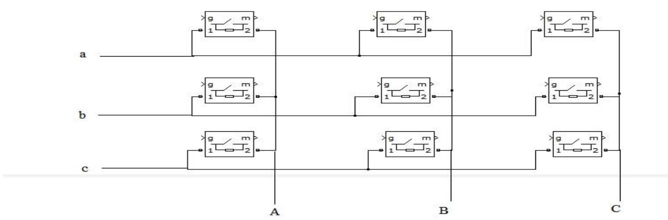

Figure 2. Direct AC/AC converter

The main features of matrix converter are the following [3]:

a) Sinusoidal input current and sinusoidal output voltage.
b) It employs bidirectional switches, which enables regenerating energy back to the source.
c) It ables to adjust the input power factor of the converter despite the type of the load connected. Unity power factor is easily achievable.
d) There is no intermediary DC-link energy storage. Since the converter is DC-link less, the size and cost of the converter is relatively reduced. In addition, the power at the input is seen at the output.
e) It has found utility in high temperature, high vibration and low volume/weight applications such as aerospace.

3. MATRIX CONVERTER

The study of the matrix converter has been going on for the last 25 years. The progress in the development of power device (silicon) technology and large power integrated circuits encouraged the interest of research to explore an AC-AC matrix converter as an elegant silicon-intensive and efficient way to convert electric power for the following: AC motor drives, uninterruptible power supplies, variable frequency generators, and reactive energy controls. However, the power converter is still not utilized in industry because of the difficulties involved in the practical implementation related to bidirectional switch realization, PWM control method, the synchronization and the protection problems [3]. This section describes a mathematical tools and models which are used to analyse the different control methods commonly employed for matrix converter implementation.

3.1. Working Principle

In general, the matrix converter is a single-stage converter with m×n bidirectional power switches, designed to connect an m-phase voltage source to an n-phase load. The matrix converter of 3×3 switches, shown in Figure.3, is the most important converter from a practical point of view, because it connects a three-phase source to a three phase load. In the basic topology of the MC shown in Figure 3, Vi,i={a,b,c} are the source voltages, i_i i ={a,b,c}, are the source currents, V_{jn}, j ={A,B,C}, are the load voltages with respect to the neutral point of the load n, and i_j , j={A,B,C} are the load currents. Additionally, other auxiliary variables have been defined to be used as a basis of the modulation and control strategies and VjN, j = {A,B,C} are the load voltages with respect to the neutral point N of the source.

Each switch S_{ji}, i ={a,b,c}, j ={A,B,C}, can connect or disconnect phase I of the input stage to phase j of the load and, the proper combination of the conduction states of these switches, arbitrary output voltages V_{jN} czn be syntheized. Each switch is characterized by a switching function called existence function, proposed by Wood [4] , provides a mathematical expression for describing switching patterns, defined as follows:

$$S_{ji}(t) = \begin{cases} 0 & \text{if switch } S_{ji} \text{ is open} \\ 1 & \text{if swich } S_{ji} \text{ is closed} \end{cases} \quad (1)$$

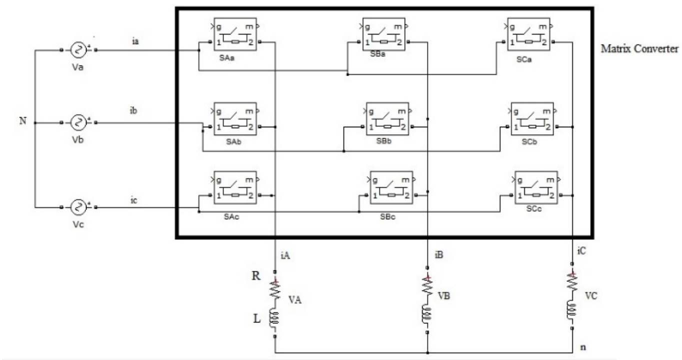

Figure 3. Basic Power Circuit of the Matrix Converter

3.2. Mathematical Model of Matrix Converter

A simplified three-phase matrix converter model is shown in Figure 2 and consists of 9 ideal bidirectional switches which allows each of the three output lines to be connected to any of the three input lines. The three converter inputs are connected to a 3-phase system, Va, Vb, Vc. The output lines are connected to a three-phase current source, iA, iB and iC, which acts as the load.

Input voltages and output currents are given by Equation (2) and (3), respectively.

$$\text{Viph} = \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \text{Vin} \begin{bmatrix} \cos(\omega_i t) \\ \cos\left(\omega_i t + \frac{2\pi}{3}\right) \\ \cos\left(\omega_i t - \frac{2\pi}{3}\right) \end{bmatrix} \quad (2)$$

$$\text{Ioph} = \begin{bmatrix} iA \\ iB \\ iC \end{bmatrix} = i_{out} \begin{bmatrix} \cos(\omega_o t - \varphi_o) \\ \cos\left(\omega_o t - \varphi_o + \frac{2\pi}{3}\right) \\ \cos\left(\omega_o t - \varphi_o - \frac{2\pi}{3}\right) \end{bmatrix} \quad (3)$$

Where Va, Vband Vcare three-phase input sinusoidal voltages and Vinis the peak value of the input voltages. Assuming that the output voltage waveforms are sinusoidal and assuming a linear load, the output currents iA, iBand iC are also sinusoidal. $i_{out}$is the peak value of the output currents and $\varphi_o$is the phase between output voltages and currentsω_i and ω_o are the input and output angular frequencies respectively. The column matrices $V_{iph}$and i_{oph}provide a compact mathematical form of expressing the input voltages and output currents, respectively.

4. VENTURINI METHOD

The Matrix Converter control strategies were first mentioned by Alesina [1] and Venturini [5]. Various modulation techniques can be applied to the AC-AC matrix Converter to achieve sinusoidal output voltages and input currents. An optimal modulation strategy should minimize the input current and the output voltage harmonic distortion and device power loss. The first modulator proposed for Matrix Converters, Known as the Venturini modulation, employed a scalar model [6]. This model gives a maximum voltage transfer ratio of 0.5. The concept of switching functions is used to derive a mathematical model of the Matrix Converter which is done in the previous chapter.

In this analysis, a three-phase input, three-phase output converter is considered. Because the Matrix Converter is symmetrical, the designation of input and output ports is arbitrary. However, for any sensible mode of operation, one port should be considered to have a voltage stiff characteristic and the other port a current stiff characteristic. In this case stiff means that the voltage or current must be constant with no interruptions or sudden variations. For the following analysis it is assumed that the input port is voltage stiff and the output port is current stiff. In a practical Matrix Converter an input filter is included to circulate the high frequency switching harmonics and provide the voltage stiff characteristic. The output inductance is usually part of the load giving a current stiff characteristic. This study considers that upper case suffixes always denote the output phases and lower case suffixes denote the input phases as shown in Figure 3.

If conventional PWM is employed the switching sequence Tshas a fixed period.A modulation duty cycle should be defined for each switch in order to determine the average behaviour of the Matrix Converter output voltage waveform. The modulation duty cycle is defined by:

$$mAa(t) = \frac{t_{Aa}}{T_s} \tag{4}$$

Where tA are presents the time when switch Aa is ON and Ts represents the time of the complete sequence in the PWM pattern. The modulation strategies are defined by using these continuous time functions. Equation (4) shows the use of these functions for the three-phase Matrix Converter.

$$\begin{bmatrix} VA(t) \\ VB(t) \\ VC(t) \end{bmatrix} = \begin{bmatrix} mAa(t) & mAb(t) & mAc(t) \\ mBa(t) & mBb(t) & mBc(t) \\ mCa(t) & mCb(t) & mCc(t) \end{bmatrix} \cdot \begin{bmatrix} Va(t) \\ Vb(t) \\ Vc(t) \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} ia(t) \\ ib(t) \\ ic(t) \end{bmatrix} = \begin{bmatrix} mAa(t) & mBa(t) & mCa(t) \\ mAb(t) & mBb(t) & mCb(t) \\ mAc(t) & mBc(t) & mCc(t) \end{bmatrix} \cdot \begin{bmatrix} iA(t) \\ iB(t) \\ iC(t) \end{bmatrix} \tag{6}$$

Voltages VA, VB &VCand currents ia, ib&icin (5) and (6) are now values averaged over the sampling time Ts. In (7) and (8), which is a representation in a more compact notation of (5) and (6), the matrix M(t) is known as the modulation matrix.

$$[Vo(t)] = [M(t)] \cdot [Vi(t)] \tag{7}$$

$$[i_i(t)] = [M(t)]^t \cdot [i_o(t)] \tag{8}$$

In this section, the basic Venturini modulation strategy for matrix converter will be presented.Modulation is the procedure used to generate the appropriate firing pulses to each of the nine bidirectional switches (Sji) in order to generate the desired output voltage. In this case, the primary objective of the modulation is to generate variable-frequency and variable-amplitude sinusoidal output voltages (VjN) from the fixed-frequency and fixed-amplitude input voltages (Vi). The easiest way of doing this is to consider time windows in which the instantaneous values of the desired output voltages are sampled and the instantaneous input voltages are used to synthesize a signal whose low frequency component is the desired output voltage. If tji is defined as the time during which switch sjiis on and Tsas the sampling interval, the synthesis principle described above can be expressed as:

$$VjN(t) = \frac{(tja \cdot Va(t)) + (tjb \cdot Vb(t)) \cdot (tjc \cdot Vc(t))}{Ts} \quad \forall \text{ j= \{A, B, C\}} \tag{9}$$

Obviously, Ts = tja + tjb + tjc ∀ j and therefore duty cycles can be defined as:

$$mja(t) = \frac{tja}{Ts},\ mjb(t) = \frac{tjb}{Ts}\ ,mjc(t) = \frac{tjc}{Ts} \tag{10}$$

Input Voltage and output currents are sinusoidal and can expressed as:

$$\text{Viph=} \begin{bmatrix} Va \\ Vb \\ Vc \end{bmatrix} = \text{Vim} \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - \frac{2\pi}{3}) \\ \cos(\omega_i t + \frac{2\pi}{3} \end{bmatrix} \tag{11}$$

$$\text{ioph=} \begin{bmatrix} iA \\ iB \\ iC \end{bmatrix} = i_{out} \begin{bmatrix} \cos(\omega_o t - \varphi_o) \\ \cos(\omega_o t - \varphi_o - \frac{2\pi}{3}) \\ \cos(\omega_o t - \varphi_o + \frac{2\pi}{3} \end{bmatrix} \tag{12}$$

Suppose that the desired output voltage and input current vectors is given by:

$$\text{Voph=} \begin{bmatrix} VA \\ VB \\ VC \end{bmatrix} = \text{qVim} \begin{bmatrix} \cos(\omega_o t) \\ \cos(\omega_o t - \frac{2\pi}{3}) \\ \cos(\omega_o t + \frac{2\pi}{3} \end{bmatrix} \tag{13}$$

$$\text{iiph=} \begin{bmatrix} ia \\ ib \\ ic \end{bmatrix} = i_i \begin{bmatrix} \cos(\omega_i t) \\ \cos(\omega_i t - \frac{2\pi}{3}) \\ \cos(\omega_i t + \frac{2\pi}{3} \end{bmatrix} \tag{14}$$

And that the following active power balance equation must be satisfied with:

$$Po = \frac{3qV_i i_0 \cos(\varphi)}{2} = \frac{3V_i i_i}{2} = Pi$$

The explicit form of matrix M (t) can be obtained from (Alberto et al. 1981)and it can be reduced to the following expression [7]:

$$mji(t) = \frac{1}{3}\left[1 + 2\frac{Vi(t)VjN(t)}{Vi^2}\right] \tag{15}$$

Where i= {a, b, c} and j= {A, B, C}

Note that, because of the averaging working principle, the output voltage low frequency component cannot exceed the maximum available amplitudes for all instants. The reference can attain its maximum at an arbitrary time, therefore the worst-case maximum available amplitudes are equal to 0.5Vi as in Figure 4 and, therefore, the voltage gain of the matrix converter is restricted to be less than 0.5. It must be clarified, however, that this limit is small since the modulation under consideration uses the phase-to-neutral voltages to synthesize the output voltages, i.e. this is a limitation arising from the modulation used, not from the matrix converter [7].

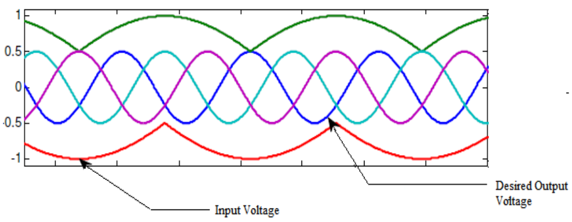

Figure 4. Output voltages, Vo = 0.5 Vi

5. SIMULATION MODEL AND RESULTS

In order to verify the effectiveness of this power supply and the output voltage control strategy proposed, the Matrix Converter system is simulated considering practical values for the electronic component and load conditions. The system has main technical specifications as follow [8]:

a) Rated input voltage: Three-phase 415V (rms, line voltage), 50Hz mains supply.
b) Rated output power: The Matrix Converter system is designed for a total power of 3kVA.
c) Rated output voltage: Three-phase 117V (rms, phase voltage).

The total output power is 7.5kVA. The power per phase is calculated as:

$$S = \frac{3000}{3} = 1000\ kVA \quad (16)$$

An equivalent load impedance can be obtained as:

$$S = V \cdot I = V \cdot \frac{V}{Z} = \frac{V^2}{Z} \quad (17)$$

$$\therefore\ z = \frac{V^2}{S} = \frac{117^2}{1000} = 13.689$$

Considering a value of 0.8 for the power factor (*pf*),

$$\text{Pf}= 0.8 = \cos(\theta) \quad \therefore\ \theta = \text{acos}(0.8) = 36.87^0 \quad (18)$$

$$|z| = \sqrt{(R^2 + X_L{}^2)} \quad (19)$$

$$R = |z|\cos(\theta) = 10.95\Omega \quad (20)$$

$$\text{Xl}= |z|\sin(\theta) = 8.2\Omega \quad (21)$$

$$X_L = \omega L = 2\pi f L = 300\pi L \quad (22)$$

$$L = \frac{X_L}{300\pi} = 8.7mH \quad (23)$$

The final values for the equivalent phase resistive-inductive load, considering a *pf* =0.8, are:

R = 10Ω
L = 8.7mH

5.1. Simulation Model

Details of Basic Venturini control Method was explained in detailed in section VI. This model designed and simulated using the Matlab - Simulink package to demonstrate the basic principle of the matrix converter. Equaation (15) is used to obtain the elements of the low-frequency transfer matrix M (t) and times tji. Figure 5 shows the general structure of the module that generates the components mjiof matrix M(t), taking as inputs the current samples of the MC input voltages (Vi) and of the desired output voltages.

(VjN= Vjref)

The most important part of the simulation is the generation of the switching functions of the bidirectional switches (Sji(t)). These functions correspond to the gate drive signals of the power switches in the real converter. Figure 6 presents the block diagram used to generate these functions in the case of the jth output phase.

If we consider the variables and waveforms shown in Figure7 the "Introduction" chapter can ultimately result in "Results and Discussion" chapter, so there is compatibility. Moreover, it can also be added the prospect of the development of research results and application prospects of further studies into the next (based on result and discussion).

Frequencyfs=2 kHz ie sampling time Ts=0.5ms and conduction time's tja = 0.23 ms, tjb = 0.1ms and tjc= 0.17ms.

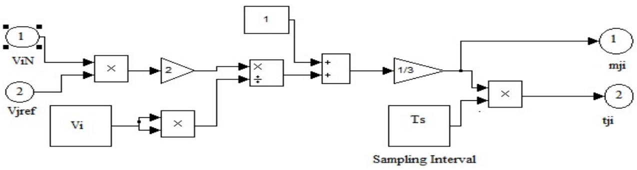

Figure 5. Generation of duty cycle mji in Matlab –Simulink software package

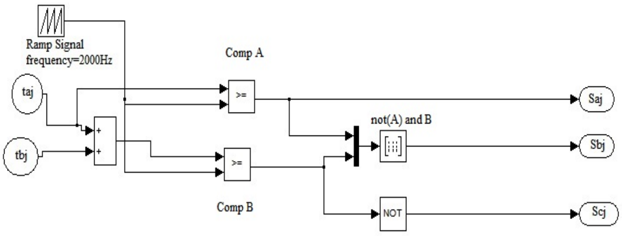

Figure 6. Pulse generation scheme for one output phase

The ramp function starting from zero with slope 1 at the beginning of each sampling interval. This ramp signal is compared with times tjaand tja+tjb, using comparators Comp A and Comp B respectively. The output of comparator Comp A is the required switching function Sja, which corresponds to a pulse of amplitude 1 with a duration equal to tja. The following logic decision is used to generate switching functions for Sjb, Sjc.$Sjb = not(A)\ AND\ B$.

$Sjb = not(\mathrm{B})$ (23)

5.2. Results

Some studies have been done using the following parameters: source voltage amplitude 230V, 50 Hz, load resistance R =10Ω, load inductance L=8mH, voltage gain q=0.45, output frequency f0=50Hz this means that the reference has an amplitude equal to 0.45×230=103.5V and a frequency of 50Hz, switching frequency fs=1/Ts=2kHz. For the resolution of the equations a five-order fixed-step solver, included in Matlab_–Simulink (ODE5 (Dormand-Price)), has been used. Figure 8 shows the output voltage VAN and Figure 9 shows the load current iAfor the above conditions. The working principle of the MC is clearly demonstrated. The low-pass characteristic of the load produces an almost sinusoidal current ia. In addition, it can be observed that the MC can generate output frequencies that are not restricted by the source frequency,which typically is the case in phase-controlled cycloconverters.

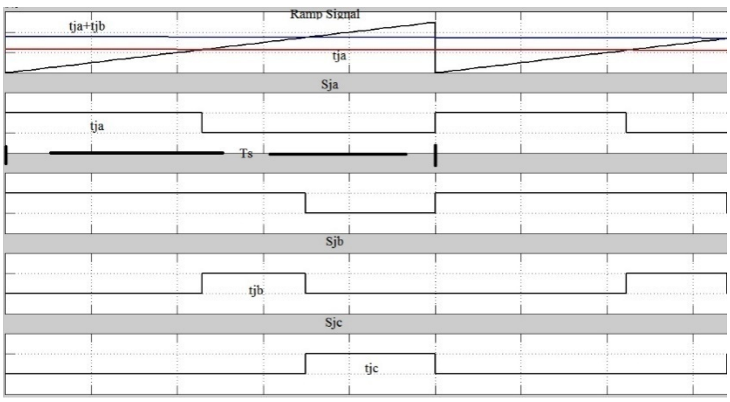

Figure 7. Variables used for the pulse generator of one output phase

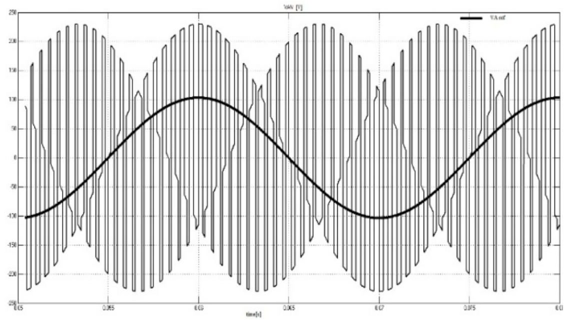

Figure 8. Output Voltage VAN, its reference (bold line)

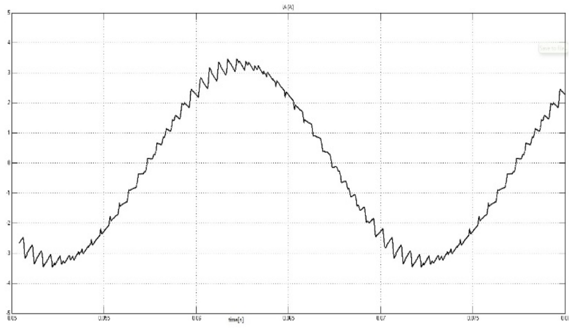

Figure 9. Output current iA

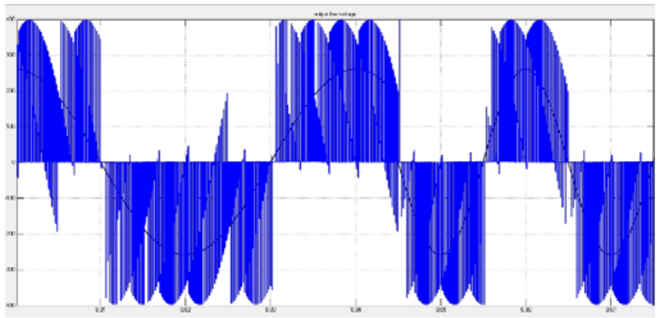

Figure 10. Output frequency changes as the reference frequency changes

It is important to note that the proposed simulation strategy Figure 10 shows the output phase voltage in the same conditions of Figure 8, but considering a voltage gain of q=0.9 and an output frequency of f0=20Hz. Note that the voltage gain is greater than the maximum allowable (q=0.5) and therefore the low-frequency component of the generated voltage is heavily distorted. There are intervals in which the input voltage level is not enough to synthesize the desired output voltage.

6. CONCLUSION

The paper presents Venturini modulation techniques for three phase-to-three phase matrix converter. In this technique we will assume the desired output voltage and from that we will derive the modulation matrix from this we will find the duty ratio of each switches, so will get the sinusoidal input current and output voltage. The feasibility and validity of the method were verified by MATLAB simulation. It can be conclude that this method is ac to ac conversion in matrix converter.

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