IMPLEMENTING SINGLE PHASE CYCLOCONVERTER USING SINGLE PHASE MATRIX CONVERTER TOPOLOGY WITH SINUSOIDAL PULSE WIDTH MODULATION

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Abstract: In the modern era, Power Electronics' and motion control has emerged as a very important technology in the industrial automation. In the industrial process, most of the drives are constant torque type and needs to drive distinct type of loads at different speeds. Revolutionizing the field the Matrix Converters offers possible "all silicon" solution for all the power electronic conversions removing the need for reactive energy storage components used in conventional systems. In this work the Single-phase Matrix Converter (SPMC) topology for cycloconverter operation are proposed for direct AC-AC conversion with step-down frequency operation. The well-known Sinusoidal Pulse Width Modulation (SPWM) scheme is used to synthesize the output.
Keywords: Power Electronics, Single-Phase Matrix Converter (SPMC), Cycloconverter, Sinusoidal Pulse Width Modulation (SPWM), Insulated Gate Bipolar Transistors (IGBT).

I. INTRODUCTION

Thyristor controlled Cycloconverter today, found its way in higher power applications such as in electric traction, rolling mills, variable frequency speed control for AC machines, constant frequency power supply and controllable reactive Power supply for an AC system.
As Cycloconverter is a power frequency changer, the most desirable features in power frequency changers are:
1) Simple and compact power circuit.
2) Generation of load voltage with arbitrary amplitude and frequency.
3) Sinusoidal input and output currents.
4) Operation with unity power factor for any load.
5) Regeneration capability.

Moreover, these characteristics are not fulfilled by the conventional frequency changers. This is the reason for the tremendous interest in matrix converter topology as the ideal features can be fulfilled.
The matrix converter (MC) offers possible "all silicon" solution for AC-AC conversion removing the need for reactive energy storage components used in conventional rectifier-inverter based system. Gyugyi first described the topology in 1976. Obviously all published studies dealt with mainly the three-phase circuit topologies. The Single-phase matrix converter variant on the same philosophy denoted as SPMC was first realized by Zuckerberger.

II. CYCLOCONVERTER

Traditionally, the AC-AC converters using semiconductor switches are commonly classified into indirect converter which utilizes a DC link between the two AC systems and direct converter that provides direct conversion. Indirect converter consists of two converter stages and energy storage element, which convert input AC to DC and then reconverting DC back to output ac with variable amplitude and frequency as shown in Fig1(a). In direct converter there is no need of DC link as shown in Fig 1(b).

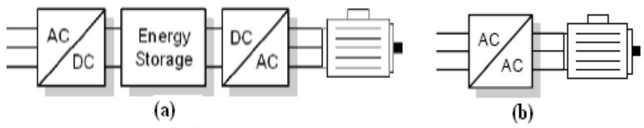


Fig 1: AC/AC converter (a) indirect converter (b) Direct converter

Cycloconverters are the direct type converters used in high power applications driving induction and synchronous motors. They are usually phase-controlled and they traditionally use thyristors due to their ease of phase commutation. The basic block diagram of Cycloconverter is shown in Fig 2.

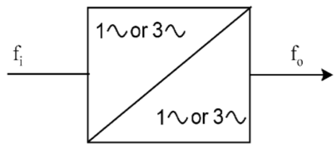


Fig 2: Block diagram of Cycloconverter

A Cycloconverter is a type of power controller in which an alternating voltage at supply frequency is converted directly to an alternating voltage at load frequency without any intermediate DC stage. In a line commutated Cycloconverter, the supply frequency is greater than the load frequency. The operating principles were developed in the 1930s when the grid controlled mercury arc rectifier became available. The techniques were applied in Germany, where the three phase 50 Hz supply was converted to a single phase AC supply at 16⅔ Hz for railway traction. In the United States, a 400 HP scheme in which a synchronous motor was supplied from a Cycloconverter comprising 18 thyratrons was in operation for several years as a power station auxiliary drive. However, because these early schemes were not sufficiently attractive technically or economically, they were discontinued. A Cycloconverter is controlled through the timings of its firing pulses, so that it produces an alternating output voltage. By controlling the frequency and depth of phase modulation of the firing angles of the converters, it is possible to control the frequency and amplitude of the output voltage. Thus, a Cycloconverter has the facility for continuous and independent control over both its output frequency and voltage. This frequency is normally less than 1/3 of the input frequency. The quality of the output voltage wave and its harmonic distortion also impose the restriction on this frequency. The distortion is very low at low output frequencies. The Cycloconverters are normally used to provide either a variable frequency from a fixed input frequency or a fixed frequency from a variable input frequency. A Cycloconverter can handle load of any power factor and allows power flow in both the directions. The output voltage wave shape inevitably contains harmonic distortion components in addition to the required sinusoidal component. These distortion terms are produced as a necessary outcome of the basic mechanism of the Cycloconverter, whereby the output voltage is fabricated from segments of the input voltage waves. These distortions can be minimized by adequate filters at the output. The distortion of the output voltage increases if the ratio of the output and input frequency increases.

III. MATRIX CONVERTER

The Conventional Cycloconverter has the disadvantages of having more number of harmonics, high conduction losses and also doesn't meet the all the requirements of the ideal frequency converter features. Hence, Matrix Converter is proposed. It is one of the newly emerging technologies. It has attracted the attention of many numbers of researchers due to its high potential use in AC-AC conversion Systems, military and aerospace systems. It also meets all the requirements of the ideal frequency changer. Through this paper we will detail the implantation of single phase cycloconverter on single phase matrix converter topology. The Matrix Converter is a single-stage converter which has an array of m × n bidirectional power switches to connect, directly, an m-phase voltage source to an n-phase load. It is also defined as is a forced commutated converter which uses an array of controlled bidirectional switches as the main power elements to create a variable output voltage system with unrestricted frequency. The Single-Phase Matrix Converter (SPMC) consists of a matrix of input and output lines with four bi-directional switches connecting the single-phase input to the single-phase output at the intersection. Normally, the matrix converter is fed by a voltage source and, for this reason the input terminals should not be short circuited. On the other hand, the load has typically an inductive nature and, for this reason, an output phase must never be opened.

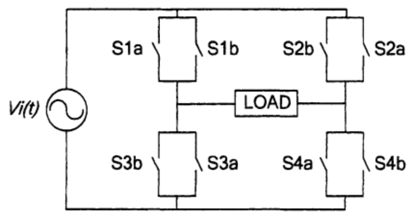


Fig 3: Basic circuit of 1-Φ matrix converter

The SPMC circuit as shown in Fig 3 uses four bi-directional switches for the implementation of single phase Cycloconverter. It requires the use of bi-directional switches capable of blocking voltage and conducting current in both directions. Unfortunately there is no discrete semiconductor device. Currently that could be fulfilling the needs and hence the use of common-emitter anti-parallel IGBT, diode pair as shown in Fig 4. Diodes are in place to provide reverse blocking capability to the switching module. The IGBT were used due to its high switching capabilities and high current carrying capabilities desirable amongst researchers for high power applications.

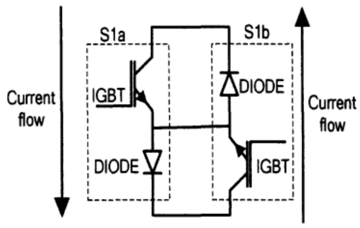


Fig 4 Schematic view of Bi-directional switch (common - emitter)

IV. SWITCHING STRATEGY

A. Step Down Operation:

The implementation of the SPMC as a Cycloconverter requires different bi-directional switching arrangements depending on the desired output frequency. The output voltage of the converter is controlled by Sinusoidal Pulse Width Modulation (SPWM), but the frequency of the converter is changed by controlling the duration of operation of the switch. In this project the input frequency used is set at 50Hz and the desired output frequency synthesized at the 25 and 12½ Hz for step down Cycloconverter as shown in Fig 5. The SPWM helps to give the gate triggering pulses in sequence as required to the get the desired frequency at the output voltage.

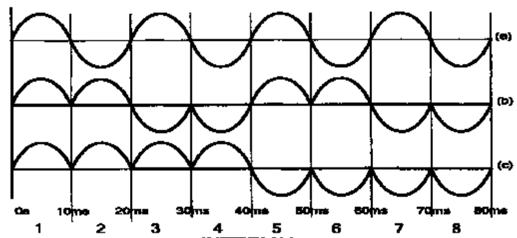
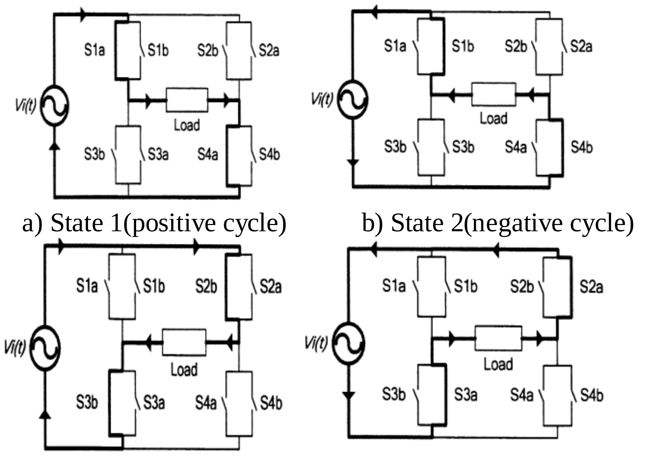


Fig 5(a): Wave forms of a) I/P at 50 HZ,
b) O/P at 25 HZ, c) O/P at 12 ½ HZ

During the positive half-cycle of the input voltage, the switches S1a, S2b, S3b and S4a are forward biased and during the negative half cycle of the input voltage, the switches S1b, S2a, S3a and S4b are forward biased. To get the positive half-cycle at the load, the switches S1a and S4a are triggered during the positive half-half cycle of the input and are shown in Fig 6(a). And to get the negative half-cycle at the load the switches S2b and S3b are triggered and are shown in Fig 6(c).More over during negative half cycle of the input voltage, switches S4b and S1b are triggered to get the negative half-cycle at the load and are shown in Fig 6(b).

To get the positive half-cycle at the load switches S3a and S2a are triggered and are shown in Fig 6(d). Table7 shows the different states of switching in sequence to get the desired frequency of the output voltage. The switching sequences are dependent on the time interval and the state of the driver circuit following table 7 as shown (for one cycle).



a) State 1(positive cycle) b) State 2(negative cycle)

c) State 3(positive cycle) d) State 4(negative cycle)

Fig 6: Different states for the operation of the Cycloconverter

Input frequency	Target output frequency	Time interval	State	Switch "modulated"
50 Hz	25Hz	1	1	S1a and S4a
		2	4	S2a and S3a
		3	3	S2b and S3b
		4	2	S1b and S4b
	12½ Hz	1	1	S1a and S4a
		2	4	S2a and S3a
		3	1	S1a and S4a
		4	4	S2a and S3a
		5	3	S2b and S3b
		6	2	S1b and S4b
		7	3	S2b and S3b
		8	2	S1b and S4b

Table 7: Switching Sequence of step down Cycloconverter

B. Commutation:

As the matrix converter has no DC link energy storage, any disturbance in the input supply voltage will affect the output voltage immediately and a proper protection mechanism has to be incorporated, particularly against over voltage from the supply and over current in the load side. Since we are using Sinusoidal Pulse Width modulation (SPWM) as the switching algorithm in the SPMC, there exist possible reversal current from the inductive load available during switch turn-off. Theoretically the switching sequence in the SPMC must be instantaneous and simultaneous; unfortunately impossible for practical realization due to the turn-off IGBT characteristic, where the tailing-off of the collector current will create a short circuit with the next switch turn-on. This problem occurs when inductive loads are used. A change in current due to PWM switching will result in current and voltage spikes being generated resulting in the occurrence of a dual situation. First current spikes will be generated in the short-circuit path and secondly voltage spikes will be induced as a result of change in current direction across the inductance. Both will destroy the switches in use due to stress. A systematic switching sequence is required that lengthens the dead time between conduction of each IGBT's in SPMC so as to allow for a complete turn-off prior to the next switching sequence. This is to protect the converter from being damaged as a result of voltage and current spikes as described. In conventional converter this is normally implemented in the form of free-wheeling diodes in inverter systems arranged in anti-parallel with power switching devices as shown in Fig 8.

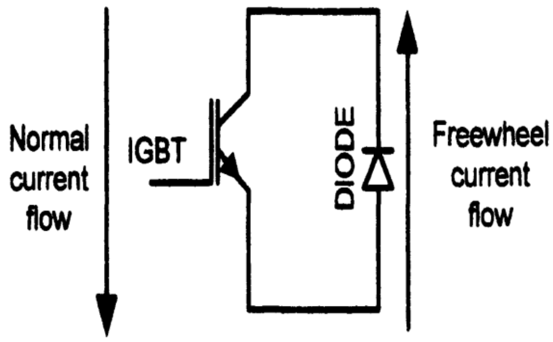


Fig 8: Normal switch with Freewheeling Diode

C. Step Up Operation:

Input Frequency	Output Frequency	Time Interval	State	Switch Modulated	Commutation Switch "ON"
50Hz	50Hz	1	1	S1a & S4a	S2a
		2	2	S1b & S4b	S2b
	100Hz	1	1	S1a & S4a	S2a
		2	3	S2b & S3b	S1b
		3	4	S2a & S3a	S1a
		4	2	S1b & S4b	S2b
	150Hz	1	1	S1a & S4a	S2a
		2	3	S2b & S3b	S1b
		3	1	S1a & S4a	S2a
		4	2	S1b & S4b	S2b
		5	4	S2a & S3a	S1a
		6	2	S1b & S4b	S2b

In this paper, the input frequency is set at 50Hz and the desired output frequency synthesized at the 50Hz, 100Hz and 150Hz i.e. multiples of the input frequency, for step-up Cycloconverter and the switching is described.

Table 9: Switching sequence of step-up Cycloconverter

Power switches, comprising IGBT's in the SPMC circuit are controlled where the switching angles, of the 4 bi-directional switches uses the form Sij (i = 1,2,3,4 and j = a, b), where 'a' and 'b' are representing drivers one and two respectively. The rules are then modified to incorporate the following new switching rules and are also tabulated in table 9

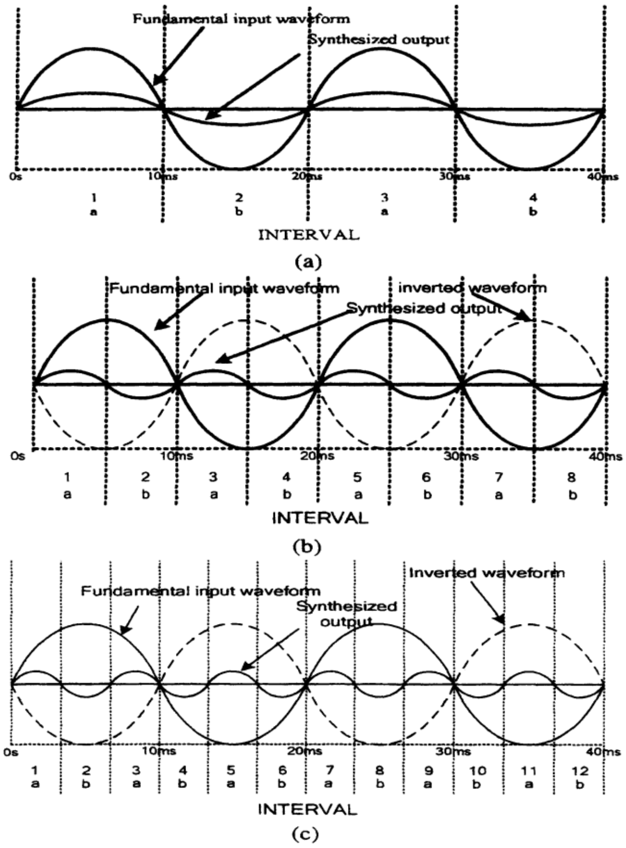
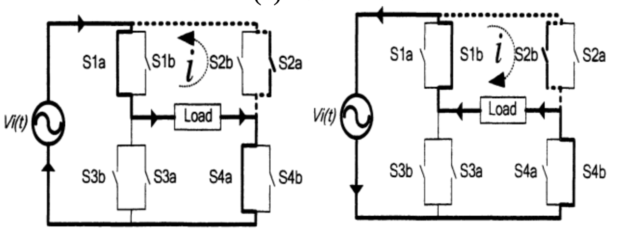
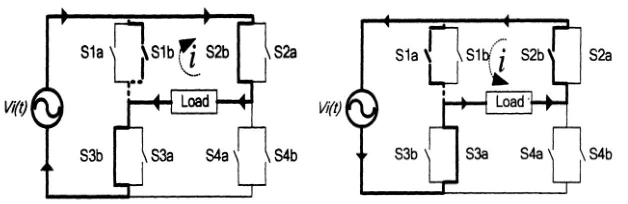


Fig 10: sinusoidal input and synthesized output (a) 50Hz (b) 100Hz (c) 150Hz reference



a) State1 (positive Cycle) b) State 2(negative Cycle)



c) State 3 (positive Cycle) d) State 4 (negative Cycle)

Fig 11: Different States for step-up operation of Cycloconverter

The sequences of switching and commutation switching strategies are dependent on the time interval and state of the driver circuit as tabulated (for the one cycle). Implementation of those rules is best illustrated with Figs. 11(a) to 11(d) shown below, for each switching state. The dotted line in the diagram represents the safe commutation switch during each particular state. Let's say the output frequency is 50 Hz. To achieve this, when the supply voltage is positive the switch is in state 1. Here, S4a is the controlling switch to synthesize the SPWM pattern Sla and S2a are maintained as continuously ON during this cycle; Sla to complete the loop for SPWM return and acts in conjunction with S2a to provide free-wheel operation whenever S4a is turned OFF. Due to the nature of operation the commutation period has to extend over the dead-time period to allow for energy to dissipate and hence current reversals due to inductive loads are eliminated. Similarly switching state 2 are used during negative cycle to produce the next half cycle. The time delay during 'td' between each switch commutation is around 97µs. This will allow for the current to decay until zero prior to the next switching sequence. A timing diagram for the delay during commutation is shown in Fig.12

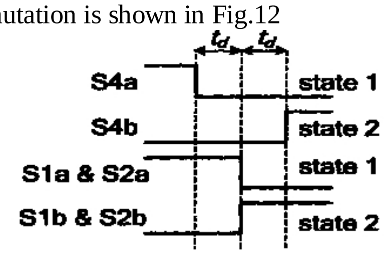


Fig 12: Timing diagram for commutation strategies

For the output frequencies, the sequence of switching is as listed in the table 9. There are a total of four (4) different switching states capable of being used in various combinations to produce the desired effect. This method allows commutation between switching states with out producing those damping spikes.

V. SINUSOIDAL PWM

The sinusoidal PWM technique is very popular for industrial converters and is discussed extensively in the literature. The general principle of SPWM, an isosceles triangle carrier wave of frequency fc sinusoidal modulating wave, and the points of intersection determine the switching points of power devices. This method is also known as the triangulation, sub harmonic, or sub oscillation method. The pulse width is a sinusoidal function of the angular position of the pulses in a train as shown in the Fig 13 For realizing sin M, a high frequency triangular carrier wave *vc* is compared with a sinusoidal reference wave *vr* of the desired frequency. The intersection of *vr* and vc waves determines the switching instants and commutation of the modulated pulse. In the figure, Vc is the peak value of the triangular carrier wave and Vr that of the reference, or modulating, signal.

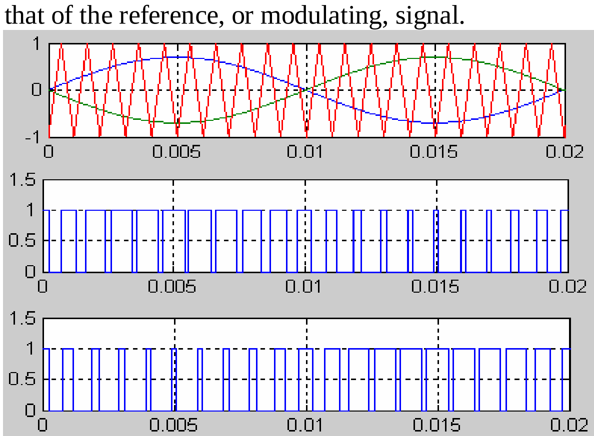


Fig 13: Sinusoidal Pulse Width Modulation of mi<1

The carrier and reference waves are mixed in a comparator. When a sinusoidal wave has magnitude higher than the triangular wave, the comparator output is high, otherwise it is low. When a triangular carrier wave has its peak coincident with the reference sinusoid, there are N= fc/2f pulses per half cycle. In case zero of the triangular wave coincides with zero of the reference sinusoidal, there are (N-1) pulses per half cycle. When the modulating signal is a sinusoidal of amplitude Vr, and the amplitude of the triangular carrier is Vc, the ratio mi= Vr/Vc is known as the modulation index. Note that by controlling the modulation index the output voltage of the system is controlled. With a sufficiently high carrier frequency, the high frequency components do not propagate significantly in the AC network (or load) due the presence of the inductive elements. However, a higher carrier frequency does result in a larger number of switching's per cycle and hence it increases the power loss. Typically switching frequencies in the 2-15 kHz range are considered adequate for power systems applications. Generally the modulation index is less than 1 i.e. mi<1. For mi>1, there are periods of the triangle wave in which there is no intersection of the carrier and the signal as shown in Fig 14.

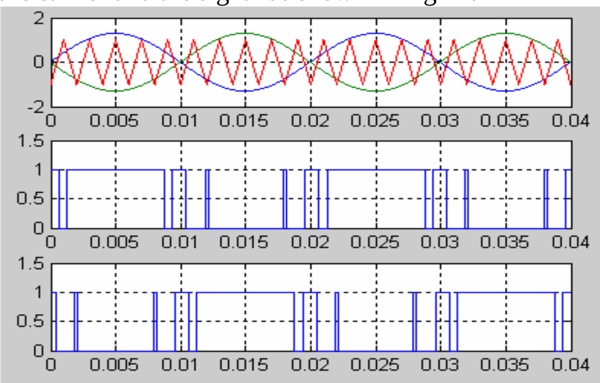


Fig 14: Sinusoidal Pulse Width Modulation of mi=1.3

However, a certain amount of this "over modulation" is often allowed in the interest of obtaining a larger AC voltage magnitude even though the spectral content of the voltage is rendered somewhat poorer. Modulation index controls the harmonic content of the output voltage wave form. The magnitude of fundamental component of the output voltage is proportional to modulation index (mi), but m can never be more than unity. Thus the output voltage is controlled by varying modulation index (mi).

Harmonic analysis of the output modulated voltage reveals that sin M has the following important features:

- For mi less than 1, largest harmonic amplitudes in the output are associated with harmonics of order fc/f±1 or 2N±1, where N is the number of pulses per half cycle. Thus, by increasing the number of pulses per half cycle, the order of dominant harmonic frequency is raised, which can then be filtered out easily. If we take N=5 then harmonics of order 9 and 11 become significant in the output voltage. It may be noticed that the highest order of significant harmonic of a modulated voltage wave is centered around the carrier frequency fc.
- It is observed that as N is increased, the order of the significant harmonic increases and the filtering requirements are accordingly minimized. But higher value of N entails higher switching frequency of thyristors. This amounts to more switching losses and therefore an impaired the efficiency. Thus a compromise between the filtering requirements and efficiency should be made.
- For mi greater than 1, lower order harmonics appear, since mi >1, pulse width is no longer a sinusoidal function of the angular position of the pulse.

VI. SIMULATION

The MLS implementation of the SPMC configuration is as shown below:

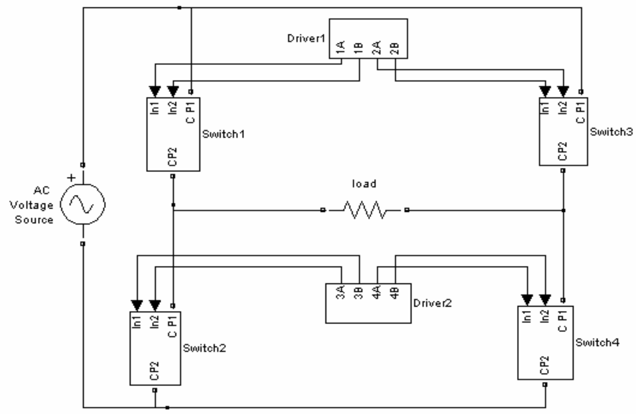


Fig 15: Top level main model of SPMC in MLS

Switches used are the bi-directional switches used to block the voltage and conduct the current in both directions. The Matlab design of the bi-directional is shown as shown in Fig 16.

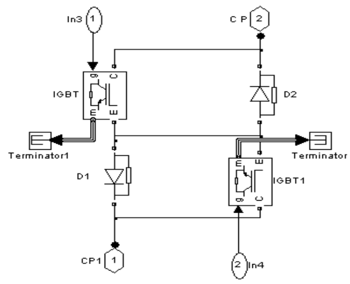
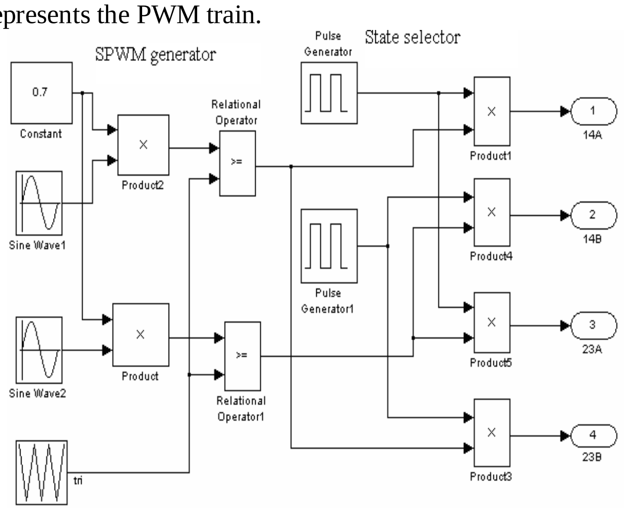


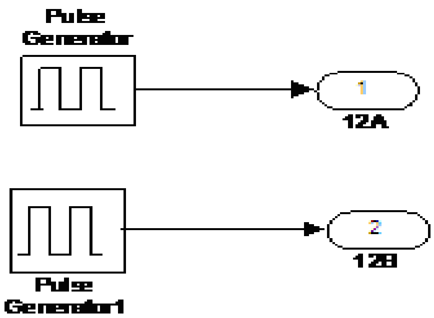
Fig 16: Bi-directional switch module in MLS

A. *Driver Circuit Model:*

Driver circuits were designed to generate the SPWM pattern that is controlled using the switching states as in tables 7 and 9. The driver circuit algorithm are designed by using MLS is shown in Fig 17, comprising SPWM generator portion and state portion. From the Fig 17, a two "sine wave" blocks are used to generate two sinusoidal references signal 'Vref1' and 'Vref2'. Output from the "sine wave" block is multiplied using a "multiply" block with the output from the constant block that represents the modulation index, thus magnitude could be varying changing this "constant" value. The "repeating sequence" block is used to generate the triangular carrier signal 'Vc'. To produce the SPWM the "relational operation" block are used as a comparator that triggers an output switching function between "0" and "1" that represents the PWM train.



(a)



(b)

Fig 17: Design of Diver Circuit using MLS

Fig 17(b) shows the commutation circuit for safe commutation during the R-L load. During R-L load, switch S2 acts as the commutation switch. The state selector portion has shown in 17(a) and it implements the operation of required switching state of tables 7and 9. Here, the Square wave pulse represents the desired output frequencies that are generated by the "pulse generator" block. The final switching pattern for the Cycloconverter is produced by multiplying the output from SPWM generator with the state selector using the "multiply" block. Each output from the "pulse generator" is multiplied with both outputs from the SPWM.

B. Simulation Results of R Load

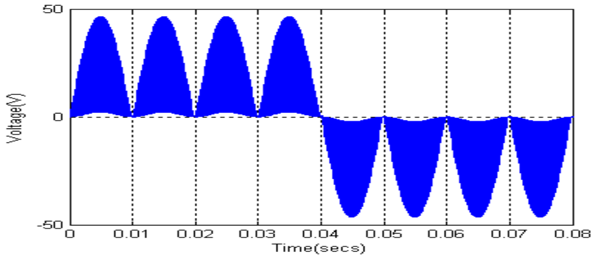


Fig 18.1: O/P voltage wave form of 12½Hz of modulation index of 0.7

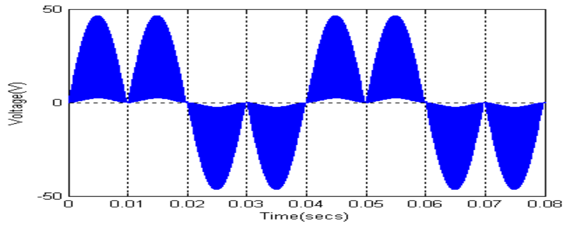


Fig 18.2: O/P voltage wave form of 25Hz of modulation index of 0.7

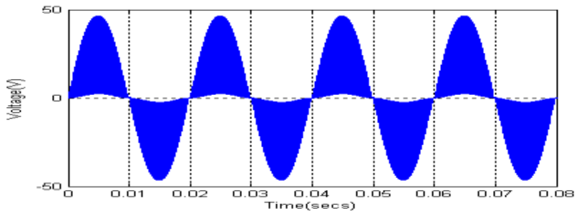


Fig 18.3: O/P voltage wave form of 50HZ of Modulation Index 0.7

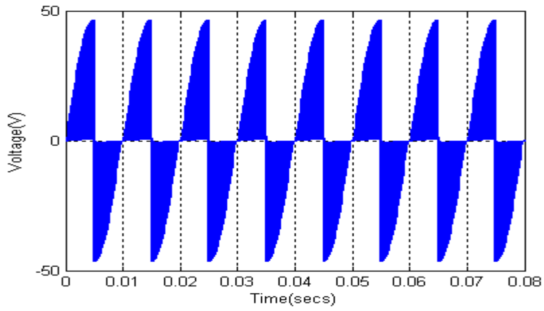


Fig 18.4: O/P Voltage wave form of 100 HZ of modulation index 0.7

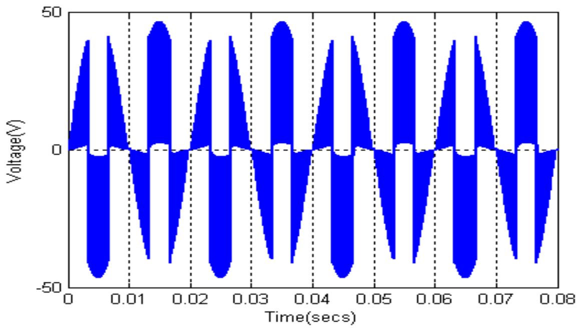


Fig 18.5: O/P Voltage waveform of 150 Hz of modulation index 0.7

C. Simulation Results of R-L Load

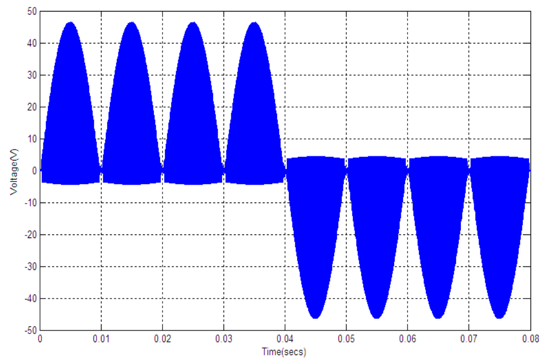


Fig 18.6: O/P Voltage waveform of 12½ Hz of modulation index 0.7

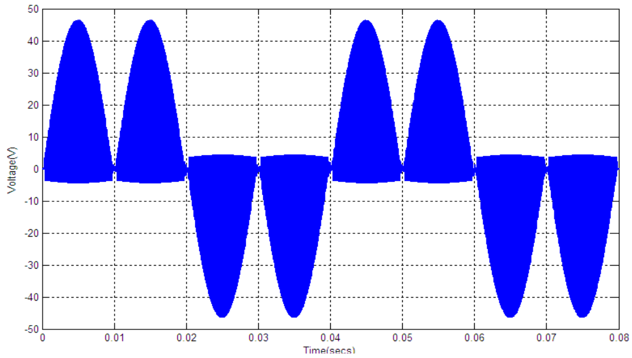


Fig 18.7: O/P Voltage waveform of 25 Hz of modulation index 0.7

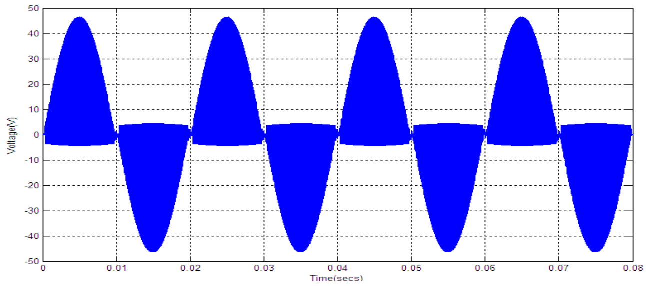


Fig 18.8: O/P Voltage waveform of 50 Hz of modulation index 0.7

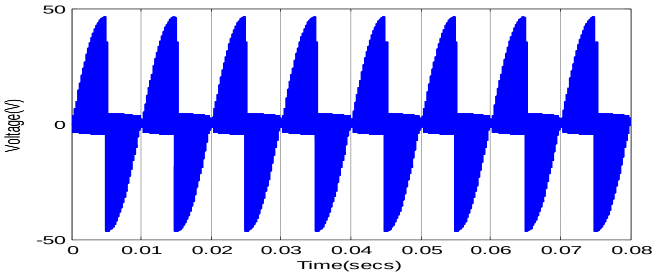


Fig 18.9: O/P Voltage waveform of 100 Hz of modulation index 0.7

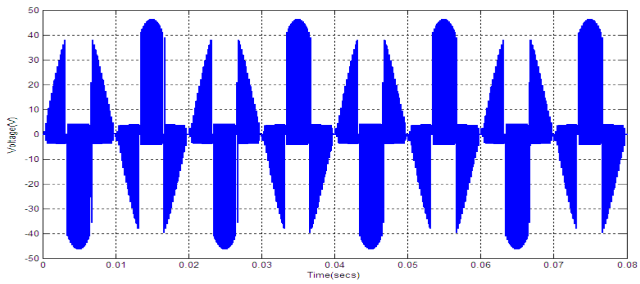


Fig 18.10: O/P Voltage waveform of 150 Hz of modulation index 0.7

VII. CONCLUSION

In this project, the computer simulation model on SPMC for Cycloconverter operation using MATLAB/Simulink (MLS) software package has been presented.

- It includes the implementation of SPWM to synthesize the AC output supply for a given AC input. Matrix converter has many advantages like simple and compact circuit.
- Operation at unity power factor.
- Regeneration capabilities.
- Simulation results of SPMC illustrates that it is feasible to realise the converter in the various basic AC-AC converters that includes; AC controller, Step-up and Step-down frequency changer.
- A safe commutation technique is implemented to avoid current spikes by allowing the dead time.
- Matrix converter technology has potential benefits especially for applications where size, weight, and long term reliability are the important factors.
- Having these advantages, MC has very limited applications due to non-availability of full controlled bi-directional switch, complex control system.

In the near future, MC places a vital role by developing suitable control strategies.

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