# Single Phase Matrix Converter Operating as a Four Quadrant DC Chopper controlled using Xilinx FPGA

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***Abstract*—This paper is concerned on FPGA design for control implementations of the Single-Phase Matrix Converter (SPMC) operating as a Four Quadrant DC Chopper. The Pulse Width Modulation (PWM) technique is used to synthesize the output voltage with. The power circuit uses the Insulated Gate Bipolar Transistor (IGBT) as switching device in the SPMC implementation. Safe-commutation strategy was incorporated to solve switching transients. The Power System Block Set (PSB) within the MATLAB/Simulink (MLS) environment is used to study the behaviour of the proposed converter. A Xilinx Field Programmable Gate Array (FPGA) was used at the heart of the control electronics, implemented to verify operation. Selected simulation and experimental results are presented. It has been shown that the FPGA could effectively be used in SPMC with the four bidirectional switching arrangements. Experimental results achieve good agreement with those predicted in simulations.**

***Index Terms*— Matrix Converter (MC), MATLAB/Simulink (MLS), Pulse Width Modulation (PWM), Single-Phase Matrix Converter (SPMC), DC Chopper.**

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## I. Introduction

DC Choppers are widely used in various applications requiring controlled DC supply used for traction motor control in electric automobiles and various portable equipments that is not connected to the supply utility. of dc chopper also include high-current DC applications in industries [1]. In utility connected systems a two stage converter is an alternative with rectifier-DC chopper arrangements are the AC voltage rectified in the first stage of the converter. In those applications, control of dc motor's speed maybe required. Other applications

The Matrix Converter (MC) is an advanced circuit topology that offers many advantages with unrestricted switch control, possible "all silicon solutions" or with minimal reactive devices use. MC can be classified into two types: direct MC and indirect MC [2]. They have the ability to regenerate energy back to the utility, sinusoidal input and output current and controllable input current displacement factor [3]. The topology was first introduced by Gyugyi [4] in 1976. Ever since three-phase circuit topologies [5-6] have been studied.

The Single-phase version called the single-phase matrix converter (SPMC) was first introduced by Zuckerberger [7]. Subsequently works with practical realisations has emerged focussing mainly on AC-AC applications Khoei et el. [8] and more recently as frequency changer [9-10] with new applications in induction machine control [11]. In [12] operation has been extended to inverter operation with basic DC converter proposed in [13]. However very limited work has been reported in this advanced converter topology.

This paper presents the design and development of a pulse-width modulation (PWM) generator suitable for SPMC operating as DC Chopper. It is based on the Xilinx chip XC4005XL FPGA with IGBTs as the power switching device. The output voltage is synthesized using PWM. The proposed design enables the modulation index, quadrant operation and the switching frequency to be changed externally. Results are provided to demonstrate successful implementation of the design. Prior to hardware implementation, simulations were performed to predict the behaviour. A laboratory model test-rig of the SPMC was then constructed to experimentally verify the result. This paper introduces the steps and techniques for generating the PWM pattern for SPMC operating as a single-phase DC Chopper, which is placed in one chip without using external memory chips, where design re-uses are advantages in this development. The result from the hardware implementation will be compared with those simulations using MATLAB/ Simulink.

## II. CONVENTIONAL FOUR QUADRANT DC CHOPPER

A four quadrant DC Chopper (FQDC) converts a fixed DC input into a variable DC output statically and can be depicted in Fig.1. The four quadrant operation is summarised in Fig.2 and the load representation during operation is shown in Fig.3. It is considered as a dc equivalent of an AC transformer with a continuously variable turn's ratio and can be used to step down or step up a dc voltage source. Power semiconductor devices such as IGBT and MOSFETs are used with a variety of high frequency switching controls [14-15]. The circuit maybe loaded with possible resistive, inductive or a DC motor load [16]. They are widely used in variable DC drives because of their high efficiency, flexibility, quick response and regenerative capabilities [17-18].

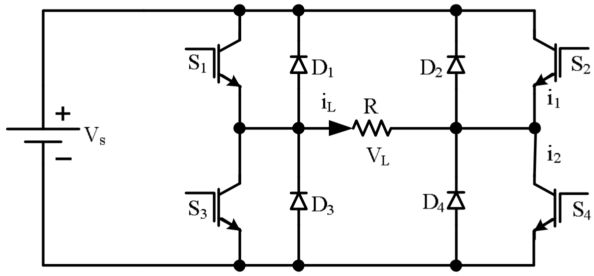



Fig. 1. Classical Four Quadrant DC Choper

## III. SINGLE PHASE MATRIX CONVERTER

The SPMC is generally used in direct AC-AC converter which requires four bi-directional switches and the topology is as shown in Fig. 4; capable of blocking voltage and conducting current in both directions and ideally switching between states without any delays. Unfortunately the use of practical devices has resulted with switching spike phenomena and hence requires the use of safe-commutation switching strategies [19].

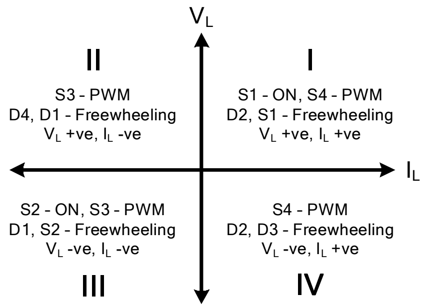



Fig. 2. Four Quadrant Operation

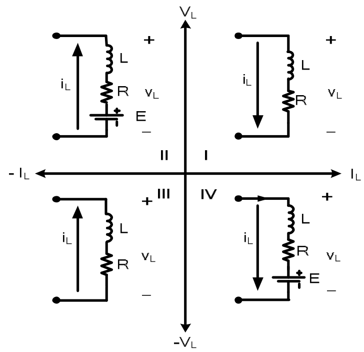



Fig. 3. Load Representation for Four Quadrant Operation

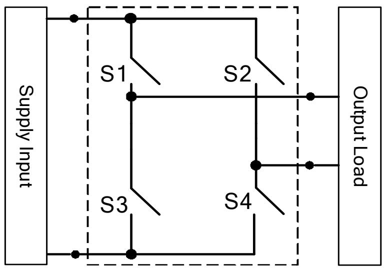



Fig. 4. Single-phase Matrix Converter Topology

## IV. DC Chopper Based On SPMC

The proposed DC chopper is shown in Fig. 5. Practical realization of matrix converters require the use of four-quadrant switch capable of bi-directional operation. In comparison with the conventional dc chopper of Fig. 1 it has four bi-directional switches as opposed to the use of four switch and four diodes. This arrangement has the advantage of allowing switching process within each switch-cell, independent control of the current in both directions. In this circuit configuration, the IGBTs were used because of its high switching frequency and high current handling capabilities leading to medium-power applications. It is a robust switching device with reasonably fast switching frequency suitable during research and investigations due to the presence of switching spikes inherent in any matrix converter when feeding inductive loads. Diodes arranged in series provide reverse voltage blocking capability [20].

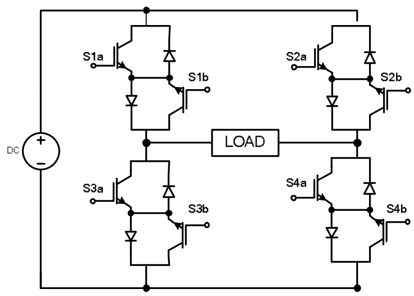



Fig.5. Four Quadrant DC Chopper using SPMC

### A. *Pulse-Width Modulation (PWM)*

The output of the DC chopper can be controlled using PWM, generated by comparing a triangle wave signal with an adjustable dc reference and hence the duty cycle of the switching pulse could be varied to synthesize the required dc to dc conversion. This technique is used to produce a stream of PWM train to turn on and off the switches as illustrated in Fig. 6.

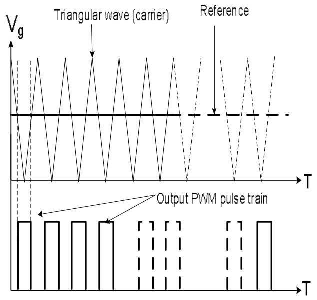



Fig. 6. PWM waveform

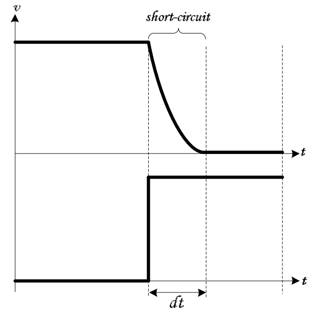



Fig. 7. Switch Transition and Commutation

Theoretically the switching sequence in the SPMC must be instantaneous and simultaneous; unfortunately this creates a change in instantaneous current across the inductance when inductive loads are used, hence large voltage spikes maybe generated. These will destroy the switches in use due to stress condition. During the switching transitions and commutation, short-circuit currents may also exist which leads to device damage due to overheating as a result of short-circuits as illustrated in Fig. 7. A systematic switching sequence is thus required that allows for the energy flowing in the IGBT's to decay and dissipates itself within the system. A dead-time is also required to ensure no short circuit occurs. In the conventional dc chopper, free-wheeling diode is used for this purpose. In SPMC this does not exist, hence a switching sequence needs to be implemented and in this case similar approach to the conventional FQDC can be employed.

In implementation of pulse width modulation (PWM), the reference signal is a straight line defined as in (1);

$$V_{ref}(t_k) = round[25.5 \times ma] \quad (1)$$

The turn-on width $tma,2.k+1$ is defined as in (2).

$$tma,2.k+1 = (Vref(t_k)-1).2.t_{step} + t_{step} \quad (2)$$

The turn-on width $tma,2.k+1$ varies with respect to modulation index, $ma$ . The result obtained when comparing the reference signal with the 'W' shape of carrier signal is shown in Fig. 8.

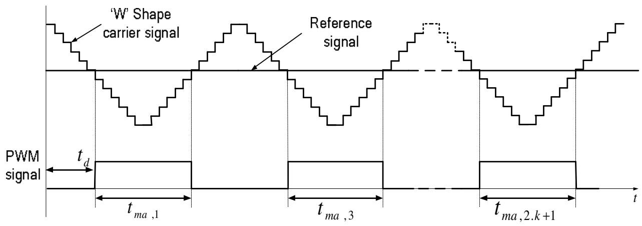



Fig. 8. The width of UPWM pattern

In Fig. 8, there is time delay, $t_d$ in the beginning of the PWM signal during transition period between one state to another that incorporates safe switch commutation strategy. The time delay is defined as in (3).

$$t_d = t_k - \frac{t_{ma,2.k+1}}{2} \quad (3)$$

$$t_d = 2.k+1.\left(\frac{T_{carrier}}{2}\right) - \frac{t_{ma,2.k+1}}{2}$$

The time delay varies in accordance to variation of modulation index and carrier frequency. The time delay at the initial stage (k=0) of the PWM signal is defined in (4);

$$t_d = 1.\left(\frac{T_{carrier}}{2}\right) - \frac{t_{ma,1}}{2} \quad (4)$$

## B. Commutation Problem

In matrix converter, there is serious problems associated with the control of four quadrant switches; neither dead-time nor conduction overlap is allowed when the two switches commutate the inductive load current. In matrix converter, there is no free-wheel paths, therefore the load current need to be safely commutated with various methods [7], [20-22]. Another factor related to commutation problem is the finite switching times and propagation delays of devices when using the semiconductor switches resulting with possible short circuit.

The use of PWM as the switching technique in this converter, results with voltage spikes being generated due to possibilities in change of current if inductive loads are used, during switching [19].

## C. Switching Strategies

The Switching sequence used is the conventional FQDC the principle of operations are illustrated in Fig. 9 to Fig.12. The dotted line flow of current in the diagram represents the safe commutation switching during each particular state that is continuously turned-on. The dark arrow on the switch indicates that the switch is turned-on and behaves as the power switches performing the required converter operation. The operation for each switch could be summarised as shown in Fig. 13. The magnitude of the output voltage of the converter is controlled by PWM and its variations in duty cycle. To allow the energy in the inductance to be dissipated a dead-time is introduced during switching transitions. The final switching sequences are best illustrated using Fig.14.

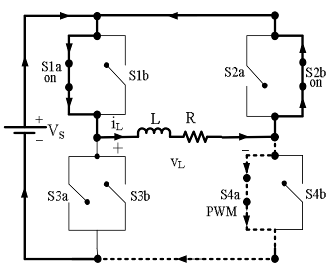



Fig. 9. First quadrant operation in DC

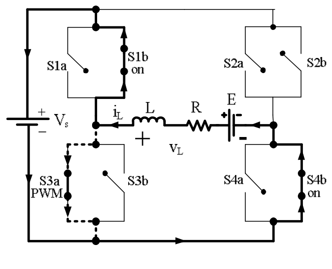



Fig. 10. Second quadrant operation

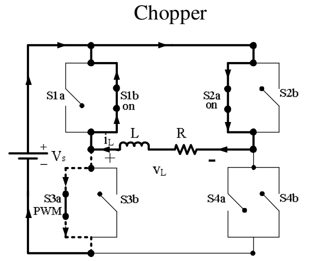



Fig. 11. Third quadrant operation in DC Chopper

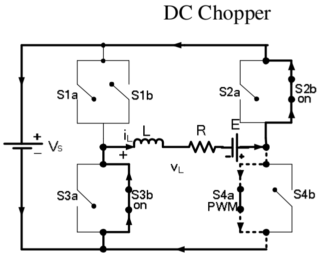



Fig. 12. Fourth quadrant operation in DC chopper

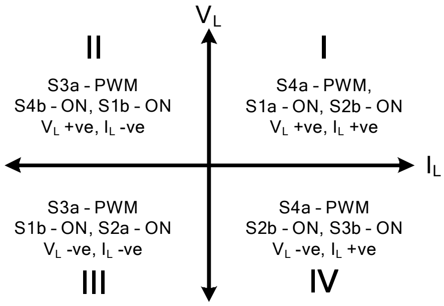



Fig. 13. Four Quadrant Operation Using SPMC

## V. SIMULATION MODEL

In the simulation implementation, the MLS is used to model and simulate the circuit. The FQDC is supplied by a 30V DC voltage source; the load takes the form of a pure resistive 50 Ω, inductive load 4mH with battery E representing a back emf of a dc motor. Figure 15 is the top-level simulation model with the power circuit switch arrangements as in Figure 16. The PWM model is as shown in Figure 17; a constant representing a straight line or reference signal is used to compare with the triangular wave as a carrier signal producing the required switching control output.

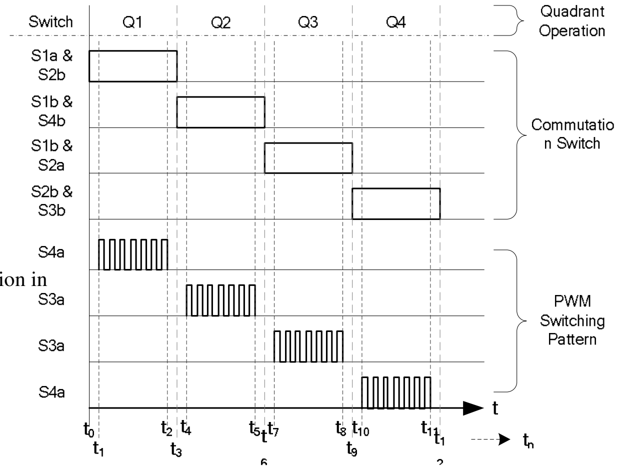



Fig. 14. Switching Sequence of FQDC Using SPMC

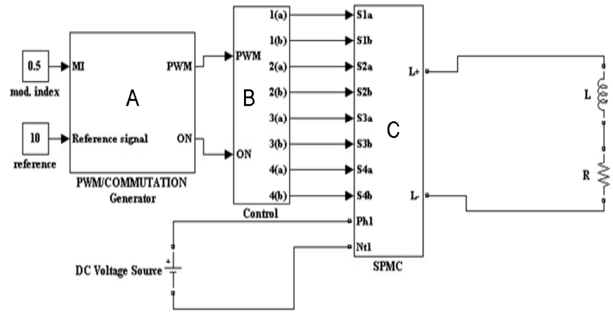



Fig. 15. Top level main model of SPMC in MLS

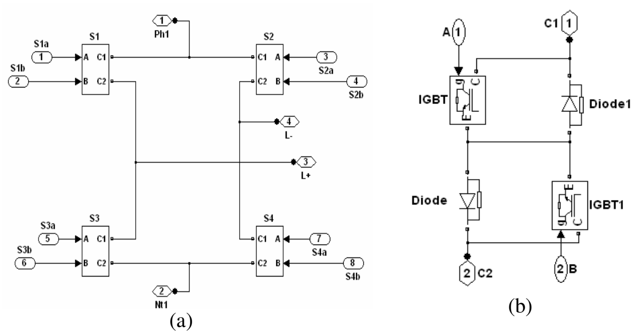



Fig. 16. (a) SPMC Model in MLS and (b) Bidirectional switch cell module

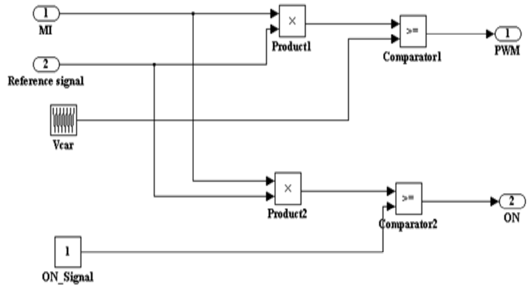



Fig. 17. PWM/Commutation model circuit in MLS

## VI. FPGA IMPLEMENTATION

The overall block diagram of the SPWM generator in FPGA is as shown in Fi.18 and the top level XILINX schematic diagram is shown in Fig.10. There are 6 major components, namely; 1) external main clock, 2) 'W' shape carrier signal, 3) comparator, 4) modulation index, 5) quadrant operation, 6) control (switch selector). PWM signal generated when reference signal and 'W' shape digital carrier signal waveform are compared.

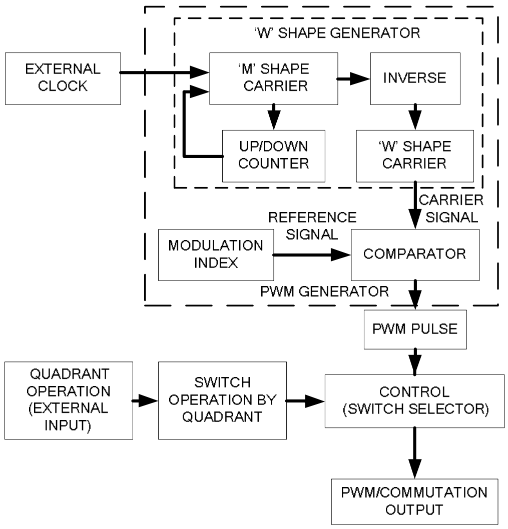



Fig. 18. XILINX FPGA schematic diagram flow of DC Chopper

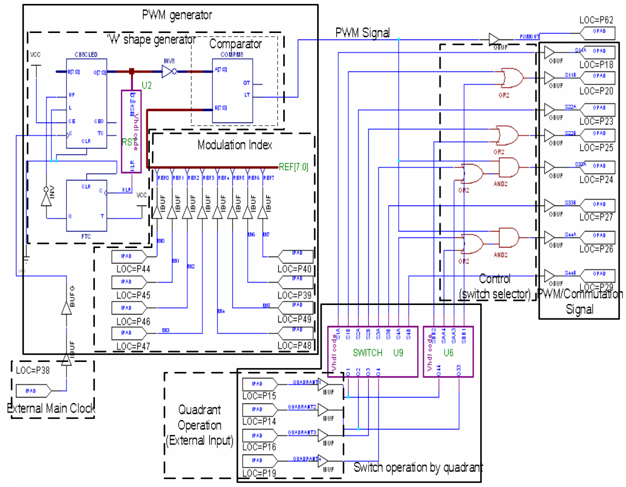



Fig. 19. Schematic Diagram of XILINX FPGA to produce PWM signal for DC Chopper

The basic block diagram of PWM generator is as shown in Fig. 19. There are four major components, namely; 1) external main clock, 2) 'W' shape generator including 'M' shape carrier, inverter and up-down counter, 3) comparator and 4) modulation index.

An external main clock input is also required as shown in Fig. 19. The clock was used as the clocking signal for the FPGA counter since variation frequency in carrier signal can be used in this work. The 8 bit up/down counter, CB8CLED is clocked at 1.02 MHz to produce a 2 kHz carrier signal according to (5).

$$f_{carrier} = \frac{2*N}{T} \quad (5)$$

where N is the number of carrier pulses per half-cycle. $f_{carrier}$ is the carrier frequency and T is the period of modulating signal.

To produce the triangular waveform which is 'W' shaped carrier signal, the 8 bit up/down counter, CB8CLED and the toggle flip-flop, FTC is used as 'W' shape generator as shown in Figure 19. The counter starts counting from 0 to 255 when the reset signal, 'RST block' is received. After 255, it will count back to 0.

The carrier frequency has a relationship with the main clock frequency and the up-down counter and can be expressed by equation (6).

$$f_{clock} = f_{carrier} * (2^n - 1) * 2 \qquad (6)$$

where $f_{carrier}$ is the carrier frequency, $f_{clock}$ is the main clock frequency and n is the bit size of the up-down counter.

Determination of the carrier frequency or switching frequency is the first step of design process, where the clock frequency needs to be calculated precisely. The carrier frequency, $f_C$ have been decided to operate in steps of 2 kHz for DC Chopper.

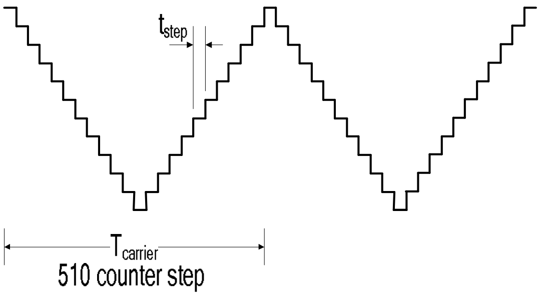



Fig. 20. Pattern of W shape carrier signal

In Fig. 20, the time for each step counter changes, $t_{step}$ is given by (7).

$$t_{step} = \frac{T_{carrier}}{step_{total}} = \frac{T_{carrier}}{510} \qquad (7)$$

Total step for a carrier frequency is 510 governed by (8)

$$step_{total} = (2^n - 1) * 2 \qquad (8)$$

where n is the bit size of an up-down counter. Therefore the time to generate the carrier wave, $T_C$ uses (9) [18].

$$T_c = step_{total} * T_{clock} \qquad (9)$$

$$= step_{total} * \frac{1}{f_{clock}} \qquad (10)$$

The output from inverter (INV8) shown in figure 19 which is a triangular wave in ‘W’ shape will be compared with the modulation index by using eight bit comparator, COMPM8 logic block producing the required PWM pattern. The ‘W’ shape of carrier signal is shown in Figure 8 using the following condition:

> “’W’ shape carrier signal ≤ Reference signal (desired modulation index), then output = 1”

The required modulation index is determined by configuring the 8-bit external switches denoted as ‘Modulation Index’ in Fig. 19. The type of quadrant required for operation is also externally controlled using an 8-bit input within the XC4005XL board. VHDL code is used in logic block ‘switch operation by quadrant (SWITCH U9 and U6). These switch blocks are used for switch selection in each quadrant. The AND and OR gate are used in the switch selector as shown in Figure 19. The function of the switch selector is to determine and ensure that the PWM pulse train generated follows the switching sequence as in Fig. 14.

## VII. RESULTS AND DISCUSSIONS

A laboratory model of a four quadrant single phase matrix converter was constructed and tested to compare the behaviour of the SPMC. The block diagram of the experimental set-up is as shown in Figure 21, employing 8 units of IGBTs module. DC source of SPMC is set greater than 20Vdc connected to those IGBT modules controlled by gate drive circuit that could turn-on the IGBT. The operation of SPMC is controlled by digital techniques employing the use of XILINX FPGA board and a personal computer (PC).

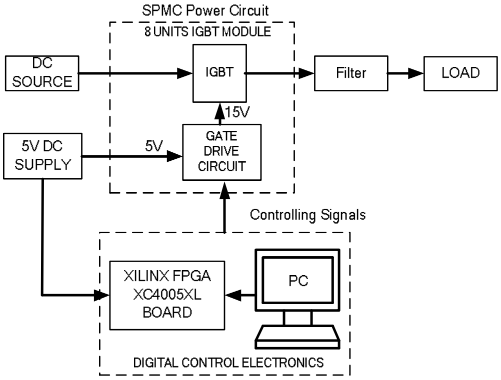
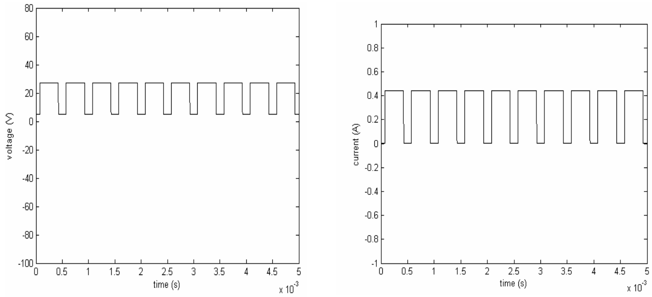



Fig. 21. The Experimental Set up of SPMC

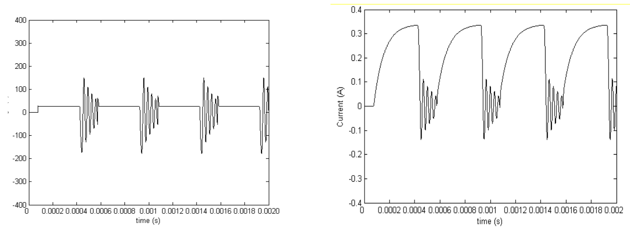
Fig. 22 to Fig.24 are selected results obtained from simulations, illustrating the operation in the first quadrant. Due to the symmetrical nature of the converter this approach is sufficient to illustrate its basic operation. Notice that without safe commutation strategies as in Fig.25a to Fig.26a; damaging voltage and current spikes are apparent. The current transient on the other hand although can be significant but is within the normal operating magnitude and hence may not be considered critical. The introduction of commutation strategies as proposed has resulted with both the voltage spikes and current transients being dissipated making a safe operation for the semiconductor switches. This is also verified experimentally as shown in Fig. 25b to Fig.26b.

Although conventional FQDC has less controllable switch but the implementation of full controllable regenerative operation is not possible with diodes and hence advanced features may not be possible in the future. This versatility is a desirable feature in the future as increases in costs for skilled manpower maybe overcome by having a versatile technology.



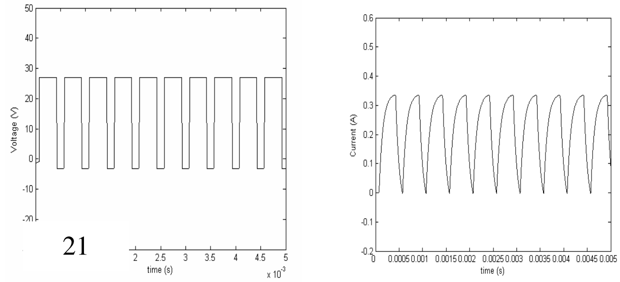
(a) (b)

Fig.22. Simulation result of quadrant 1 at $f_s$ =2kHz for resistive load with $m_a$=0.7; a) output voltage; b) output current



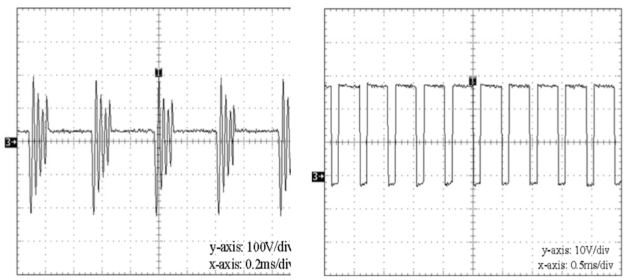
(a) (b)

Fig. 23. Simulation result for quadrant 1 at $f_s$ =2kHz for inductive load with $m_a$=0.7; a) output voltage; b) output current



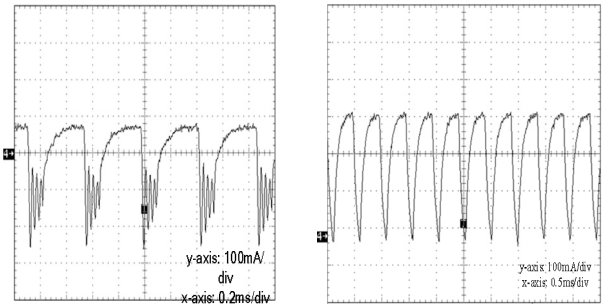
(a) (b)

Fig24. Simulation result ofquadrant 1 at $f_s$ =2kHz for inductive load implemented with commutation strategy and $m_a$=0.7; a) output voltage; b) output current




(a) (b)

Fig. 25. Experimental result of output voltage for quadrant 1 at $f_s$ =2kHz for inductive load with $m_a$=0.7 (a) without commutation; (b) with commutation strategy




(a) (b)

Fig. 26. Experimental result of output current for quadrant 1 at $f_s$ =2kHz for inductive load with $m_a$=0.7 (a) without commutation; (b) with commutation strategy

In Figures 25a to 26a, severe voltage spikes are noticeable. From an input of 30V, a damaging voltage spike with a range of +198 to -220V was observed (418V swing that equals to a multiplication factor of 14), a cause for concern. Table I shows the maximum and minimum voltage spikes of converter for quadrant 1 and quadrant 3 operation.

TABLE I
EXPERIMENTAL RESULT FOR INDUCTIVE LOADS WITHOUT COMMUTATION

| Operation Quadrant | Output Peak Voltage (V) | Output Peak Voltage Spike (V) | |
|---|---|---|---|
| | | Vpositive | Vnegative |
| 1 | 29 | 198 | -220 |
| 3 | -29 | 240 | -180 |

The DC chopper output is varied through changes of turn-on width, $t_{on}$ relating to modulation index, *ma* [23]. The turn on width, $t_{on}$ in XILINX is measured using Logic Simulator interface and compared with those obtained using calculations governed by (1) and (2). When the modulation index is increased from 0.1 to 1.0, turn-on width will be increased in steps of 10% of the modulation index. This variation is independent on the quadrant of operation; which only effects the polarities of voltage and current. Figure 27 shows the turn-on width with modulation index 0.5, 0.7 and 0.9.

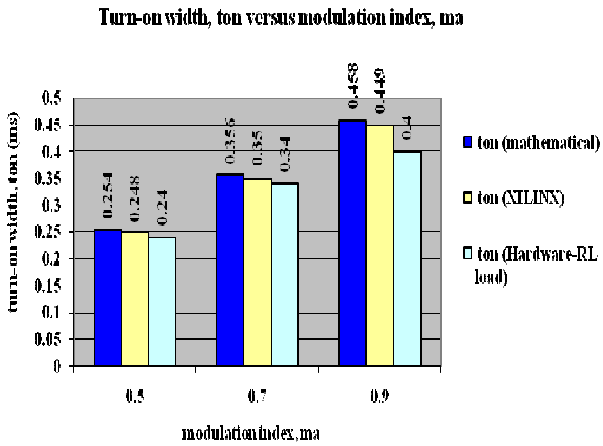



Fig. 27. Variation of turn-on width with respect to modulation index

Figures 28 to 29 shows the variations of mean voltage and current with respect to modulation index, *ma*. Mean Voltage and current increased non-linear with the variation of modulation index maybe due to low values of voltage used resulting in higher possible inaccuracies in measurements. Modulation index 1.0 gives the highest mean output voltage and current.

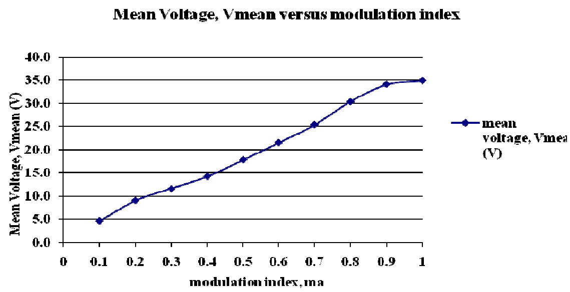



Fig. Fig. 28. Variation of mean voltage, $V_{mean}$ respect to modulation index for DC Chopper supplied by $35V_{DC}$ loaded with RL loads with switching frequency, $f_s = 2kHz$

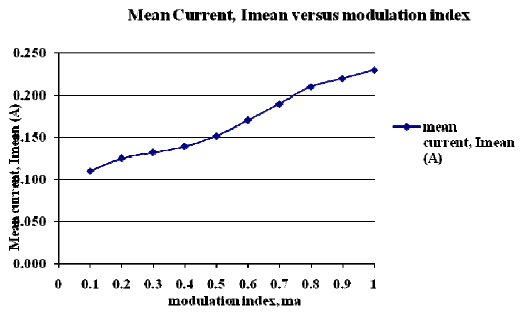



Fig. 29. Variation of mean current, $I_{mean}$ respect to modulation index for DC Chopper supplied by $35V_{DC}$ loaded with RL loads with switching frequency, $f_s = 2kHz$

The variation of turn-on width and time-delay with respect to modulation index for a carrier frequency, $f_C = 2kHz$ for the DC Chopper operation is shown in Table II. Calculation of time delay, $t_d$ of carrier frequency, $f_c = 2kHz$ (switching frequency, $f_s$) with modulation index, ma = 0.5 for the XILINX FPGA is done using Mathcad and illustrated in Figure 30.

TABLE II

VARIATION OF TIME DELAY, $t_d$ RESPECT TO MODULATION INDEX

| Modulation index, ma | $f_s = 2kHz$ | | Different in XILINX compare to mathematical (%) |
|---|---|---|---|
| | $t_d$ $(ms)$ (calculation) | $t_d$ $(ms)$ (XILINX) | |
| 0.1 | 0.225 | 0.226 | 0.44 |
| 0.2 | 0.199 | 0.199 | 0 |
| 0.3 | 0.174 | 0.176 | 1.14 |
| 0.4 | 0.148 | 0.15 | 1.33 |
| 0.5 | 0.123 | 0.126 | 2.38 |
| 0.6 | 0.090 | 0.1 | 10 |
| 0.7 | 0.070 | 0.075 | 6.66 |
| 0.8 | 0.046 | 0.05 | 8 |
| 0.9 | 0.021 | 0.025 | 16 |
| 1.0 | 0 | 0.0004 | 0 |

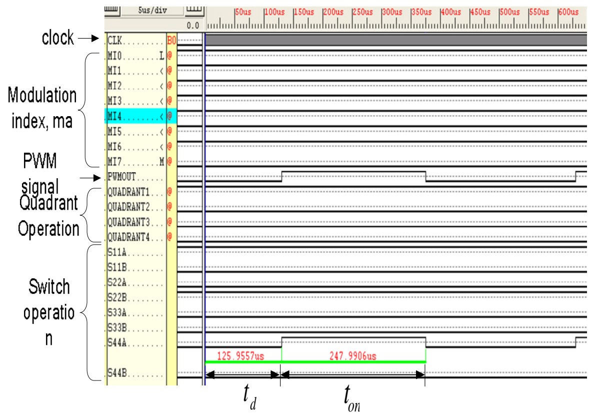



Fig. 30. XILINX FPGA simulation PWM output for ma = 0.5

## VIII. CONCLUSION

The principles of four quadrant DC-DC chopper have been studied and the switching function has been implemented in the operation of Single-phase Matrix Converter (SPMC). Experience in designing the FPGA for the implementation of DC Chopper using single-phase matrix converter is outlined. It has been shown that the FPGA could effectively be used in SPMC with the four bidirectional switching arrangements. Experimental results achieved good agreement with those implemented in simulations. PWM controlling algorithm is placed on a single chip of XC4005XL FPGA and is capable of providing flexibility and design reuse. The overall system is compact with no external memory system required. Tests have been carried out to show the effectiveness and flexibility of the proposed method. Selected experimental result has also shown that this could be practically realised in future applications.

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