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# Trapezoidal Modulated Direct Matrix Converter: For Higher Frequency AC/AC Conversion

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In this paper a digital controller has been developed based on Field Programmable Gate Arrays (FPGA) to improve the quality of output (o/p) waveforms produced from a direct matrix converter (DMC), for o/p frequencies higher than the input frequency. In order to reduce the harmonics (present in the o/p voltage waveforms), the performance of proposed DMC is analysed by applying an advanced modulation technique, "Trapezoidal modulation (TM)". The observed total harmonic distortion (THD) associated with the o/p voltage waveforms is reduced to a satisfactory level with the application of TM. The developed hardware arrangement is quite compact. Working of the proposed digital controller for the DMC has been successfully verified for a range of the o/p frequency, $f_0$ values extending from 100 Hz to 50 kHz.

**Keywords:** Direct Matrix Converter (DMC), Field Programmable Gate Arrays (FPGA), Modulation Techniques, Total Harmonic Distortion (THD), Trapezoidal Modulation (TM).

## 1 Introduction

The development of digital controllers for generating pulse width modulation (PWM) pulses has been a fact of intense attention in the academic world and research fraternity[1,2]. Numerous controllers based on microprocessors/ microcontrollers can be designed to generate PWM pulses[3,4]. Though, the performance of these processors is quite limited, as these are built on generic hardware. In distinction, the Field programmable gate arrays (FPGA) based digital controllers can provide the liberty to form customizable functionalities, absolutely improved to distinct requirements, relating to specific application(s)[5-10]. The FPGA based designs, permit easy customization of the hardware as well as the software both and that to, at a very minimal budget[11-15]. In this paper, the FPGA based digital controller has been designed and developed to produce firing signals applied to a modulated direct matrix converter (DMC)[16-19].

The DMCs are used to convert an alternating voltage at fixed frequency, directly to an adjustable voltage with an adjustable frequency (AVAF)[20,21]. The proposed single-phase DMC can produce output (o/p) signals with frequencies higher than the input (i/p) frequency. Because of regular switching of the power switches, the produced o/p voltage comprises of a lot of harmonics. These harmonics are required to be minimized[20-22]. For minimizing the total harmonic distortion (THD), triggering signals sent to every power IGBT switch, can be modulated by employing a range of modulation techniques (MTs)[20,21]. In this paper, an advanced MT, "Trapezoidal modulation (TM)" has been explained in detail and successfully implemented, to reduce the unwanted THD content, to a greater extent. The performance analysis of the DMC has been carried out for the TM, by considering the THD values associated with the o/p voltage for a range of o/p frequency, $f_0$ values, extending from 100 Hz to 50 kHz.

## 2 Power Circuit and Principle of Working

The power circuit of proposed single phase DMC is illustrated in Fig. 1(a). As illustrated, the schematic circuit is based on bi-directional power switches, capable of blocking the voltage and conduct the current in both the directions. The IGBTs (arranged in the common emitter configuration along with a pair of

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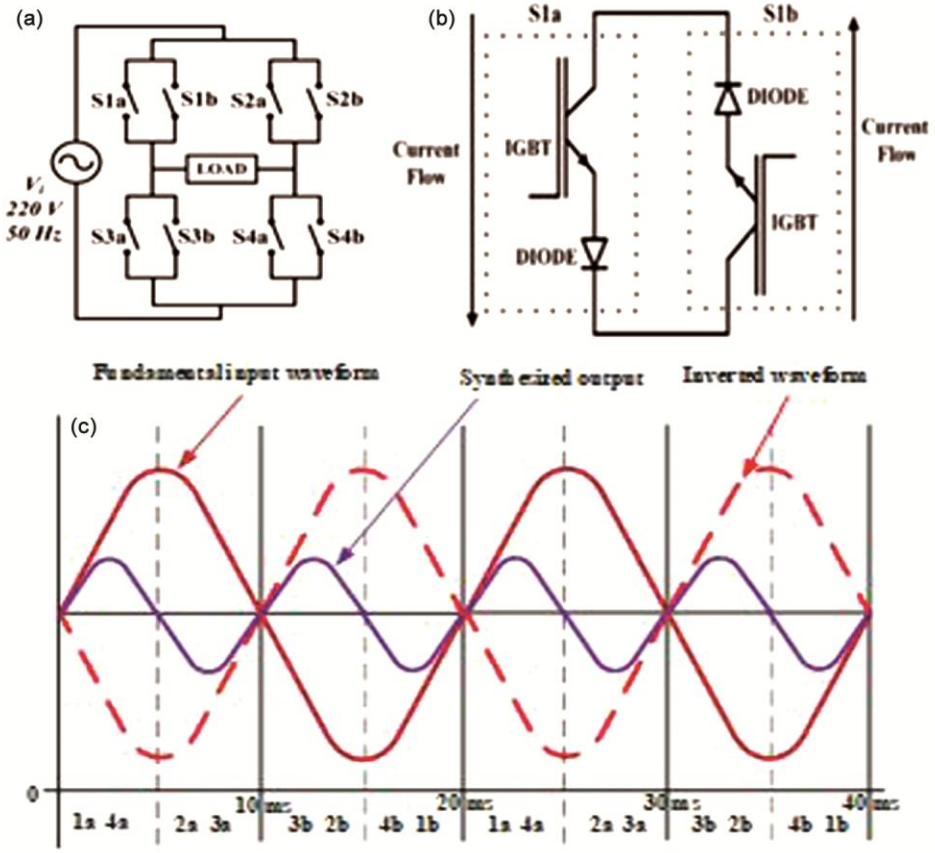


Fig. 1 — Proposed DMC and it's waveforms: (a) Power circuit, (b) IGBT switches (Common emitter configuration) and (c) Waveforms along with firing patterns of IGBTs for $f_o = 2f_i$.

diodes) as illustrated in Fig. 1(b), are employed in the power circuit. The IGBT switches are preferred as these possess comparatively higher switching capability as well as higher capacity for carrying current. The expected o/p voltage can be produced from the DMC by appropriate triggering of the IGBT switches. The proposed DMC can produce signals varying with o/p frequency, $f_o$ generally related to the i/p frequency, $f_i$ with a formula:

$$f_o = N.f_i \quad \ldots (1)$$

where, $N$ is an integer.

By properly choosing the values for $N$, the o/p voltage for higher o/p frequencies (than $f_i$) can be produced. For example, when the value of $f_0$ is set as double of the $f_i$, *i.e.* $f_o = 2.f_i$, the desired o/p voltage can be produced by employing a particular switching sequence of the IGBT switches. To generate desired o/p signal of frequency double to that of the i/p frequency, the adopted firing sequence is as shown at the bottom side in Fig. 1(c). The standard i/p and o/p waveforms for the DMC are also shown in Fig. 1(c).

Due to regular switching for the power IGBTs, the o/p voltage generated from the proposed DMC comprises of harmonic content. The quality of the produced o/p voltage can be improved by reducing these harmonics. As this DMC can generate signals of higher frequency than the applied signal, the routine way of using filter(s) is not an effective solution in this case for minimizing the THD content. This is because the o/p voltage generated has a frequency, that keeps on altering. Alternately, for reducing these harmonics, the firing pulses applied to trigger the IGBT switches can be modulated. Therefore, the effective way to deal with this condition is to use advanced MTs [21].

## 3 Trapezoidal Modulation Technique

Trapezoidal modulation (TM) is used to advance the control ability, by means of the on-line

computation of the PWM patterns[14]. To increase the computation speed of PWM patterns, the sinusoidal MS, is substituted by a trapezoidal MS, $e_{mt}(t)$. The produced trapezoidal modulated o/p signal, $e_{mod}(t)$, comprises of low order harmonics (LOH). The standard waveforms for the TM technique are depicted in Fig. 2. The TM is based on the classical unipolar PWM switching (UPPWMS). The UPPWMS scheme employs multiple TM signals along with a sole triangular signal.

In comparison with the bipolar PWM switching, the UPPWMS outcomes a superior o/p signal. Further it also results in the superior frequency response, since the effective switching frequency of the o/p signal produced, is doubled and the ripples are suppressed[14]. In TM, a trapezoidal MS, $e_{mt}(t)$ having a maximum intensity of, $E_{mt}$ volts and varying with a frequency, $f_{mt}$ Hz, is compared with a triangular CS, $e_{ctri}(t)$. This CS, $e_{ctri}(t)$ has a maximum intensity of, $E_c$ volts and varies with a frequency, $f_c$ Hz (where, $f_c > f_m$). The frequency of the produced o/p voltage of the DMC is finalized based on the frequency of the trapezoidal MS, $e_{mt}(t)$. For TM, the depth of modulation, $m_d$ is given as:

$$m_d = \frac{E_{mt}}{E_c} \text{ , for } 0 < m_d < 1 \qquad \ldots (2)$$

## 4 Simulated Results

The simulation studies are carried out for the single phase DMC using Simulink (MATLAB) platform, for o/p frequency, $f_o$ extending from 100 Hz to 50 kHz. The load considered under tests, employs a resistance, R = 1 kΩ and inductance, L = 100 mH. With these parameters, the measured THD value is found to be the least for the 100 % depth of modulation, i.e. $m_d$ = 1. For this reason, results for the TM technique are presented, by setting the $m_d$ = 1. The waveforms of the o/p voltage and the allied THD, for the TM technique with $f_o$ = 1 kHz, are presented in Fig. 3. The observed THD value associated with the o/p voltage waveform found to be around 6.2 %, as shown in Fig. 3(b).

## 5 FPGA Realization for DMC

The TM has been developed on the Xilinx FPGA by means of VDHL codes. Efforts are put for producing the o/p voltage of the DMC, nearly close to sinusoidal shape. This is achieved with the aid of an input/ reference signal (RS), that controls the DMC o/p voltage too. The block diagram of the FPGA based implementation of the suggested digital controller is shown in Fig. 4. As shown, the RS generator block generates the essential RS, further the

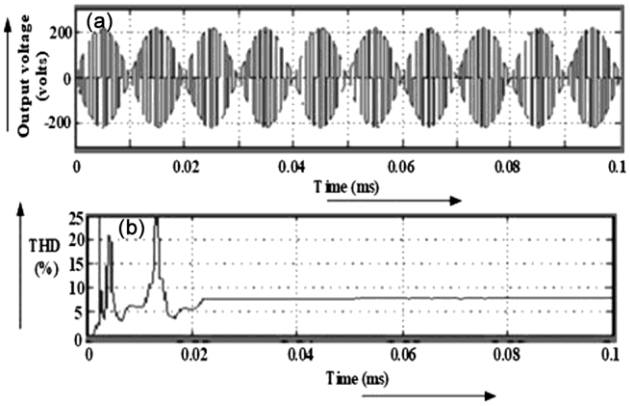


Fig. 3 — Performance curves of the DMC with TM for $f_o$ = 1 kHz: (a) O/p voltage and (b) THD waveform associated with the o/p voltage.

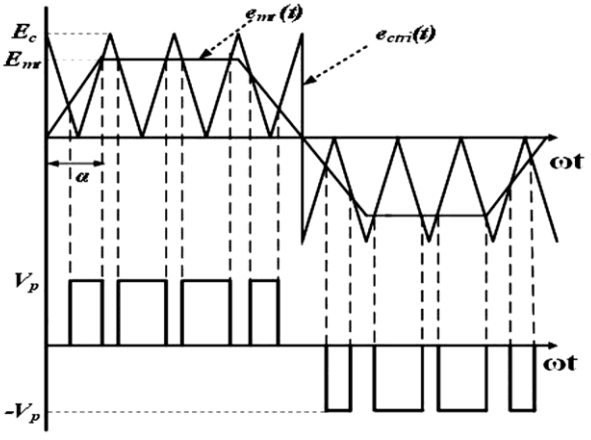


Fig. 2 — Trapezoidal modulation waveforms.

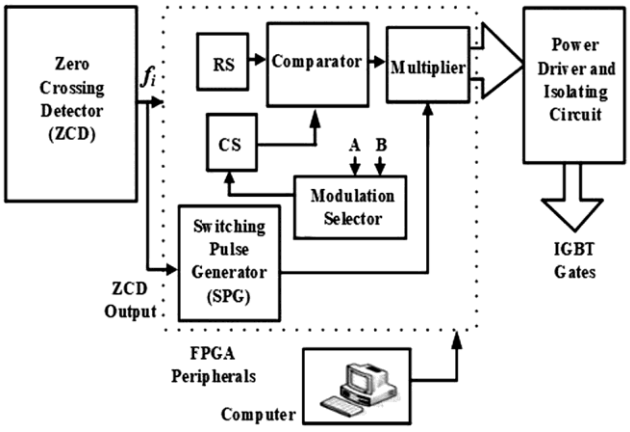


Fig. 4 — Block diagram of the FPGA based implementation.

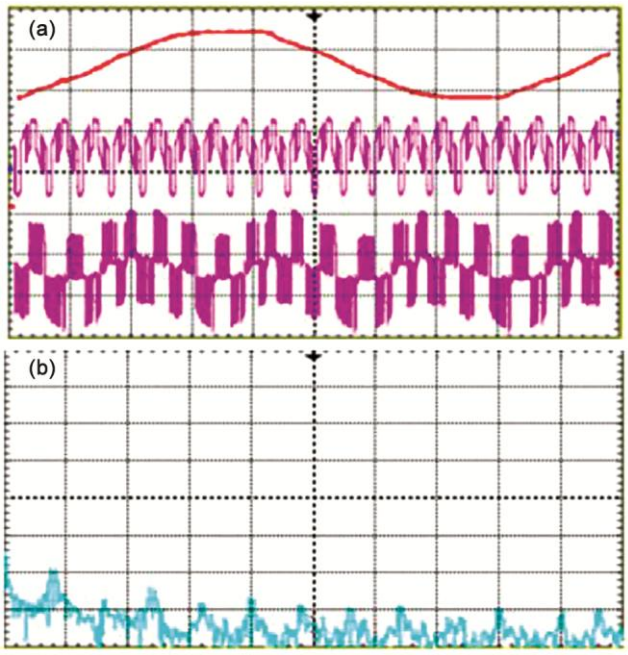


Fig. 5(a) — Performance curves [I/p voltage (upper trace: 100 V/div, 2ms/div), o/p current (middle trace: 2 A/div, 2ms/div) and o/p voltage (lower trace: 50 V/div, 2ms/div)] of the DMC with TM. & 5(b)–FFT Analysis of the DMC o/p voltage with the TM (5dB V/div).

CS generator block generates the CS of anticipated switching frequency.

The resultant pulsed waveforms generated by Switching Pulse Generator (SPG) block are being multiplied to the signal produced from the comparator block. This signal produced after multiplication is the vital modulated signal used for triggering. The amplification is achieved by means of a driver. These boosted waveforms and the power circuit are supposed to work in isolation. The required isolation is achieved by employing an opto-coupler 4N35. Finally, these pulses are fed to the respective gates of the IGBT switches.

## 6 Experimental Results

Experimental results have been achieved experimentally, by writing the VHDL codes with different settings of the $f_o$, for the TM technique, followed by dumping these codes on the FPGA kit (SPARTAN-3E). The waveforms have been captured on the Tektronix DSO (TDS-2014) by interfacing it with the FPGA kit.

Fig. 5(a) shows the different waveforms of the i/p voltage, o/p current & o/p voltage for the DMC with TM at o/p frequency, $f_o$ = 1 kHz. Fig. 5(b) illustrates the different waveforms for the FFT analysis of the

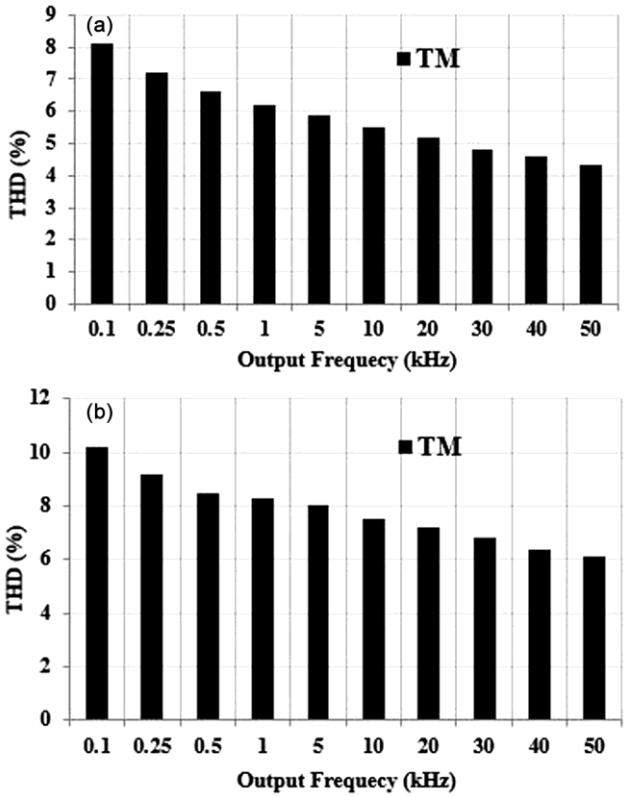


Fig. 6(a) — Software based performance analysis of the proposed DMC & 6(b) FPGA based performance analysis of the proposed DMC.

THD value associated with the o/p voltage for the DMC at o/p frequency, $f_o$ = 1 kHz, for the TM. After computing the FFT followed by its analysis, the THD acquired is 8.3 % for the TM technique.

Satisfactory working of the proposed DMC has been tested for a range of the o/p frequencies, $f_o$ = 100 Hz to 50 kHz. The comparative performance analysis of the single-phase DMC with the TM technique with variation in o/p frequencies is illustrated in Fig. 6(a) and (b). With the increment in the o/p frequency, the THD reduces significantly.

## 7 Conclusion

The laboratory prototype of a single-phase direct matrix converter (DMC) is developed, along with a digital controller using FPGA. This digital controller produces firing pulses for different IGBT switches used in the power circuit of the DMC to produce a voltage varying with higher output (o/p) frequency than the input frequency. An advanced modulation technique "Trapezoidal modulation (TM)" has been implemented on the FPGA kit, by writing VHDL codes. Functioning of the DMC has been simulated on Simulink (MATLAB) platform followed by the

experimental validation and fruitful verification for the o/p frequency range of 100 Hz to 50 kHz. The performance of the DMC has been found to be satisfactory for both the verifications. It has been observed for TM, that the total harmonic distortion (THD) associated with the o/p voltage of the DMC is obtained as low as 4.4 % for simulations, whereas 6.1 % for FPGA based hardware results.

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