Implementation of multi-carrier PWM using a DSP TMS320F28335. Application to series multicellular single-phase inverter

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Abstract

In this paper, the design procedures of single phase PWM multicellular inverter prototype using MATLAB / Simulink blocksets and code generation tools for TMS320F335 floating-point digital signal processor (DSP) is presented.
The control circuit is realized on a digital signal processor TMS320F28335 development board based on triangular-sinusoidal PWM control strategy which is specially designed for multicellular converters.
Single phase inverter is used to convert the PWM signal from the digital signal processor to an analog signal. For this the single-phase IGBT multicellular inverter is designed with the gate driver. The experimental results of PWM strategy controlled by a digital signal processor TMS320F28335 chip has been observed.

Keywords: Multicellular inverter, Multi-carrier PWM, DSP-TMS320F335, Implemented PWM, Simulink Tools, code composer.

1. Introduction

In recent years, multilevel-inverters are rapidly emerging as a viable alternative for high power applications such as electrical drives, renewable energy [1-2-3].

The main advantages of these converters are: possible to series connected, switching devices to obtain a higher voltage output without Snubbers to maintain safe switching, use of IGBTs for higher power levels, generation of output voltage signal with low harmonic distortion and reduction of switching frequency [1; 2].

A multicellular converter is based on a series-association of elementary commutation cells. It allows the distribution of the voltage constraints among series-connected switches. Multicellular converters are in preference to the NPC and CHB ones as considering appreciable advantages such as: modularity, non- interdependency of cells as the fault occurs and ease of reaching higher voltage levels just by introducing new cells [2; 4]. Thus, they are more and more used in industrial application, especially for active power filters, electrical traction and renewable energy [5,6]. However, the major drawback of this kind of converter is their control complexity [5].

To improve the performances of multicellular converters, we present, in this paper, the design procedure of three cells inverter prototype and we develop a TMS320F28335 Evaluation board to implement triangular-sinusoidal PWM control strategy using MATLAB / Simulink block sets.

2. Analysis of Three Cells Converter

2.1. Topology

Fig.1 shows the general structure of the single-phase multicellular converter. The both phases consist of three cells. Each cell consists of one voltage source (a DC voltage source equal to E in the third cell and capacitors possessing specific voltages in remaining cells) and two complementary power electronics components controlled by a binary switch to avoid short-circuiting of voltage sources. It noted that each switch sustains just a fraction of DC link voltage, i.e. E/3.

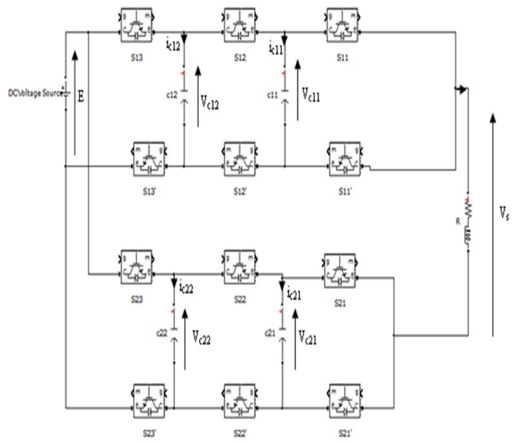


Fig. 1 Single-phase multicellular inverter structure

To ensure a stable operation of such a topology, the floating voltages need to be balanced at their correct value. In this case, (V_{c11}, V_{c21}) should be equal to *E/3* and (V_{c12}, V_{c22}) to *2E/3*.

This 3-cell single phase inverter is characterized by 2^6 configurations which permit to generate seven levels of voltage with a peak to peak value of E at the converter output.

2.2. Control Strategy

Triangular-Sinusoidal Pulse Width Modulation technique is the most common control scheme which is applied to switching strategy of multicellular converter to guaranty both best harmonic performance and voltage balancing mechanism in clamping capacitors [1, 3].

This strategy consists in comparing three bipolar triangular carriers UPI (me is the number of cells = 1, 2 & 3) with two AC reference signals V_{refk} (k is the number of phases = 1,2) as it's shown in Fig.2. These carriers are shifted to each other by $2\pi/3$ to generate seven levels of output voltage and harmonics around ($3{*}k{*}f_s$), where k and f_s are the integer number and the switching frequency, respectively. We defined for this strategy the magnitude modulation index r and the frequency ratio m as:

$$r = \frac{V_m}{U_p}, \quad m = \frac{f_s}{f} \tag{1}$$

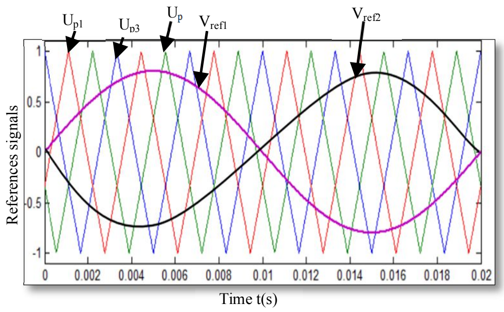


Fig. 2 Multi-carrier control strategy signals

The algorithm of this strategy can be summarized as follows:

$$\begin{cases} \text{if } V_{refk} \le U_{pi} \text{ then } & S_{ki} = 1 \\ \text{if } V_{refk} \prec U_{pi} \text{ then } & S_{ki} = 0 \end{cases} \tag{2}$$

Where S_{ki} is the control gate of the switches s_{ki}.

The three cells VSI, shown in Fig. 1, has been verified in a detailed SIMULINK simulation that fully defines all component elements of the circuit. DC voltage source E was 300V; the VSI was operated with a modulation index of 0.8, an output frequency of 50 Hz, and a carrier switching frequency of 2 kHz (modulation index m= 40).

Fig. 3 shows the output voltage V_s of the three cells VSI. This later becomes a 7-level waveform, taking its values among (-E, -2E/3, -E/3, 0, E/3, 2E/3, E), then the output voltage has practically sinusoidal waveform.

The harmonic spectrum of the output voltage is shown in the Fig.4. A zoom of this spectrum (Fig.5) shows that the highest harmonic magnitude is less than 1.5% of fundamental magnitude. We note, also, that the harmonic voltage gather with families around frequencies multiple of 3*mf.

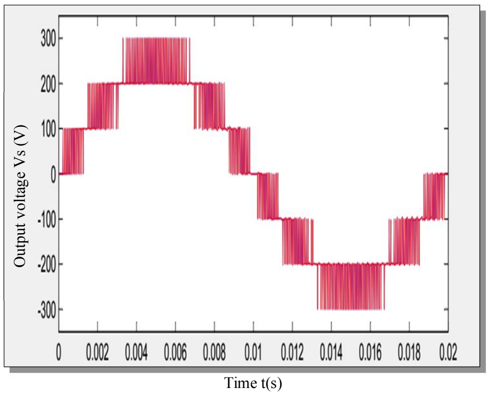


Fig. 3 Output voltage of single-phase multicellular VSI

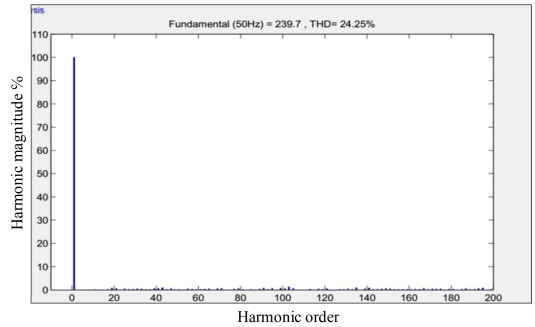


Fig. 4 Harmonic spectrum of output voltage

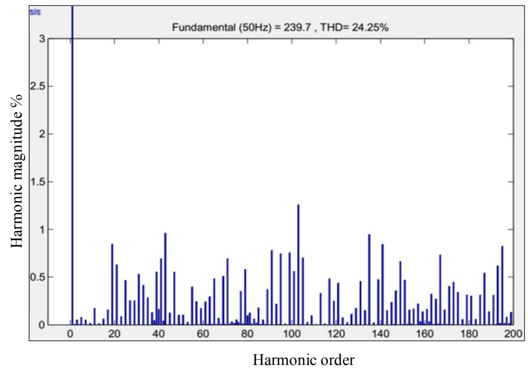


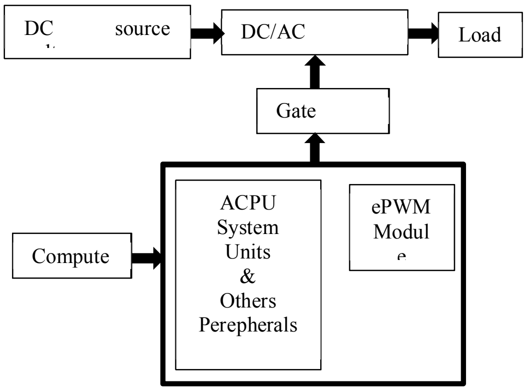
Fig. 5 Zoom of the harmonic spectrum of output voltage

3. Digital PWM Control Strategy

In many applications, it is desirable to control, a power converter using a microcontroller or a digital signal processor (DSP) for the implementation of digital PWM control strategy [7]. The block diagram of such a configuration is depicted in Fig. 6.

3.1. 32-Bit C2000 Controllers for Digital PWM

The C2000 family of devices possesses the desired computation power to execute complex control algorithms along with the right mix of peripherals to interface with the various components of the DMC hardware like the analog-to-digital converter (ADC), enhanced pulse width modulator (ePWM), quadrature encoder pulse (QEP) and so forth [7].



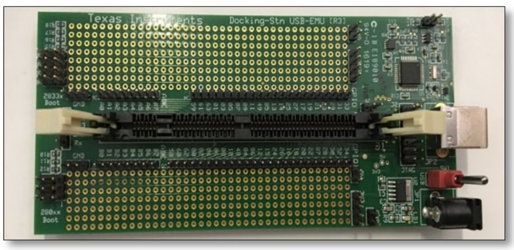
C2000 Controller for TMS320F28335

Fig. 6 Block diagram for digital control of multicellular inverter

These peripherals have all the necessary hooks for implementing systems, which meet safety requirements, like the trip zones for PWMs and comparators. Along with this, the C2000 ecosystem of software (libraries and application software) help in reducing the time and effort needed to develop a Digital motor control solution.

The designed board to implement triangular-sinusoidal PWM control strategy is shown in the Fig.7. Normally, we use the C2000 Experimenter Kit for TMS320F28335 under the control of a PC via USB port [7]

a- Control Card



b- USB Docking Station

Fig.7 C2000 Experimenter Kit for TMS320F28335

The C2000™ is ideal for applications combining digital signal processing, microcontroller processing, Matlab/Simulink, efficient C code execution, and operating system tasks [7].

3.2. The Proposed PWM

The objective is to implement multicarrier triangular-sinusoidal PWM control strategy for multicellular single-phase inverter.

For that we design a very simple project for the Texas Instruments C28x family of DSP devices using MATLAB® and Simulink® and Run the project in real-time on the Texas Instruments F28335. In developing this Laboratory, the following hardware and software were used:

- MATLAB R2013a with Embedded Target for TI C2000.
- Code Composer Studio (CCS) v4.
- C2000 Experimenter Kit for TMS320F28335 Hardware.

The block diagram of the proposed PWM architecture is shown in Fig. 8.

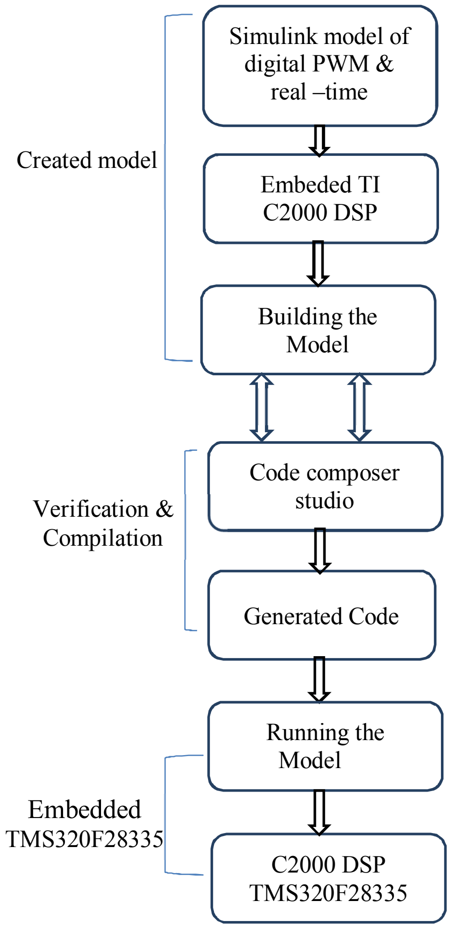


Fig.8 Block diagram of the proposed PWM architecture

The microcontroller TMS320F28335 is supplied with the Code Composer Studio (CCS) Software. CCS is used to run our program on the TMS320F28335 as well as to effectively “look inside” the DSP chips themselves. It also links seamlessly with MATLAB [5].

Fig.9 shows the Simulink model that will be used to generate the gate switch control for single-phase multicellular VSI.

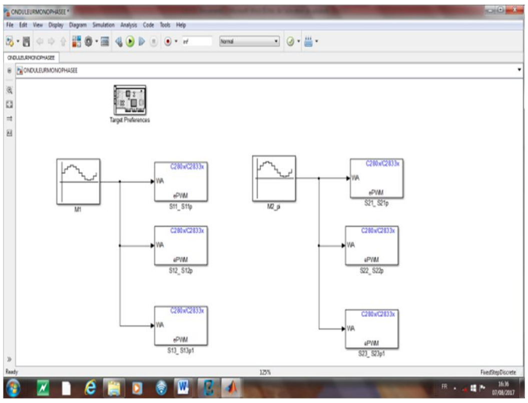


Fig.9 Simulink model of the proposed PWM

Three Enhanced Pulse Width Modulator (ePWM) module units, with programmable dead-band, are used to control each phase of the converter.

The procedure to generate signal consist of counting modes, CPU Timer compares operation and carrier signal generation. For generation of carrier signal two counting modes are used, continuous up modes gives an asymmetric carrier waveform and continuous up down modes gives a symmetric carrier waveform. In this work, we have shoos the symmetric mode.

The three ePWM blocks will be configured as follows:

-The timer period register set to 37500 clock cycles (desired f_{dec}=2 kHz PWM frequency). It is calculated as:

$$Time\ period = \frac{SYSCLKOUT}{Clock\ prescaler.PWM\ frequency}$$

$$= \frac{150\,MHz}{1.2KHz} = 37500$$

Where: SYSCLKOUT is the CPU clock frequency (150 MHz for the TMS320F28335 DSP).

In this application the compare registers were updated each timer interrupt to obtain the 50 Hz inverter output voltage.

- A phase offset value (TBPHS) equal to 12500 clock cycles in order to shift the carriers to each other by 2π/3

- The dead band is fixed to 900 ns.

The reference signals are two sine waves shifted by π/2 and configured to obtain the magnitude modulation index r=0.8.

4. Implementation and Experimental Results

In order to validate the simulation results, we have built a complete test bench in our laboratory (LESI). The photo of this experimental bench is given in Figure 10. It consists of:

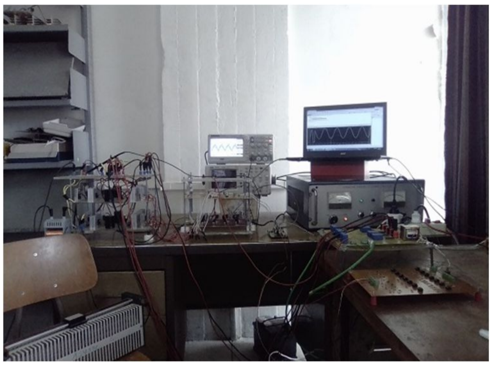


Fig.10 Experimental bench

4.1 Power Part

The power part consists of a multicellular converter, control card and drivers, IGBT switches, capacitors and the RL load. Fig .10-a shows the photo of a single-phase multicellular VSI. Each phase is composed of three cells. The switches consist of 12 IGBTs (600V/42A) transistors connected in antiparallel with 12 diodes and 4 flying capacitors of 160 µF/ 800V.

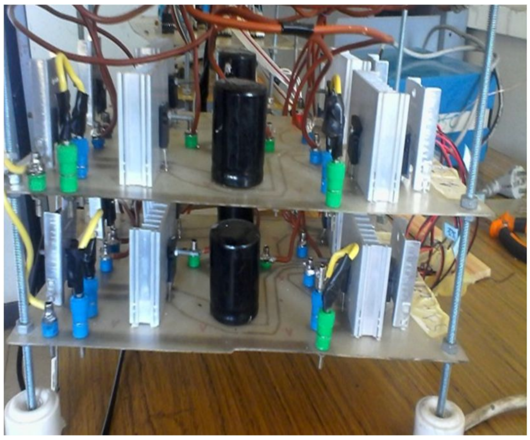


Fig.10-a Designed single-phase three cells VSI

The control card consists of two stages, the first contains 12 TLP250 drivers and the second their independent DC supplies (12V) as is shown in Fig.10-b

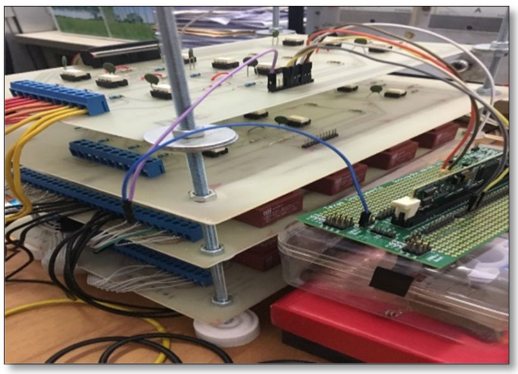


Fig.10-b Control card and IGBTs drivers

4.2 Control Part

IGBT control signals are derived from a DSP card, based on a processor dedicated to signal processing the TMS320F335 from Texas Instruments which is controlled by computer.

4.3 Experimental Results

In this section, we present experimental results obtained on a series multi-cell (six cells), full bridge, voltage source inverter feeding RL load. The experimental bench is characterized as:

- The supply voltage E = 300V
- The values of the capacitors $C_{11} = C_{12} = C_{21} = C_{22}$ =160µF
- The PWM frequency f_{dec} = 2 KHz
- Single phase AC motor.
- Passive load R
-

Note: In the majority of results the voltage×10 and the current/10 of oscilloscope

Fig 11-a & b show the output voltage of the multicellular single-phase VSI and its harmonic spectrum. The inverter is controlled by the microcontroller TMS320F28335 with a PWM frequency of 2 khz.

It is clear that this topology can output seven voltage levels (-E, -2E/3, -E/3, 0; E/3, 2E/3, E) respectively (-300, -200, -100, 0, 100, 200, 300) as is shown in Fig.11-a. We observe a little perturbation caused by the switches.

The harmonic spectrum of the output voltage is shown in the Fig.11-b; we observe that the highest harmonic magnitude is less than 1.5% of fundamental magnitude and the harmonic voltage gather by families around frequencies multiple of 3*mf which confirm the simulation results

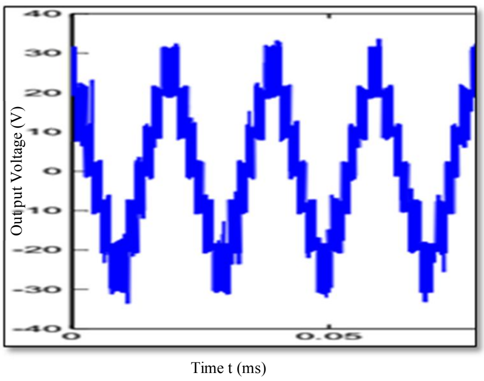


Fig.11-a Output voltage V_s of the multicellular inverter across resistive load

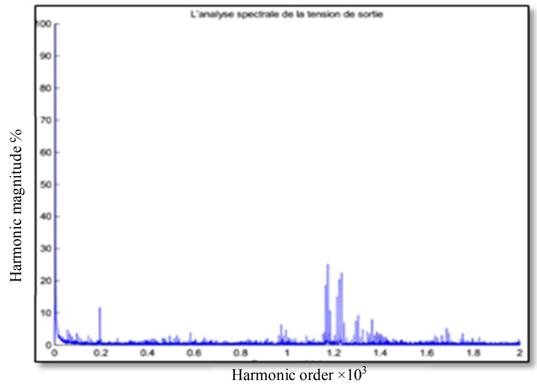


Fig.12-b Harmonic spectrum and zoom of the output voltage

The evolution of the output voltage across the AC motor and the harmonic spectrum are represented in Figs 12-a and 12-b.

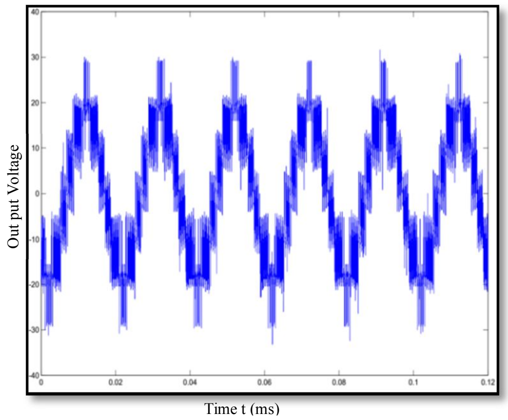
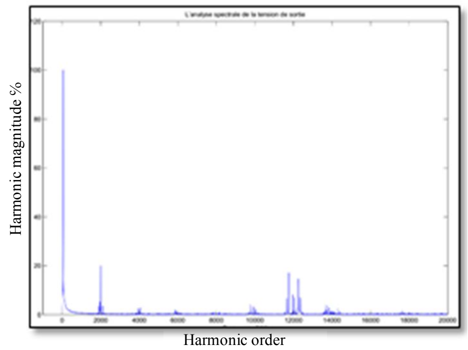


Fig.12-a Output voltage V_s of the multicellular inverter across the AC motor

Fig 12-a shows clearly that the output voltage of the multicellular VSI has 7 levels (-E, -2E/3, -E/3, 0; E/3, 2E/3, E) respectively (-300, -200, -100, 0, 100, 200, 300). We observe a little perturbation caused by the switches. The output voltage waveform is practically sinusoidal with less harmonic as is clearly represented in Fig.12. These results confirm the simulation study in Section 2 Fig.3.



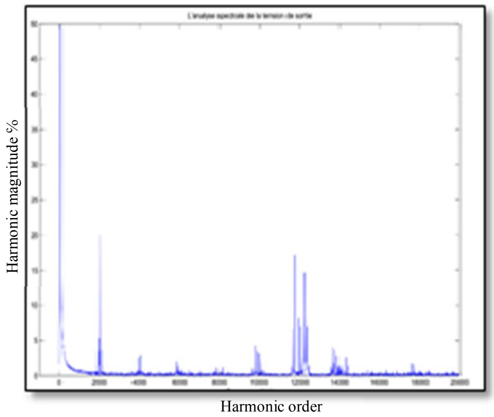


Fig.12-b Harmonic spectrum and zoom of the output voltage

Fig 13 shows line current of AC motor fed by the multicellular VSI. It is clearly observed that the current has sinusoidal wave form. Both line-line voltage and current are almost sinusoidal without the use of any output filters on the experimental converter.

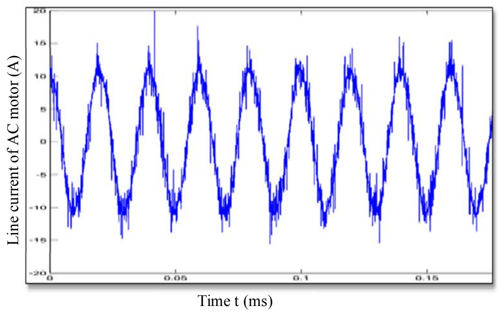


Fig.13 Line current I_s of the AC motor

5. Conclusion

In this paper, a single-phase multicellular VSI has been realized. This converter is controlled via a digital signal processor TMS320F28335 development board based on multi-carrier triangular-sinusoidal PWM control strategy.

The investigated topology is based on series connections of three cells by phase. The multilevel PWM was implemented on the microcontroller DSPTMS320F28335.

Simulation and experimental results were shown to verify the analysis and to demonstrate the following advantages of the realized converter:

- Since it can generate a seven-level line-to-line staircase waveform, this topology generates almost sinusoidal voltage and current waveforms even at the fundamental switching frequency.
- The system has low harmonics in the output voltage.
- Switches stress in the converter is low.
- Minimum of switching frequency.
- Because of their modular and simple structure, they can be used to generate unlimited number of levels

6. References

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