ATEE - 2004

SYNTHESIS OF THE DISCONTINUOUS PULSE WIDTH MODULATION ALGORITHMS

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Abstract: In this paper several discontinuous pulse width modulation (DPWM) numerical control strategies are presented, aiming at the reduction of switching losses and decrease of the number of arithmetic operations for computing the switching instants. The strategy is based on two line-to-line unitary reference voltage (the two voltages are referred to the DC supply voltage). Through cyclical permutation of the two line-to-line reference voltages at every 30 el. deg. 60 el. deg. or 120 el. deg., the optimal PWM control strategies are obtained, having some clear advantages compared to classical PWM techniques (CPWM). Simulated results and their analysis for the case of a three-phased bridge inverter demonstrate the validity of the numerical control strategies presented.

1. INTRODUCTION

Voltage source inverters are utilized in AC motor drive, utility interface and uninterruptible power supply (UPS) applications as a means for DC⇔AC electric energy conversion. The DC bus is used to generate a variable voltage and variable frequency power supply. The voltage source inverter is used to convert the DC bus to the required AC voltage and frequency. The power inverter has 6 switches (as shown in Fig.1), had are controlled in order to generate an AC output from the DC input. The phase voltage is determined by the duty cycle of the PWM signals. Upper and lower switches on the same leg should not be switched on the same time. This will prevent the DC bus supply from being shorted. A dead time must be given between switching off the upper switch and switching on the lower switch and vice versa. This ensures that both switches are not conductive when they change state from on to off or vice versa.

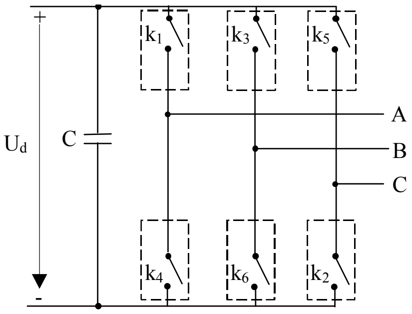


Fig.1 Structure of the three-phased inverter with two voltage levels;

The classical PWM strategies [7] allow the determination of the conduction cyclic ratios based on the line-to ground reference voltages. An exception to this is the Space Vector PWM technique which uses the magnitude and phase of the reference voltage vector [8]. The paper presents the synthesis of the discontinuous pulse width modulation algorithms (DPWM) for three phase voltage inverters. The advantage of these methods is the decrease of the arithmetic operations number for computing the switching instants.

2. DPWM CONTROL ALGORITHM

The discontinuous strategy entails the transition from three to two axes on which the control sequences are determined. The two axes are represented by two line-to-line voltages; by changing these cyclically different PWM strategies can be obtained. These strategies differ in switching losses per each bridge branch. If we consider phase A as reference the number of commutations for this leg is the four times smaller than on other legs [2]. The switching generation functions can be defined at a particular instant k from the PWM control sampling, as a functions of the reference voltages ($u_{ref\_A}, u_{ref\_B}, u_{ref\_C}$) for each phase separately, but related to the continuous source voltage (U_d):

$$m_{A1g}(k)=\frac{u_{ref\_C}(k)-u_{ref\_A}(k)}{U_d}$$

$$m_{A2g}(k)=\frac{u_{ref\_B}(k)-u_{ref\_A}(k)}{U_d} \qquad (1)$$

The block diagram for an inverter with three switching cells, two switches per cell (Fig.1) and the generation functions waveforms (Fig.2) are presented for the case in which phase A is taken as reference. The reference voltage should form a symmetrical three phased system. The maximum value of these voltages is $U_d/\sqrt{3}$, thus covering the entire linear zone of operation. In this case, the switching generation function exhibits a continuous variation inside the segment [-1, 1] when $T_p \rightarrow 0$ (T_p denotes the commutation period).

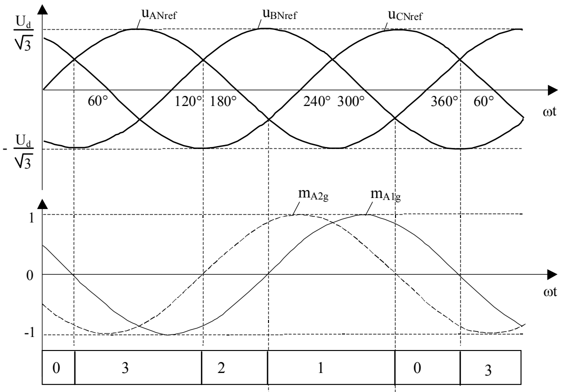


Fig.2 Commutation generating function in the DPWM strategy case

Depending of the sign of functions m_{A1g} and m_{A2g}, four sectors can be distinguished (see Fig.2). The duty cycle ratio can be determined graphically for each sector, so that a certain bridge leg is able to keep its particular commutation state over the entire sector. The duty cycles (τ_A, τ_B, τ_C) represent the time while the upper switches on each leg are on during one commutation period (see equations (2)). With (a_A, a_B, a_C) the conduction cyclic ratios for the upper switches have been denoted, and for lower switches these are complementary.

In table I (Fig3), the relationship between duty cycle and switching generation functions are listed.

SECTOR	SIGN	CONDUCTION CYCLIC RATIO
0	$m_{A1g} > 0;\ m_{A2g} < 0$	$a_A(k)=-m_{A2g}(k);\ a_B(k)=0;\ a_C(k)=m_{A1g}(k)-m_{A2g}(k)$
1	$m_{A1g} > 0;\ m_{A2g} > 0$	$a_A(k)=0;\ a_B(k)=m_{A2g}(k);\ a_C(k)=m_{A1g}(k)$
2	$m_{A1g} < 0;\ m_{A2g} > 0$	$a_A(k)=-m_{A1g}(k);\ a_B(k)=m_{A2g}(k)-m_{A1g}(k);\ a_C(k)=0$
3	$m_{A1g} < 0;\ m_{A2g} < 0)$	$a_A(k)=1;\ a_B(k)=1+m_{A2g}(k);\ a_C(k)=1+m_{A1g}(k)$

Fig.3 Table I relationship between duty cycle and switching generation functions

$$
\begin{aligned}
\tau_A(k) &= a_A(k)\cdot T_p\\
\tau_B(k) &= a_B(k)\cdot T_p\\
\tau_C(k) &= a_C(k)\cdot T_p
\end{aligned}
\tag{2}
$$

The definition domain of sector 0 and 2 is of 60^0 el. and for sector 1 and 3 it is of 120^0 el. As a result, the transistors on leg A will commute four time less than the ones on the other two legs [3]. This method allows for a better dissipation of the heat in the semiconductor devices on the phase considered as a reference.

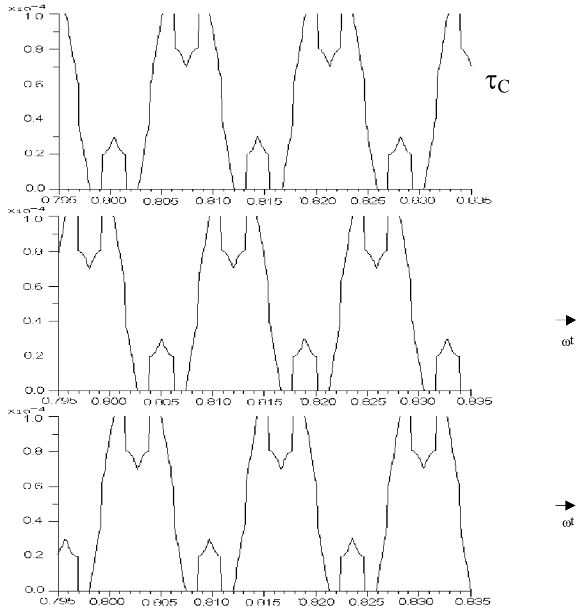
2.1 DPWM1 CONTROL ALGORITHM

By a cyclic change of the reference phase, different DPWM control algorithms can be obtained. Thus, Fig. 4-b presents the duty cycles for the case when axes are changed at every 30^0 el. (DPWM1) [5]. For sector 1, the two phase voltage references m_{A1g}, m_{A2g}, are positive and switch k_1 (see Fig.1) must be "*off*", while on the other switches k_3, k_5 are commanded by PWM technique. The same control is use for sectors 4, 5, 8, 9 and 12, only depend of phase voltages reference.

For case when the two phase voltage references are negative, the computational algorithm for duty cycle is different. Thus, for sector 2 the two phase voltage references m_{B1g}, m_{B2g}, are negative and switch k_3 (see Fig.1) must be "*on*" by all the definition domain of sector, while on the other two switches k_1, k_5 are commanded by PWM technique.

The reference phase voltage can be changed during operation (online) at the moment when the generation functions are equal in magnitude (the absolute value) and phase, no matter which the current reference phase is.

From simulations result, the DPWM1 control algorithm has the least THD (Total Harmonic Distortion) factor for a modulation index M great than 0.5 value.



2.2 DPWM2 CONTROL ALGORITHM

The other DPWM algorithm on two axes is defined by a complete period of reference voltage in the form of 6 sectors of 60^0 el [3] each. The 6 sectors are determined by testing the sign of each two phase voltages reference (Fig.5-a) and differ by the maximum absolute value of reference phase voltages. These sectors have been denoted 1-B, 2-A, 3-C, 4-B, 5-A and 6-C where 1…6 are the sector numbers and A, B and C are the reference phases used to compute the connection generating functions.

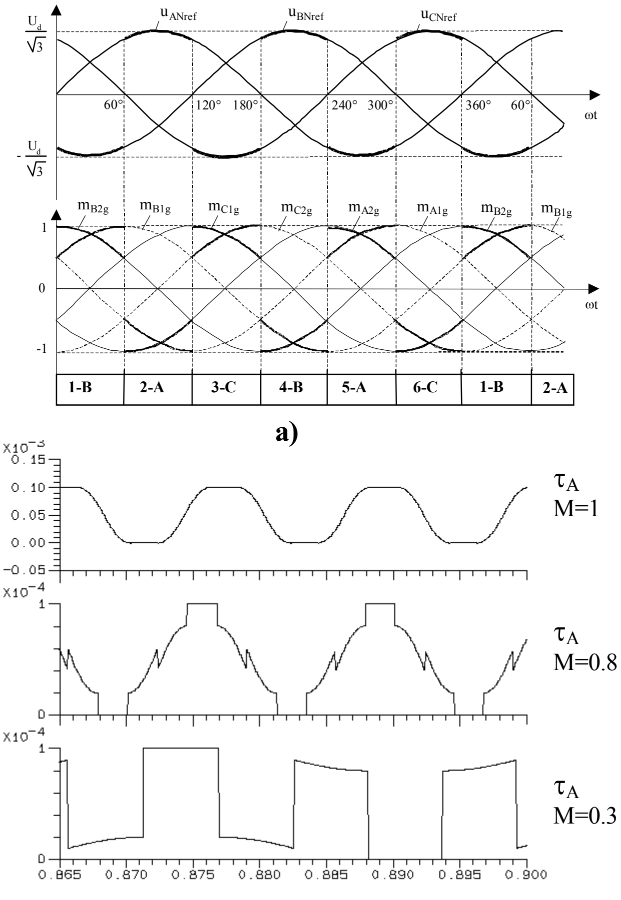
To decrease the arithmetic operations' number needed for computation, the switching generation functions have been denoted as:

$$
\begin{cases}
m_{C1g} = m_{1g};\, m_{A1g} = -m_{1g}\\
m_{A2g} = m_{2g};\, m_{B1g} = -m_{2g}\\
m_{B2g} = m_{3g};\, m_{C2g} = -m_{3g}
\end{cases}
\tag{3}
$$

This DPWM2 strategy has the particular feature that the time corresponding to the non commuting leg is synchronous with the maximum absolute value of reference voltages. This aspect can represent an advantage for converters operating at a unitary power factor, from the standpoint of commutation losses. The duty cycle evolution differs as a function of the maximum absolute value of reference voltages, as it can be seen in Fig.5-b. Thus, for smaller values than the maximum one ($\hat{U}_{ref} < U_d/\sqrt{3}$), this evolution has discontinuities at every 60^0 el.

From analyzing the waveforms presented in Fig.5-b, during rotation each phase is in turn connected directly to the positive/negative terminal of the continuous supply voltage, while on the other phases the command complies with the pulse width modulation principle.

The simulation results confirm the validity of the analyzed method. In table II (Fig.6) the relationship between duty cycle and switching generation functions is listed (below):



b)

Fig. 5 a) Commutation generating function in the DPWM2 strategy case; **b)** DPWM2 duty cycles

SECTOR	SIGN	CONDUCTION CYCLIC RATIO
1-B	$u_{ref\_A}>0\&u_{ref\_C}>=0$	$a_A(k)=-m$[illegible](k); $a_B(k)=0$; $a_C(k)=m$[illegible](k)
2-A	$u_{ref\_B}<=0\&u_{ref\_C}<0$	$a_A(k)=1;\ a_B(k)=1+m_{2g}(k);\ a_C(k)=1-m_{1g}(k)$
3-C	$u_{ref\_A}>=0\&u_{ref\_B}>0$	$a_A(k)=m_{1g}(k);\ a_A(k)=-m_{3g}(k);\ a_C(k)=0$
4-B	$u_{ref\_A}<0\&u_{ref\_C}<=0$	$a_A(k)=1-m_{2g}(k);\ a_B(k)=1;\ a_C(k)=1+m_{3g}(k)$
5-A	$u_{ref\_B}>=0\&u_{ref\_C}>0$	$a_A(k)=0;\ a_B(k)=m_{2g}(k);\ a_C(k)=-m_{1g}(k)$
6-C	$u_{ref\_B}<0\&u_{ref\_A}<=0$	$a_A(k)=1+m_{1g}(k);\ a_B(k)=1-m_{3g}(k);\ a_C(k)=1$

Fig.6 Table II relationship between duty cycle and switching generation functions

2.3 DPWM3 & DPWM4 CONTROL ALGORITHMS

By a cyclic change of the reference phase at every 120^0 el. other two DPWM control algorithms (DPWM3 and DPWM4) [4] can be obtained (see Fig.7).

This DPWM strategy is characterized by the simplest algorithm from the standpoint of microprocessor implementation.

In the case of DPWM3 algorithm, it takes into account only the positive part of the reference phase, and the DPWM4 algorithm takes into account only the negative part of the reference phase. The computational algorithm for the conduction interval on each sector is detailed in table III (see Fig.8).

By analyzing the waveforms presented in Fig.9-a and Fig 9-b we can observe than the discontinuities can't occur in the case of this algorithms (DPWM3, DPWM4).

SECTOR	SIGN	CONDUCTION CYCLIC RATIO
1-A-120	$m_{A2g} >0 \& m_{A1g} >=0$	$a_A(k) = 0;\ a_B(k) = m_{A2g}(k);\ a_C(k) = m_{A1g}(k)$
1-B-120	$m_{B2g} >0 \& m_{B1g} >=0$	$a_A(k) = m_{B1g};\ a_B(k) = 0;\ a_C(k) = m_{B2g}(k)$
1-C-120	$m_{C1g} >0 \& m_{C2g} >=0$	$a_A(k) = m_{C1g}(k);\ a_B(k) = m_{C2g}(k);\ a_C(k) = 0$

Fig.8 Table III relationship between duty cycle and switching generation functions

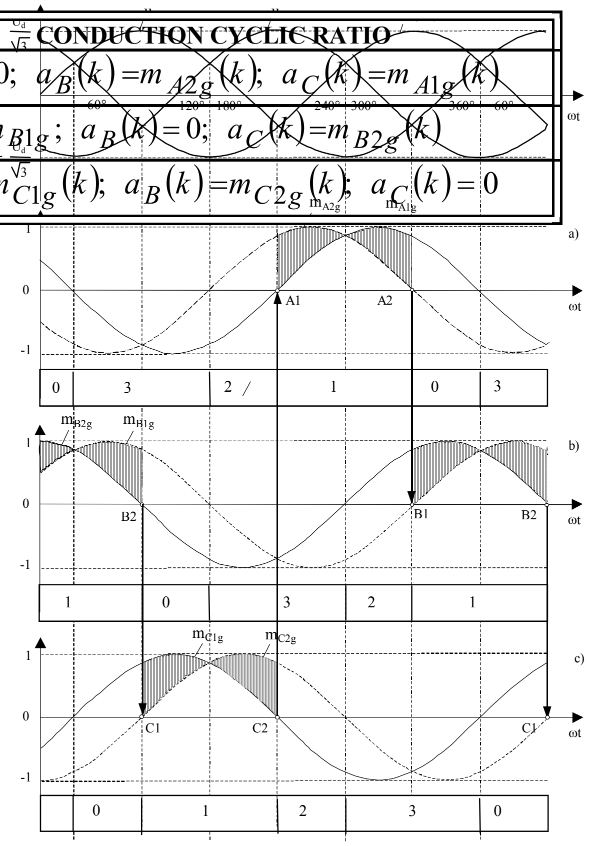


Fig.7 Commutation generating function in the DPWM3 strategy case

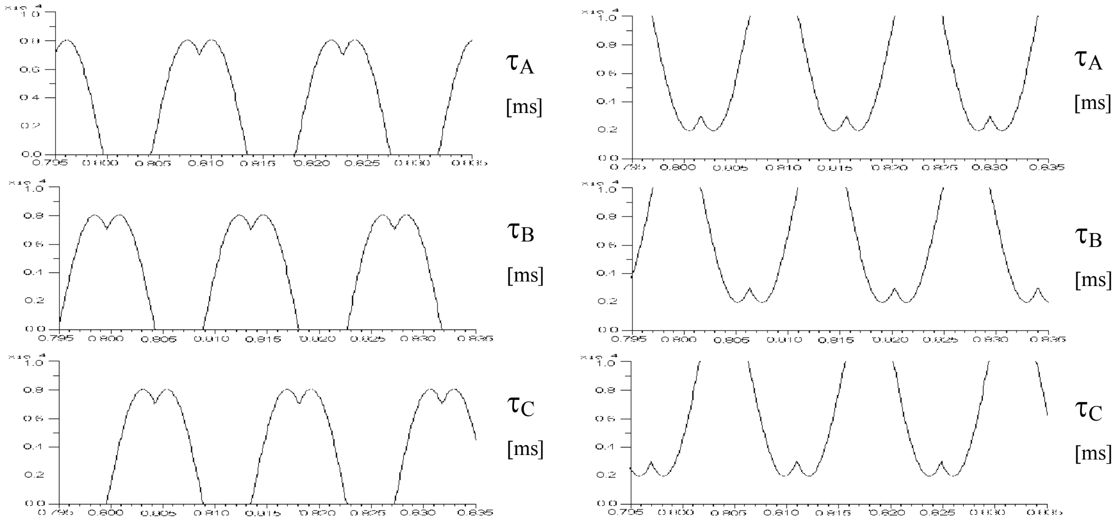
The advantages that characterize DPWM3 & DPWM4 are as follows:

- the control impulses are centered;
- the computation time of the conduction cyclical ratios is reduced; only 2 multiplications and 2 additions are necessary for one control sequence;
- the switching losses are reduced by 33% comparatively with CPWM.

The switching losses depend mainly on the switched current and for case of DPWM methods are significantly influenced by the modulation method and load power factor [4].

The disadvantage of these DPWM3 & DPWM4 methods is that the switching losses are not the same for all switches.

The presented modulation offers an important advantage from the standpoint of real time implementation with microcontroller systems; this advantage is the reduced computational time. All the DPWM algorithms can be easily and efficiently programmed into a microprocessor or a Digital Signal Processor (DSP) leading to a low cost, high performance drive. The only cost in realizing the optimal modulator is increased DSP software code and small increments in computational requirements. Thus, the algorithms are suitable over a wide range of applications where low cost, high performance, and high-energy efficiency are in demand.



a) b)

Fig.9 The switching cyclic ratios evolution for M=0,8 for a) MDID3; b)MDID4

3. CONCLUSION

The advantage of these methods is a very simple computation algorithm. An important advantage from the standpoint of the THD is offered by the DPWM1 control algorithm, for a modulation index great than 0.5 . For the case of converters operating with a unitary power factor, by using the DPWM2 strategy, switching losses can be reduced with 50%, in comparison to the case of a PWM control with continuous operation. The DPWM2 strategy offers the advantage that, in rotation, each of the legs stops switching when the reference phase voltage reaches maximum absolute value. The DPWM3 and DPWM4 are characterized by the simplest algorithm with respect to microprocessor implementation. Thus, only two multiplications and two additions are necessary for one control sequence under the assumption that the phase-to-ground reference voltages are available for control. Command pulses are centered during the *on* commutation period, making it possible to use standard peripherals of the count and compare types. For numerical simulation of the presented modulation techniques, the POSTMAC (Programme Ouvert de Simulation pour Test et l'Etude de Machine Asynchrone Commandée) software package has been used [9].

4. REFERENCES

1. Floricău, D.: "Metodă numerică de comandă pentru reducerea timpului de calcul a momentelor de comutație pentru un invertor trifazat de tensiune", Brevet Nr. 113508/17.09.1997, OSIM Bucureşti, 1997.
2. Floricău, D.: "Metodă de modulare discontinuă a impulsurilor în durată pentru convertoarele trifazate de tensiune", Brevet Nr. 114.953/28.08.1998, OSIM Bucureşti, 1998.
3. Floricău, D.; Fodor, D.; Hapiot, J.C.: "Two Axis Control Formalism for Three-phased Bridge Voltage Source Static Converters", Electromotion, Vol. 5, No. 1, 8-14, 1998.
4. Ahmet M.Hava, Thomas Lipo A.: "A High-Performance Generalized Discontinuous PWM Algorithm", IEEE, Vol 34 no5, Sept.1998
5. Floricău, D.: "Metodă de comandă pentru convertoarele trifazate mono şi multicelulare", Brevet Nr. 1092/12.10.1999, OSIM Bucureşti, 1999.
6. Floricău, D.; Hapiot, J.C.; Dumitrescu, M.: "Discontinuous command of the three-phase rectifiers with sinusoidal absorbtion" - Critical study, EEA, Vol.47, no.11-12, 1999.
7. Floricău, D, J.C.Hapiot: "Convertoare statice de putere: Structuri şi comenzi" Editura Printech, Bucureşti ISBN 973-652-248-2 (173 pg.), 2000.
8. Keliang Z., Danwei W.: "Relationship between Space Vector Modulation and Three Phase Carrier-Based PWM: a comprehensive analysis" IEEE Feb., 2002
9. Notice d'utilisation du logiciel POSTMAC. Licence CNRS/INPT, Laboratoire d'Electrotechnique et d'Electronique Industielle, Version 2.0, juin 1995