Multi-modulating Pattern - A Unified Carrier based PWM method In Multi-level Inverter - Part 2

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Abstract:

This paper presents a systematical approach to study carrier based PWM techniques (CPWM) in diode-clamped and cascade multilevel inverters by using a proposed named multi-modulating pattern method. This method is based on the vector correlation between CPWM and the space vector PWM (SVPWM) and applicable to both multilevel inverter topologies. A CPWM technique can be described in a general mathematical equation, and obtain the same outputs similarly as of the corresponding SVPWM. Control of the fundamental voltage, vector redundancies and phase redundancies in multilevel inverter can be formulated separately in the CPWM equation. The deduced CPWM can obtain the full vector redundancy control, and fully utilize phase redundancy in a cascade inverter.

In this continued part, it will be deduced correlation between CPWM equations in multi-carrier system and single carrier system, present the mathematical model of voltage source inverter related to the common mode voltage and propose a general algorithm for multi-modulating modulator. The obtained theory will be demonstrated by simulation results..

Introduction

Recently, it has been introduced phased shift disposition CPWM (PSD PWM) for multi-level inverter. However, this method is not equivalent to the SVPWM. In this part, it will show that a multi-modulating system, which has been derived based on the SVPWM-CPWM correlation can be converted into the CPWM technique using only one carrier waveform. It can be seen that the multi-carrier and single-carrier techniques in multi-modulating system are only two equivalent implementing variants of multi-modulating system. And they can be simply converted each other. This continued part will present the correlation between the multi-modulating systems. It shows that carrier PWM methods can be described systematically by a unified algorithm. For voltage source multilevel inverter, the effective zero sequence function can represent the SVPWM attributes and become a proper reference input.

3.3 The correlation between the multi-carrier multi-modulating system and the single carrier multi-modulating system

From the mathematical formulation of a full multi-carrier MMS CPWM, each modulating signal is modulated within one carrier wave. The same results would be obtained by a vertical shifting of the carrier waves and modulating signals to the standard carrier wave (0,1). The standard carrier wave will be enough to implement a MMS CPWM. A practical implementation could be simpler. The deduced system is called as single carrier multi-modulating system.

Let's rewrite a PMMP in a summation form as

$$\left[\vec{Q}_{xjk}\right]=\begin{bmatrix} Q_{ajk1}\, Q_{ajk2} \cdot\cdot Q_{ajk,p} \\ Q_{bjk1}\, Q_{bjk2} \cdot\cdot Q_{bjk,p} \\ Q_{cjk1}\, Q_{cjk2} \cdot\cdot Q_{cjk,p} \end{bmatrix}=\begin{bmatrix} Q_{10}\, Q_{20} \cdot\cdot Q_{p0} \\ Q_{10}\, Q_{20} \cdot\cdot Q_{p0} \\ Q_{10}\, Q_{20} \cdot\cdot Q_{p0} \end{bmatrix}+\begin{bmatrix} Q'_{ajk1}\, Q'_{ajk2} \cdot\cdot Q'_{ajk,p} \\ Q'_{bjk1}\, Q'_{bjk2} \cdot\cdot Q'_{bjk,p} \\ Q'_{cjk1}\, Q'_{cjk2} \cdot\cdot Q'_{cjk,p} \end{bmatrix}$$

$$=\left[\vec{Q}_0\right]+\left[\vec{Q}'_{jk}\right]$$

$$j=1,2,3\,;k=0,1,2,\ldots,l_{rj} \qquad (28)$$

where Q_{j0} are constants, $0 \le Q'_{ajk} \le 1$, $0 \le Q'_{bjk} \le 1$ and $0 \le Q'_{cjk} \le 1$. By substituting (28) into (26) and using (2),(8) [13], the result can be obtained as follows:

$$\left[\vec{v}_r\right]=\left[\vec{Q}_0\right]+\sum_{j=1}^{3}K_1.\left(\xi_{j0}.\left[\vec{Q}'_{j0}\right]+\xi_{j1}.\left[\vec{Q}'_{j1}\right]+\xi_{j2}.\left[\vec{Q}'_{j2}\right]+\ldots+\xi_{j,lrj}.\left[\vec{Q}'_{j,lrj}\right]\right) \qquad (29)$$

By subtracting the original reference modulating signals $[\vec{v}_r]$ by a constant matrix $[\vec{Q}_0]$, a new CPWM equation, which describes the single carrier MMS can be obtained as follows:

$$\left[\vec{v}'_r\right]=\sum_{j=1}^{3}K_1.\left(\xi_{j0}.\left[\vec{Q}'_{j0}\right]+\xi_{j1}.\left[\vec{Q}'_{j1}\right]+\xi_{j2}.\left[\vec{Q}'_{j2}\right]+\ldots+\xi_{j,lrj}.\left[\vec{Q}'_{j,lrj}\right]\right) \qquad (30)$$

where each element of the reference matrix varies in the range of (0,1) as $0 \le v'_{rat} \le 1$, $0 \le v'_{rbt} \le 1$ and $0 \le v'_{rct} \le 1$, $t=1,2,\ldots,p$.

In the previous example of five-level inverter [13], the constant matrix is determined as

$$\left[\vec{Q}_0\right]=\begin{bmatrix} Q_{10}\; Q_{20}\; Q_{30}\; Q_{40} \\ Q_{10}\; Q_{20}\; Q_{30}\; Q_{40} \\ Q_{10}\; Q_{20}\; Q_{30}\; Q_{40} \end{bmatrix}=\begin{bmatrix} 1\,0-1-2 \\ 1\,0-1-2 \\ 1\,0-1-2 \end{bmatrix}.$$

The $PMMP$s of the single carrier MMS for diode-clamped and cascade inverters can be rewritten as shown in tables 6 and 7. All $PMMP$s are described in a sequence of two digit numbers of 0 and 1. As a result, the algorithm (30) in tables 6 and 7 for generating $PMMP$ from PMP can be derived considerably easily in comparison with the generating PMMP of the multi-carrier described in [13]. The procedure of producing a MMP in a single carrier MMS is applicable to a higher level inverter and shown in table 8. The diagrams in fig.8 describe the A-phase modulating signals of the single carrier system, which implements three switching states $\vec{U}_{10},\vec{U}_{20},\vec{U}_{30}$ ($\xi_{10}=\xi_{20}=\xi_{30}=1$).

Table 6. Components of *MMP* in five-level diode clamped inverter with single carrier full modulating system					
PMP	-2	-1	0	1	2
PMMP	(0,0 ,0,0	(0,0,0,1)	(0,0,1,1)	(01,1,1)	(1,1,1,1)

Table 7. Components of *MMP* in five-level cascade inverter with single carrier full modulating system					
PMP	-2	-1	0	1	2
PMMP	(0,0 ,0,0)	(1,0,0,0) (0,1,0,0) (0,0,1,0) (0,0,0,1)	(0,1,0,1) (1,0,1,0) (1,0,0,1) (1,1,0,0) (0,1,1,0) (0,0,1,1)	(1,0,1,1) (1,1,0,1) (1,1,1,0) (01,1,1)	(1,1,1,1)
set 1	0,0, 0,0	(1,0,0,0)	(1,1,0,0)	(1,1,1,0)	(1,1,1,1)
Set 2	0,0, 0,0	(1,0,0,0)	(1,0,1,0)	(1,1,1,0)	(1,1,1,1)

Similarly, by setting $\xi_{10}=\xi_{20}=\xi_{30}=\xi_{11}=\xi_{21}=\xi_{31}=0.5$, six voltage vectors $\vec{U}_{10},\vec{U}_{20},\vec{U}_{30},\vec{U}_{11},\vec{U}_{21},\vec{U}_{31}$ will be involved in a switching sequence. The corresponding A-,B- and C-phase modulating signals are drawn in fig.9.

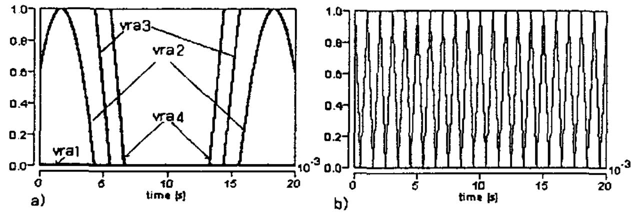

Figure 8: The single carrier multi-modulating system: Diagrams of the A-phase modulating signal set and the standard carrier wave.

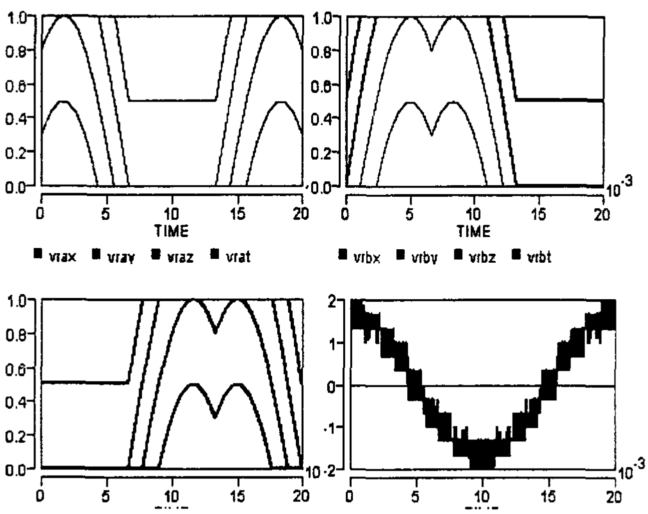

Figure 9: Five-level inverter: The single carrier multi-modulating system and PWM with six-switching states : the modulating signal sets of A-,B- and C- phases and the A-phase voltage.

3.4 Algorithm for producing multi-modulating signals

The results described in a digit form using numbers of 1 and 0 remind of states ON/OFF of switching pairs. Elements of the matrix $\vec{Q}_{jr}$ can be considered as switching states for performing the corresponding phase output and therefore a term S can be used to indicate this switching matrix. The MP will present as the address for switch state data. Modulating signals in a multi-modulating system can be expressed as a time integration of switching states as

$$[\vec{v}_r]=\sum_{j=1}^{3}K_j\left(\xi_{j0}[\vec{S}_{j0}]+\xi_{j1}[\vec{S}_{j1}]+\xi_{j2}[\vec{S}_{j2}]+\ldots+\xi_{j,lrj}[\vec{S}_{j,lrj}]\right) \quad (31)$$

If in (31), some states disappear, their corresponding time durations will be equal to zeros ($K_j.\xi_{ji}=0$), $t=1,2,..,p$. In the single carrier MMS, each individual modulating signal v_{rxt}, which corresponds to switching pair S_{xt} can be generated by a time integration of switch states or in a mathematical formula as

$$v_{rxt}=\sum_{j=1}^{3}\sum_{N=0}^{lrj}\frac{T_{jN}}{T_S}.S_{xtjN} \quad (32)$$

where parameter S_{xtjN} expresses the switch state (0 or 1) during a time duration interval T_{jN}, $T_{jN}=K_j.\xi_{jN}$. From set of PMMP shown in table 6, the state of switching pair will change from OFF to ON only once while phase voltage increases its value in half of sampling period and the equation (32) can be rewritten in the familiar form of CPWM technique as

$$v_{rxt}=\frac{T_{ON}}{T_S} \quad (33)$$

where T_{ON} is on-time duration of the switch S_{xt}.

Each modulating signal is proportional to on-time duration T_{ON} of the corresponding switching pair.

Table 8. Components of *MMP* in n-level diode clamped inverter with single carrier (n-1) modulating system				
PMP	-(n-1)/2	-(n-3)/2	-(n-5)/2	-(n-7)/2
PMMP	0,0,0,...0	0,0,0,...1	0,0,..1,1	0...1,1,1
PMP			(n-3)/2	(n-1)/2
PMMP			0,1,...,1,1	1,1,....,1,1
Total : one PMMP set for *diode clamped inverter* and (n-1)! PMMP sets for *cascade inverter*				

The described single carrier MMS and corresponding multi-carrier MMS are only two function-equally variants of a full MMS. In cascade inverter, the MMS gives a full controlling of phase redundancies i.e. switching pairs. In diode-clamped inverter, the full control of vector redundancies gives a flexible control of currents, which charges and discharges the dc capacitors at the splitting points, and influences on the balancing of the dc voltage sources. This would require further circuit analysis.

It can be seen that the single carrier MMS would be appropriately the most advantageous solution for controlling multilevel inverters. The transformation from a multi-carrier MMS into single carrier MMS or vice verse can be implemented only with the full modulating system. If the number of modulating signals per phase is less than (n-1), some modulating signal will control more than one switching pair, and the number of carrier waves will be more than one. The approach, which has been introduced for performing a PMMP in multi-carrier and multi-modulating system, can be used as a general rule.

***The proposed algorithm for generating modulating signals** as shown in fig. 10 is as follows:*

1. To determine parameters K_1, K_2, K_3. The demand on the fundamental voltage is described in the first block, which determines parameters K_1, K_2 and K_3.

2. To determine redundant parameters ξ_{jk} and corresponding MPs from the vector redundancy analysis. This algorithm will depend on the individual practical purpose. Parameters ξ_{jk} can be properly deduced from the required effective zero sequence function [8].

3. To transfer the *PMP* s to corresponding *PMMP* s using table 4/6 (a diode clamped type) and control phase redundancies by selecting PMMP in table 5/7 (a cascade type). The third block, which selects and sends the *PMMP* s $\bar{Q}_{jk}$ to the modulating generator, will solve the phase redundancy problem. The *PMMP* s can be stored in a look-up table or generated by some deduced algorithm. For diode-clamped inverter, there is only one set of *PMMP* s in this block, each element of PMMP can be derived directly (without using table) as follows:

$$Q_{xjkr} = \begin{cases} 1 & if \quad P_{xjk} \geq (\frac{n+1}{2} - r) \\ 0 & if \quad else \end{cases} ; \; j = 1,2,3 ; \; r = 1,2,..,p \quad (34)$$

Other *PMMP* sets for cascade inverter can be obtained similarly.

4. To generate modulating functions using (26)/(30).

There are only simple operators used in the calculating process. For the SMS, the MMP and MP are identical and step 3 will be avoided.

Effective zero sequence function

From the previous investigation, it can be seen that voltage source inverter can be considered as a complex source, consisting of active voltages in series with zero sequence component. The active voltage components can be determined from the vector location in vector diagram. The zero sequence component is related to the values of redundant coefficients.

For the described SMS, the zero sequence function is given as

$$v_{r0} = P_{min} - \min + \eta_1.K_1 + \eta_2 K_2 + \eta_3 K_3 \quad (35)$$

In multi-carrier MMS, the zero sequence function loses its meaning. The effective zero sequence function v_{r0}, which is related to the zero sequence voltage v_0 can be introduced and derived from the redundant coefficients as follows:

$$v_{r0} = P_{min} - \min + \sum_{j=1}^{3} K_j.(\xi_{j1} + 2.\xi_{j2} + ... + l_{rj}.\xi_{j,lrj}) \quad (36)$$

$$v_0 = v_{r0}.V_{dc}/(n-1) \quad (37)$$

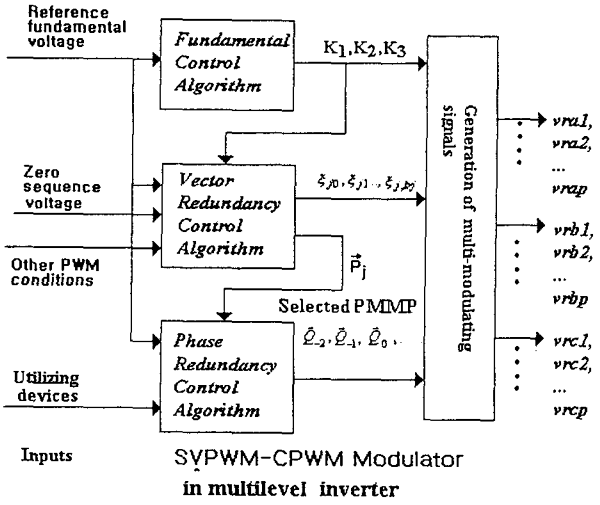

Figure 10: Multilevel inverter: Decomposition of SVPWM-CPWM modulator into three components.

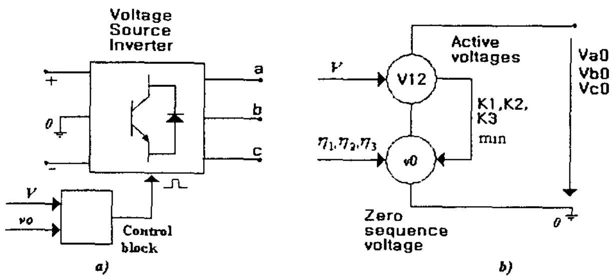

Figure 11: Voltage source inverter and its equivalent three phase source (SMS) with fundamental and zero sequence components controllable.

Since the single carrier MMS has the same output voltages as of the multi-carrier MMS, for both cases, the zero sequence function (36) is applicable.

The limited values of related zero sequence voltage are determined as follows:

$$v_{0\max} = V_{dc}/2 - V_{dc}.\max/(n-1) \quad (38)$$

for $\xi_{j,lrj} = 1$, $j = 1,2,3$ and $\xi_{j,r} = 0$ $r = 0,1,..,(l_{rj} - 1)$

$$v_{0\min} = -V_{dc}/2 - V_{dc}.\min/(n-1) \quad (39)$$

for $\xi_{j0} = 1$, $j = 1,2,3$ and $\xi_{j,r} = 0$ $r = 1,..,l_{rj}$

In the contrary, if there is known the required zero sequence function, redundant coefficients could be determined. For single-modulating PWM, a simple algorithm to determine redundant factors has been introduced in [8]. In multi-modulating PWM, depending on reference zero sequence voltage, there may exist more than one redundant coefficient set capable of producing the same zero sequence function. To fix the values of redundant coefficients, it is required to add some more conditions. This problem will be demonstrated in the following examples.

4. Examples, simulation results

Example 1: To generate multi-modulating signals in single carrier PWM for a diode clamped five level inverter which implements the smallest effective zero sequence function and m=0.75.

This corresponds to a discontinuous PWM mode. The smallest zero sequence function $v_{r0\min}$ can be obtained with following setting as

$$\xi_{10} = \xi_{20} = \xi_{30} = 1 \text{ and } \xi_{jk} = 0 \text{ for k>0}$$

$$v_{r0\min} = P_{\min} - \min$$

The CPWM equation will be

$$[\vec{v}_r] = K_1 \cdot \lfloor \vec{Q}_{10} \rfloor + K_2 \cdot \lfloor \vec{Q}_{20} \rfloor + K_3 \cdot \lfloor \vec{Q}_{30} \rfloor$$

The parameters K_1, K_2 and K_3 can be determined by using (4) and (5) [13]. To determine the patterns $\lfloor \vec{Q}_{10} \rfloor, \lfloor \vec{Q}_{20} \rfloor$ and $\lfloor \vec{Q}_{30} \rfloor$, firstly it is required to calculate the ZRC MP $\vec{P}_{10}, \vec{P}_{20}$ and $\vec{P}_{30}$ (see eq. (12) [13]).

From the obtained parameters P_{xj0}, each element of the patterns $\lfloor \vec{Q}_{10} \rfloor, \lfloor \vec{Q}_{20} \rfloor$ and $\lfloor \vec{Q}_{30} \rfloor$ can be derived from table 6 as follows:

$$Q_{xj0r} = \begin{cases} 1 & if \quad P_{xj0} \geq (3-r) \\ 0 & if \quad else \end{cases} \quad ; \begin{array}{l} x = a,b,c \\ j = 1,2,3 \\ r = 1,2,3,4 \end{array}$$

For instance: a) $P_{xj0} = -2 \Rightarrow Q_{xj01} = \ldots = Q_{xj04} = 0$;

b) $P_{xj0} = 0 \Rightarrow Q_{xj03} = Q_{xj04} = 1$ and $Q_{xj01} = Q_{xj02} = 0$.. The diagrams of modulating signals have been demonstrated in fig.8.

Example 2: To generate multi-modulating signals in multi-carrier PWM for a five level inverter, which implement the SVPWM with the smallest effective zero sequence function and m=0.75.

This corresponds to a continuous PWM mode, in which two active redundant vectors are equally centered. To perform the smallest possible zero sequence function, it is required

$$\xi_{10} = \xi_{11} = 0.5, \xi_{20} = \xi_{30} = 1$$

Other parameters are zeros.

$$[\vec{v}_r] = 0.5xK_1 \cdot (\lfloor \vec{Q}_{10} \rfloor + \lfloor \vec{Q}_{11} \rfloor) + K_2 \cdot \lfloor \vec{Q}_{20} \rfloor + K_3 \cdot \lfloor \vec{Q}_{30} \rfloor$$

The MP $\vec{P}_{11}$ can be determined using equation as

$$P_{xj} = P_{xj0} + N_j \Rightarrow \vec{P}_{11} = \vec{P}_{10} + \vec{I} \ ; (N_j = 1)$$

Four patterns $\lfloor \vec{Q}_{10} \rfloor, \lfloor \vec{Q}_{11} \rfloor, \lfloor \vec{Q}_{20} \rfloor$ and $\lfloor \vec{Q}_{30} \rfloor$ will be derived from corresponding patterns $\vec{P}_{10}, \vec{P}_{11}, \vec{P}_{20}$ and $\vec{P}_{30}$. By using the first PMMP set as (1,0,-1,-2), (1,0,-1,-1),(1,0,0,-1) (1,1,0,-1) and (2,1,0,-1) [13] and for m=1, the four reference modulating signals of the A-phase $v_{ra1}, v_{ra2}, v_{ra3}$ and v_{ra4}, the effective zero sequence function v_{r0} and output phase voltage v_a have been drawn in fig.5 [13]. The obtained effective zero sequence function v_{r0Cent} can be determined as

$$v_{r0Cent} = P_{\min} - \min + 0.5xK_1.$$

Example 3:

The described multi-modulating theory for obtaining a large number of switching states can be illustrated for a three-level inverter. For three-level inverter, a full MMS has p=2. Let's define two carrier system with three level equal to -1,0 and 1. It is required

a) to obtain the medium zero sequence voltage [8] as

$$v_{r0,mid} = \frac{v_{r0\max} + v_{r0\min}}{2} = p_{\min} - \min + \frac{l_{r1}}{2}.K_1 + \frac{l_{r2}}{2}.K_2 + \frac{l_{r3}}{2}.K_3$$

b) the equally-centered active redundant vectors always happen at the dashed circles as shown in fig.12. There are 5/4/5 switching states for corresponding areas 1/2 (or 4)/ 3, respectively.

The redundant parameters are derived as follows:

Case 1: For $l_{r1} = 2$ and $l_{r2} = l_{r3} = 1$ (Area 1):

$$v_{r0,mid} = p_{\min} - \min + K_1 + 0.5.K_2 + 0.5.K_3$$

$\Rightarrow \xi_{10} = 0$, $\xi_{11} = 1$, $\xi_{20} = \xi_{21} = 0.5$ and $\xi_{30} = \xi_{31} = 0.5$

$$[\vec{v}_r] = K_1 \cdot \lfloor \vec{Q}_{11} \rfloor + 0.5xK_2(\lfloor \vec{Q}_{20} \rfloor + \lfloor \vec{Q}_{21} \rfloor) + 0.5xK_3 \cdot (\lfloor \vec{Q}_{30} \rfloor + \lfloor \vec{Q}_{31} \rfloor)$$

Case 2: For $l_{r1} = 1$ and $l_{r2} = l_{r3} = 0$ (Area 2,4):

$$v_{r0,mid} = p_{\min} - \min + 0.5.K_1$$

$$\Rightarrow \xi_{10} = \xi_{11} = 0.5, \xi_{20} = 1 \text{ and } \xi_{30} = 1$$

$$[\vec{v}_r] = 0.5xK_1 \cdot (\lfloor \vec{Q}_{10} \rfloor + \lfloor \vec{Q}_{11} \rfloor) + K_2 \lfloor \vec{Q}_{20} \rfloor + K_3 \cdot \lfloor \vec{Q}_{30} \rfloor$$

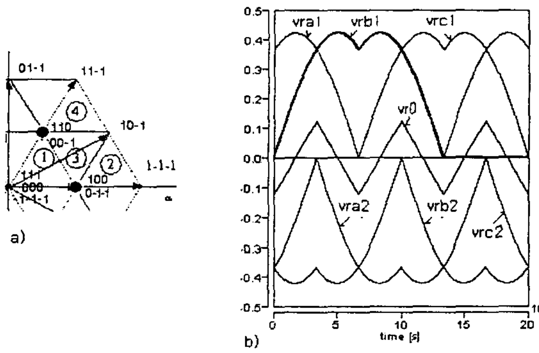

Figure 12:: Three-level inverter: diagrams of a) the locations of active redundant vectors (dashed circles) in the first sector and b) A-,B- and C- phase modulating signals and effective zero sequence function.

Case 3: For $l_{r3} = 0$ and $l_{r1} = l_{r2} = 1$ (Area 3):

$$v_{r0,mid} = p_{\min} - \min + 0.5.K_1 + 0.5.K_2$$

$\Rightarrow \xi_{10} = \xi_{11} = 0.5, \xi_{20} = \xi_{21} = 0.5$ and $\xi_{30} = 1$, and

$[\vec{v}_r]=K_1.(\lfloor\vec{Q}_{10}\rfloor+\lfloor\vec{Q}_{11}\rfloor)+0.5xK_2(\lfloor\vec{Q}_{20}\rfloor+\lfloor\vec{Q}_{21}\rfloor)+K_3.\lfloor\vec{Q}_{30}\rfloor$. The PMMP can be derived for multi-modulating system in table 9 (or single modulating system).

Determination of the MP:

For instance, in case 1:

$\Rightarrow \xi_{10}=0$, $\xi_{11}=1$, $\xi_{20}=\xi_{21}=0.5$ and $\xi_{30}=\xi_{31}=0.5$

$$P_{x11}=P_{x10}+1\,;P_{x21}=P_{x20}+1\,;P_{x31}=P_{x30}+1$$

Table 9. Phase multi-modulating pattern ($PMMP$) for a three-level diode-clamped inverter with two- carrier two-modulating system ($P_{min}=-1$)

PMP	-1	0	1
($PMMP$)-set 1	(0,-1)	(0,0)	(1,0)
($PMMP$) –set 2, (cascade type)	(0,-1)	(1,-1)	(1,0)

Determination of the MMP: From the obtained vector MP, the corresponding MMP can be derived from the table 9 (two-carrier).

If the first PMMP set in table 9 is selected, element of PMMP can be described as follows:

$$Q_{xjk1}=\begin{cases}1 & if \quad P_{xjk}=1\\ 0 & if \quad else\end{cases}$$

$$Q_{xjk2}=\begin{cases}-1 & if \quad P_{xjk}=-1\\ 0 & if \quad else\end{cases}$$

In simulation, the first PMMP set in table 9 has been selected. The diagrams of three sets of the A-,B- and C-phase modulating signals $v_{ra1}, v_{ra2}, v_{rb1}, v_{rb2}$ and v_{rc1}, v_{rc2} are drawn in fig.13. The deduced effective zero sequence function v_{r0} is also shown, its waveform obtains exactly the proposed medium common mode voltage.

5. Conclusions

In the paper, it has been formulated a complete mathematical description of the CPWM methods of multi-carrier MMS, which realize SVPWM in the smallest triangle area in both diode-clamped and cascade inverters. The CPWM equations are described based on the modulating patterns. Normally, a single modulating system (with multi-carrier) can be used to control both cascade and diode-clamped inverter. This system is advantageous for its simple modulating signals. The vector redundancy can be controlled by the corresponding factors in the zero sequence function. The disadvantage caused by a limited number of switching states in a half sampling period confines the capability of diode-clamped inverter. Another problem is the systematical utilizing of the phase redundancies in a cascade inverter.

The full MMS shows a complete solution of multilevel inverter. It provides for multilevel inverters with full controlling of both vector redundancies (ex. for controlling of dc potentials in diode clamped inverter) and phase redundancies (for cascade inverter). There are two function-equivalently variants of a full MMS: the multi-carrier MMS and the single-carrier MMS, which can be alternately converted by a proper selection of the $PMMP$s and carrier wave systems. The single carrier MMS would be more convenient to be implemented for its simple CPWM algorithm.

The deduced CPWM equation and proposed algorithm are applicable to different CPWM methods for multi-level inverters. A reduced number of modulating signals for the purpose of simplification can be obtained by the algorithm in the exchange of a lower flexibility of vector redundancy and phase redundancy control.

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