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Modelling and analysis of modular multilevel voltage source converter using harmonic domain algebra

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ABSTRACT

The VSC technology is playing major roles in recent electrical power systems projects due to its many technical advantages over the more conventional power electronics technology based on conventional thyristors and its compact modular design. YSC harmonic generation, harmonic interactions and its impact on power systems, so far, have received limited attention; this is particularly the case in onshore and offshore Oil and Gas power systems. However, these systems are rich in harmonic distortion due to the control technique employed, and the harmonic interactions of the HVDC stations with upstream and downstream machinery. Addressing this gape a new modular multi-level converter model based on the PWM-unipolar technique is developed. Its harmonic performance is investigated under periodic steady state operating conditions for seven level, nine level, eleven level and seventeen level per arm taking proper account of the DC capacitor effect. The simulation results indicates that modular multi-level converters (MMC) are very flexible technology that is capable of generating multi-level output voltage waveforms, plus reducing larger amount of harmonic contents as the level of the output voltage waveforms increases with appropriate phase-shifting. The implementation of the new model is carried out in MATLAB.

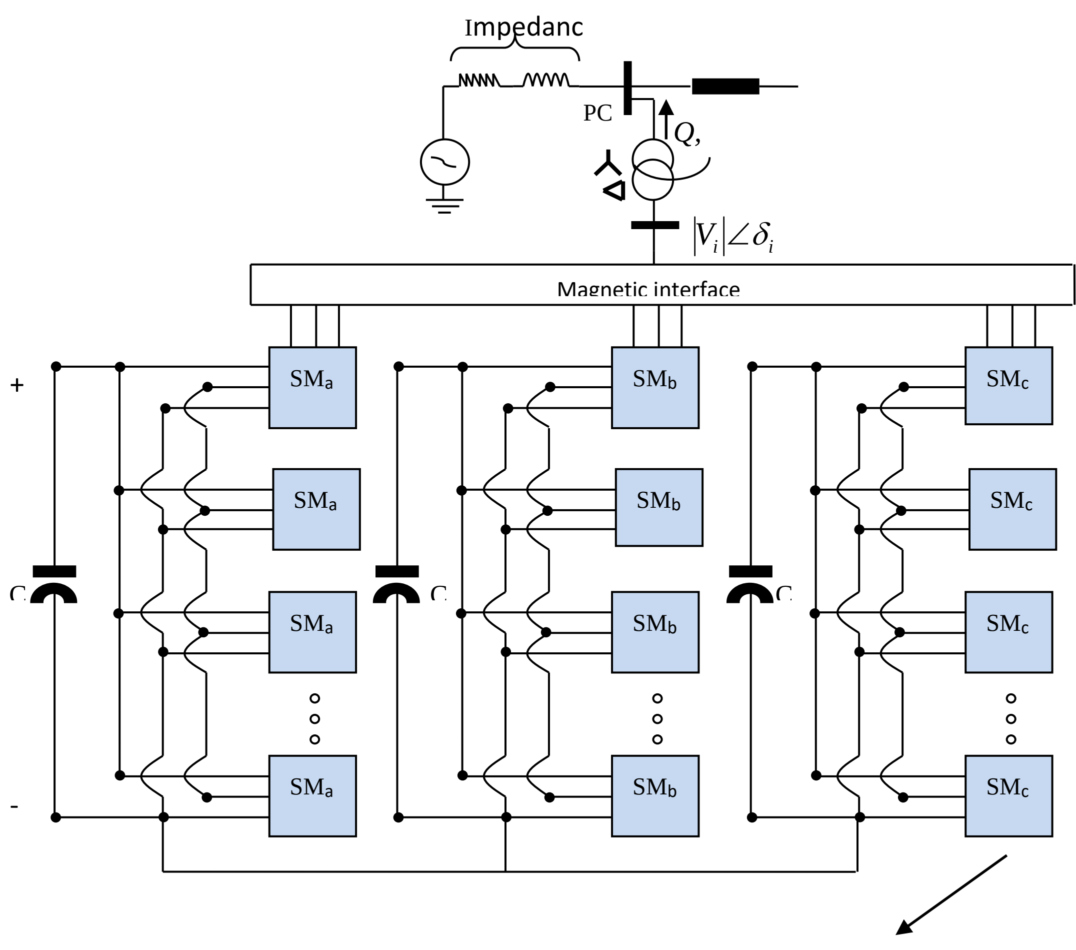
Keywords: modeling, analysis, modular multilevel, voltage source converter, harmonic domain algebra

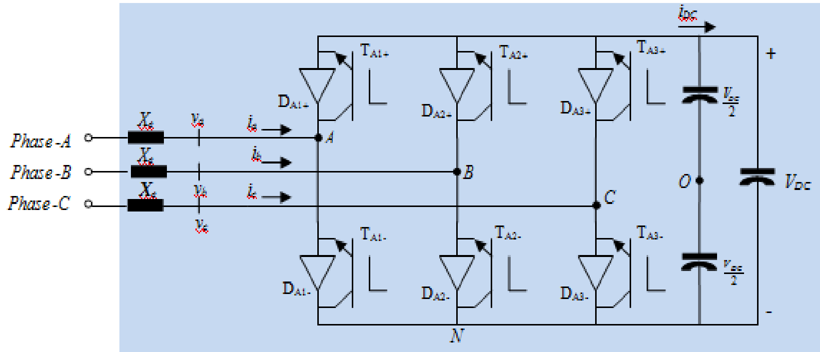
1. INTRODUCTION

Modular multilevel converters (MMC) belong to the LV family of multilevel VSC topology, owing to its structure and cascaded connection of VSCs sub modules (SM). The traditional topology of YSC H-bridge converter originate a new topology named MMC as depicted in Fig. I, it has the capability of generating higher multi-level output voltage waveforms [1-5]. Each submodule consists of three legs similar to the conventional three-phase VSC, which is minimum power unit of MMC. In which D_{A1+}, D_{AI-}, D_{A2+}, D_{A2-}, D_{A3+}, and D_{A3-} are the diodes of IGBTs [6]. This IGBT valve consists of IGBT module with its freewheeling diode (FWD) and auxiliary's snubber circuit. The SM is aimed at increasing the output voltage waveforms level, which can be termed as the expansion of three phase IGBT module [7-9]. The MMC valves are pleasant in generating high voltage level as well as controllable harmonic. Thus, the sophisticated model open door for more reduction of harmonics with proper phase-shilling compared to conventional VSCs [10].

The new MMC converters are suitable for connecting either in series or in parallel an AC grid with renewable energy sources. In addition, is appropriate for harmonic cancellation, and therefore the need for a filter equipment is eliminated [11]. An important issue of this topology is that it generates a high voltage waveform using low voltage devices and reduction of harmonic contents. MMC are more energy driven compare to two-level VSC converters due to its ability to accommodate hundreds of converter submodules [12]. Most of the MMC presented in the open literature are designed using two- terminal device. In that, its capacitors values must be sufficiently large enough to ensure voltage potential remains constant under operational condition [13]. As a result not all odd harmonics are cancelled and the rms values of the output voltage waveform at fundamental frequency are not controlled adequately. Consequently, a new modular multilevel converter coupled with three-terminal full-bridge submodule, which is capable of generating more than nine level output voltage waveforms with reduction of all harmonics is presented [14]. The developed MMC is based on solid state VSC, which enable independent, fast control of active and reactive powers with high harmonics reduction and ripple cancellation [15].

The new MMC is viewed to synthesize a multi-level output voltage waveforms with the fundamental component to sinusoidal reference [16]. The gating signals of the SM are controlled by PWM technique, of which there are two main categories, namely the carrier disposition method and the sub-harmonic method. In the former the carrier signals are shifted in magnitude, while in the latter the carrier signal are shifted in phase The aforementioned features bring forward that the configured MMC can be harmonically analyzed using phase shifted PWM technique [17-18]. The proposed MMC in this paper can accommodate 306 submodules made of IGBTs switches, cascaded series connected and in phase to produce dc operating voltage. With this arrangement the DC link capacitor is eliminated and balancing of capacitor voltages are achieved with ease, as such the MMC has a direct and fast control of the DC link voltage. The system has significant lower switching losses compared to VSCs conventional topology and the probability of dc bus short circuits is reduced [19-21].





(a) Sub-Module[SM]

Fig. 1. Modular Multi-Level Three PWM-VSC

2. DESIGN OF THE DC CAPACITOR VOLTAGE

The voltage in the DC side of the VSC is given by the voltage in the capacitor as a function of the switching functions, given by the equation

$$v_{dc}(t) = v_{cap}(t) = \frac{1}{C}\int_0^1 i_{cap}(t)dt + v_{cap}(0^+) \quad (1)$$

Where;

$$v_{cap}(0^+)\frac{1}{C}\int_0^1 i_{cap}(t)dt \quad (2)$$

which is the voltage evaluated at t= 0+ due to charging from an earlier period. The steady state changes in the instantaneous power absorbed by the Load, generate voltage fluctuations across the dc capacitor. For this reason the voltage across the de capacitor produces a little harmonic distortion. The magnitude of these voltage fluctuations can be controlled effectively with an appropriate de capacitor value.

$$C = \frac{1}{C}\int_0^1 i_{cap}(t)dt \quad (3)$$

Equation (3) represents the value of the dc capacitor C that will maintain the dc voltage above harmonic distortion.
The line voltages on the AC side and on the DC side are related to each other by:

$$v_{ab}(t) = S_{ab}(t)v_{dc}(t) \quad (4)$$
$$v_{bc}(t) = S_{bc}(t)v_{dc}(t) \quad (5)$$
$$v_{ca}(t) = S_{ca}(t)v_{dc}(t) \quad (6)$$

In harmonic domain Equ. 2.1 may be express as

$$V_{cap} = V_{dc} = \frac{1}{C}D^{-1}(jh\omega_0)I_{dc} + E_{dc} \quad (7)$$
$$E_{dc} = [0 \ldots 0 \; v_{cap}(0^+) \; 0 \ldots 0\,]^T \quad (8)$$

It should be noted here that V_{cap} is coupled with the harmonic content of $v_{dc}(t)$, also vector I_{dc} contains the harmonic content of $i_{dc}(t)$.

The state of the load voltages in terms of the active switches and the dc link voltages are given as follows

$$V_{Labc} = S_{abc}V_{dc} \quad (9)$$

Where;

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$$S_{abc} = \begin{bmatrix} SMa1SMa2SMa3 \cdots SMan \\ SMb1SMb2SMb3 \cdots SMbn \\ SMc1SMc2SMc3 \cdots SMcn \end{bmatrix} \quad (10)$$

3. LOSS MODEL OF CONVERTER

The conduction pattern of the devices can be extracted for SM8, SM and SMcn PWM converters per phase. The conduction for phase A between the fundamental voltage and current can be achieved with proper phase shift of 120°. The conduction losses P0 on state in an IGBT switches can be obtained as,

$$P_{con} = \frac{1}{T}\int_0^T \vartheta_{on}(t)i(t)dt \; .. conduction\ loss\ in\ IGBT\ switches \quad (11)$$

$$T = \frac{1}{f} = 2\pi\sqrt{LC} \; .. Fudamental\ period \quad (12)$$

Where;

$$i(t) = load\ current$$
$$\vartheta_{on}(t) = on - state\ voltage\ drop$$

The transformation expression of the on-state voltage drop that is characterized by a dynamical resistance r0 and a constant voltage drop U0 is given as

$$P_{con} = \frac{1}{T}\int_0^T (U_0 + r_0 i_L(t)^{B_{con}}) i_L(t)dt \quad (13)$$

where

U_0 is the bias voltage

r_0 is the dynamical resistance

B_{con}, is the curve fitted constant

The switching losses can be measure by the simple equation as

$$E_{sw} = A_{sw}.\, i(t)^{B_{sw}} \quad (15)$$

where

E_{sw} is the switching energy loss

$A_{sw}B_{sw}$ is the curve fitting constants

Therefore the total power losses of the converter can be demonstrated as

$$P_{total} = P_{con} + E_{sw} \quad (16)$$

4. UNIPOLAR VOLTAGE SWITCHING WITH PWM

Unipolar PWM technique shown in Fig. 2 is PWM techniques, whose control principle is to compare a reference signal with triangular carrier signals. The reference signals are sinusoidal wave with frequency (f_r) and amplitude (U_r). At every point carrier is compared with the reference signal to generate PWM voltage waveform. Unipolar PWM has the ability of doubling the switching frequency which appears in the harmonic spectrum of the output voltage waveform, where the lowest harmonics surface as sidebands of double the switching frequency.

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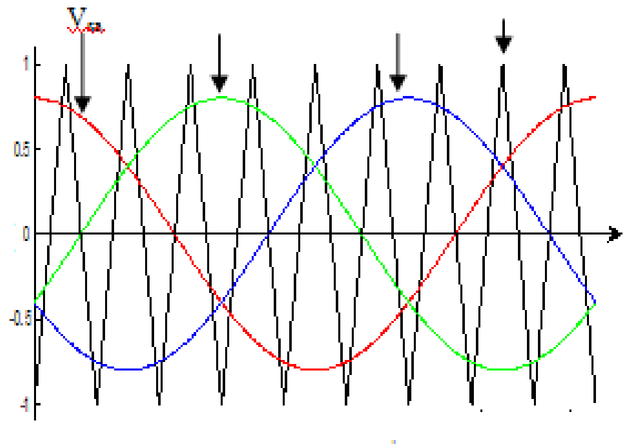

Fig. 2: Reference Signals and Carrier Signal

Effect of Transformer Phase-Shift in Modular Converter

Phase-shift transformers play important roles in the harmonic domain analysis of large industrial power systems. The incorporation of these linear elements may results in lower order harmonic cancellation. The harmonic impedance is derived similarly to passive elements, by the following equation.

$$Z_t = R\sqrt{h} + jX_t h$$

where

R is derived from the transformer power losses, h is number of harmonic order to be cancelled and X_t is the transformers short-circuit reactance.

Dividing the secondary windings into two parts, plus connecting pairs of windings from separate phases in series represented in phasor form can achieved voltage phase shifting. As depicted in Fig. 3 the voltage ratios n_a, n_b, n_c are obtained from the phasor diagram. The voltage ratios are given by

$$n_a = \frac{|V_{pri}|}{|V_{sec}|}$$

$$n_b = n_a \frac{2}{\sqrt{3}} sin\left(\frac{\pi}{3} - \theta\right)$$

$$n_b = n_a \frac{2}{\sqrt{3}} sin(\theta)$$

Based on Euler's identity it can represented as

$$|A|e^{ja} = |A|cos\ \alpha + j|A| \sin \alpha$$

The sinusoidal voltage and current can be represented by

$$v(t) = |V| \cos(\omega_0 t + \theta_v) = |V|\Re\{e^{j\theta}{}_v e^{j\omega_0 t}\}$$

$$i(t) = |I|\cos(\omega_o t + \theta_i) = |I|\Re\{e^{j\theta_i} e^{j\omega_0 t}\}$$

The steady-state response of the passive elements are expressed as

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$$|V|\Re\{e^{j\theta_v}e^{j\omega_0 t}\} = R|I|\Re\{e^{j\theta_i}e^{j\omega_0 t}\}$$
$$|V|\Re\{e^{j\theta_v}e^{j\omega_0 t}\} = j\omega_0 L|I|\Re\{e^{j\theta_i}e^{j\omega_0 t}\}$$
$$|V|\Re\{e^{j\theta_v}e^{j\omega_0 t}\} = \frac{1}{j\omega_0 C}|I|\Re\{e^{j\theta_i}e^{j\omega_0 t}\}$$

5. FORMATION OF TRANSFER MATRICES IN HARMONIC DOMAIN

The phase voltages V_a (t), V_b(t) and V_c(t) on the primary side of the transformer in Fig. 1, are proportional to the line voltages on the secondary side. While the line currents i_a (t), i_b(t) and i_c(t) on the primary side of the transformer are proportional to the phase current.

The relationship between the line currents and the direct current, in the harmonic domain is given by

$$I_{dc} = S_{ab}I_a + S_{bc}I_b + S_{ca}I_c$$

The harmonic vectors of the phase voltage and the line currents are represented as

$$\mathbf{V_{abc}} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}, \quad \mathbf{I_{abc}} = \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

In harmonic domain non-linear function Z = Fm_w^{-1} V and complex vectors with entries which are complex conjugates around the DC harmonic entry, are determine in the complex Fourier harmonic domain X, Y, Z, V and W as

$$\mathbf{X} = \begin{bmatrix} \vdots \\ X_{-2} \\ X_{-1} \\ X_0 \\ X_1 \\ X_2 \\ \vdots \end{bmatrix}; \mathbf{Y} = \begin{bmatrix} \vdots \\ Y_{-2} \\ Y_{-1} \\ Y_0 \\ Y_1 \\ Y_2 \\ \vdots \end{bmatrix}; \mathbf{Z} = \begin{bmatrix} \vdots \\ Z_{-2} \\ Z_{-1} \\ Z_0 \\ Z_1 \\ Z_2 \\ \vdots \end{bmatrix}; \mathbf{W} = \begin{bmatrix} \vdots \\ W_{-2} \\ W_{-1} \\ W_0 \\ W_1 \\ W_2 \\ \vdots \end{bmatrix}$$

$$V = a_0X^0 + a_1X^1 + \cdots a_pX^p$$

And Fm which is the Hermitian Toepliz matrix containing harmonic contents to be eliminated is obtained as,

$$\mathbf{F_m} = \begin{bmatrix} W_0 & W_{-1} & W_{-2} & & & & \\ W_1 & W_0 & W_{-1} & W_{-2} & \ddots & & \\ W_2 & W_1 & W_0 & W_{-1} & W_{-2} & & \\ & W_2 & W_1 & W_0 & W_{-1} & W_{-2} & \\ & & W_2 & W_1 & W_0 & W_{-1} & W_{-2} \\ & \ddots & & W_2 & W_1 & W_0 & W_{-1} \\ & & & & W_2 & W_1 & W_0 \end{bmatrix}$$

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6. MODULATION SIGNAL V_m

The modulation signal using sinusoidal PWM (SPWM) is given as

$$V_m = V_{mm} sin\left(\omega t + \frac{\pi}{6}\right)$$

Although the SPWM wave has harmonics of several orders in the phase voltage waveform, the dominant ones other than the fundamental are of order n and n ± 2 where n = $\frac{f_c}{f_m}$

The firing angle α_k is obtained by

$$\alpha_k = msin\left(\alpha + \frac{\pi}{6}\right) + \frac{P}{\pi}\alpha - 2K + 1 = 0$$

Also, the extinction angle β_k

$$\beta_k = msin\left(\beta + \frac{\pi}{6}\right) + \frac{P}{\pi}\beta - 2K + 1 = 0$$

The PMW of the output voltage waveform is continuously modulated for the entire ac supply cycle in agreement to the magnitude of a modulating signal. Therefore, sinusoidal PWM (SPWM) scheme that correspond to the modulating signal is employed. This scheme can be operated at higher frequencies. The power semiconductor switches are IGBT; they are self-commutated with no requirement for forced commutation compared to the thyristors that must be force commutated. The switching instants are determined by comparing a triangular carrier signal V with a modulating signal v_m as shown in Fig. 2.

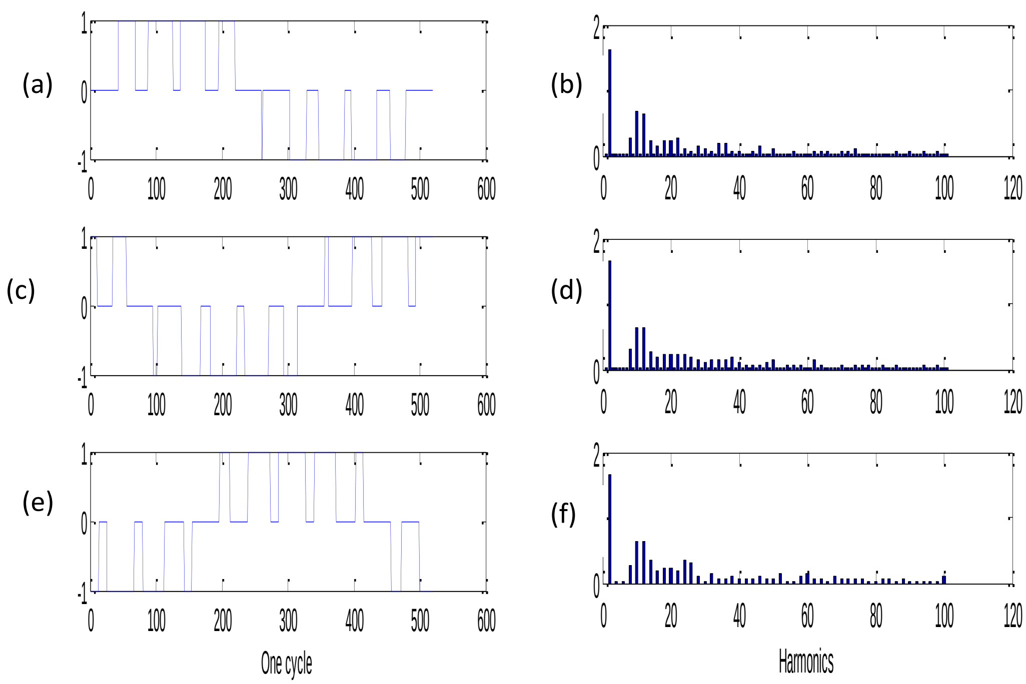

Fig. 3: Three-phase two Level PWM-Unipolar Converter (a, c, e) output voltage waveform per phase (b, d, f) harmonic spectrum

A one PWM-unipolar switch, using a signal carrier based control method with an average valve switching frequency of 1250 Hz, with no voltage ripple in the DC capacitor (ie an infinite capacitance) generate two level output voltage waveform as shown in Fig. 4(a,c,e), each waveform takes three values (V_{DC}, 0, - VDC) with 120° phase-shift between them. The harmonic spectrums of the system associated with the switching function of each converter leg are as presented in Fig. 4(b,d,f). Each phase-leg of the converter is connected through a star delta transformer to the AC systems. In order to improve the quality of the output waveform, the converter is typically controlled using PWM-Unipolar, this give rise to output waveform with a significant cancellation of low and high order harmonics as shown in five level generated by three SM, Fig. 5. When the waveforms are zero for each half of the period,

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they have a 600 interval between them and a total of 120° per period. The ratio of the amplitude of the sinusoidal waveforms with respect to the amplitude of the triangular wave produces the amplitude modulation ratio. A system in which the converter sources have impedance loads and antiparallel diode, in such a case the converter operates in all the four quadrants. Each leg can handle current in both directions at any time, since either the turned on switch or the antiparallel diode of the other switch can be the conducting element depending upon the polarity of the outputline current. The DC bus capacitor provides the required energy suchthat power flow can be controlled and DC harmonics carefully eliminated.

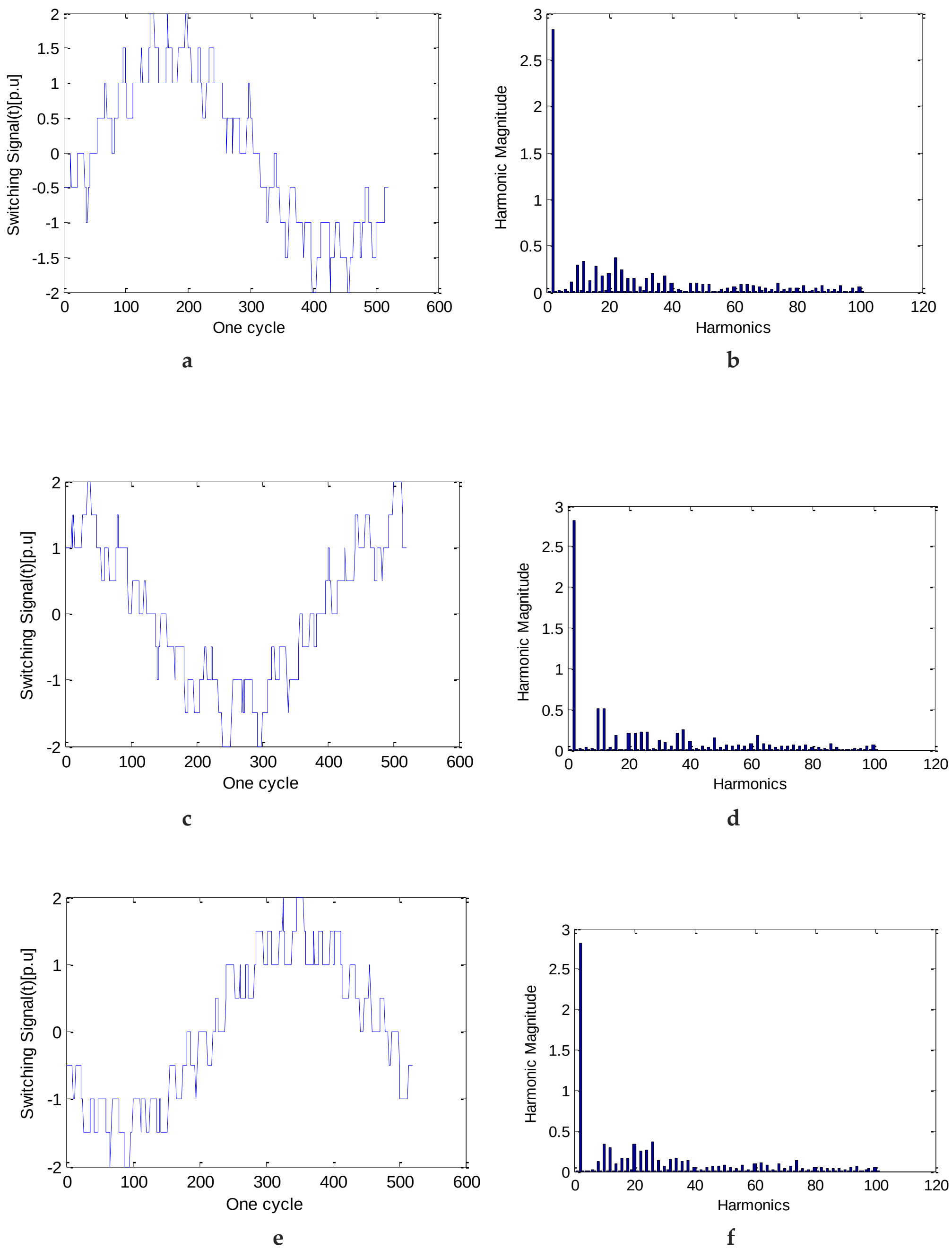

Fig. 4: Three-phase two Level PWM-Unipolar Converter (a, c, e) output voltage waveform per phase (b, d, f) harmonic spectrum

7. MULTI-LEVEL MODULAR VSC WITH PWM-UNIPOLAR

Using two or more SM with additional DC capacitors, a flexible three-phase cascaded H-bridge multilevel VSC is formed. This H-bridge converter is expanded to develop three legs per phase MMC connected to three-phase electromagnetic interface without any filter equipment as depicted in Fig. 1. As shown each arm is composed of three or more submodules with additional central capacitive energy storage at the DC side. The topology has the capability of generating voltage waveform above seven-level.

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With this configuration, the harmonic content of the output voltage is redu$|V_s| < \delta_s$cedand the harmonic elimination at the magnetic interface level can be achieved without increasing the switching frequencies in the PWM control system.

In this system under illustration, a phase-shifted carrier technique which enables harmonic cancellation is reached using phased-shifting transformer (PST). Phase shift transformer magnetically cancel lower order harmonics such as 5th and 7th, even if they are not equal in magnitude. PST is a useful tool for controlling active power flow as it offers easier modular design. The number of levels per phase half cycle of the switching function $s_m(t)$, is given by the frequency then modulation ratio m, m_6

$$m_f = \frac{f_r}{f_s}$$

where,

f_r triangular frequency

f_s sinusoidal

The harmonics occur as side bands of 2Inf and its integral multiple. The merit of unipolar switching over the bipolar switching is attributed to the frequencies of the harmonics which are doubled. This give rise in reduction in lower order harmonics and the harmonics generated by the voltage converter i are given by

$$h = 2jm_f \pm k \qquad where\ j.k = 1,2,3, \ldots$$

h are the harmonics of $S_m(t)$

The shifted angles for the cell sub-module (SM,) carrier signal are given by

$\delta_{ri} = 2\pi(i-1)/n_i$

The complex Fourier series where a periodical function $S(\omega t)$ with period of T_0 is given by

$$S(\omega t) = \sum_{n=-h}^{h} S_n e^{jn\omega_0 t}$$

The matrix representation of $S(\omega t)$ can be expressed as

$$S(\omega t) = G^T(t)$$

Using only h harmonics

$$G(t) = \begin{bmatrix} e^{-jh\omega_0 t} \\ \vdots \\ e^{-j\omega_0 t} \\ 1 \\ e^{j\omega_0 t} \\ \vdots \\ e^{jh\omega_0 t} \end{bmatrix}; S = \begin{bmatrix} X_{-h} \\ \vdots \\ X_{-1} \\ X_0 \\ X_1 \\ \vdots \\ X_h \end{bmatrix}$$

The vector G(t) is the orthogonal base of the Fourier series and S is a complex vector given by the coefficients of the series.

Where $\omega_0 = 2\pi/T_0$is the angular frequency in rad/s and S_n is the n-th harmonic coefficient of the series, and represented as

$$S_n = \frac{1}{T_0}\int_0^{T_0} S(\omega t)\, e^{-jh\omega_0 t} dt$$

where$S_{-n} = S_n^*$

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then magnitude of the harmonics are given as

$$S_{MMC} = \frac{SM1_h + SM2_h + SM3_h + \cdots + SMn_h}{ni}$$

the magnitude of the fundamental frequency component has a value of modulation index (m).

Modulation $(m) = \frac{A_m}{A_c}$

where: A_m is the sinusoid amplitude and A_c is the amplitude of the triangular carrier. It is desirable to note here that, controlling the modulation index also controls the amplitude of the applied output voltage. In sufficiently high carrier, the high frequency components do not propagate significantly in the ac network due the presence of the inductive elements. However, a higher carrier frequency dose results in larger number of switching per cycle with high power loss as a consequent.

8. SIMULATION RESULTS AND DISCUSSION

The modulation technique must be carefully determined in order to define the simulation model. Several modulation strategies exist, such as, adaptive modulation, optical modulation, coded-modulation, pulse width modulation and filter bank modulation. The choice of modulation has a great impact on the output voltage waveforms and harmonic spectrum. Other possibilities occurrences include converter power losses and voltage balancing.

The distortions of the voltage waveforms, harmonic losses in the power converter and the load are due to the operational nature in the switch mode. These bring forward the comparison of power qualities of the different output voltage levels using PWM method. The simulations of individual frequency components to a voltage waveform are expressed in a harmonic voltage spectrum, which give more detailed description than the output voltage waveform.

In practice harmonic analysis of the three arms in Fig. 1 could be done independently, therefore the remaining two arms need to be reenergized into starters operating condition (black start). In the following, a possible analysis of cancellation of harmonics per converter arm is simulated. Each submodule is holding to three-phase system through electromagnetic interface with relatively three values +v, 0, and -v.

Modelling the topology with four submodules series connected per phase as shown in Fig. I, with the use of insulated gate bipolar transistor (IOBT) as a switch and operate a switching control strategy known as pulse-width modulation (PWM) to fabricate output voltage waveforms produces seven level harmonic output voltage waveform depicted in Fig. 5(a,c,e) and harmonic spectrum, Fig. 5(b,d,f).

Increasing the PWM-unipolar converter to seven produces eleven level output voltage waveforms as shown in Fig. 6(a,c,e), the harmonic spectrums are as shown in Fig. 7(b,d,f) with huge reductions of harmonic contents compared to seven level.

Simulating the model with ten submodules per arm generate seventeen level output voltage waveform as depicted in Fig. 6(a,c,e), the corresponding harmonic spectrums are as represented in Fig. 4(b,d,f) with much reduction of harmonic order compared to eleven level.

The same procedures are carried out on the remaining two arms of the three-phase MMC.

The fact that PWM-unipolar MMC reduces harmonic contents to greater height implicates it to possess the following.

1. Have the capability for stabilization of the voltage in the high voltage oil and gas network exploration and production
2. The number of output waveform levels is higher than the level of the converter. Hence leads to output quality improvement
3. The equal switching frequency of each switch.
4. Its ability to employ the phase-shifted control technique, which allows cancellation of more harmonics.

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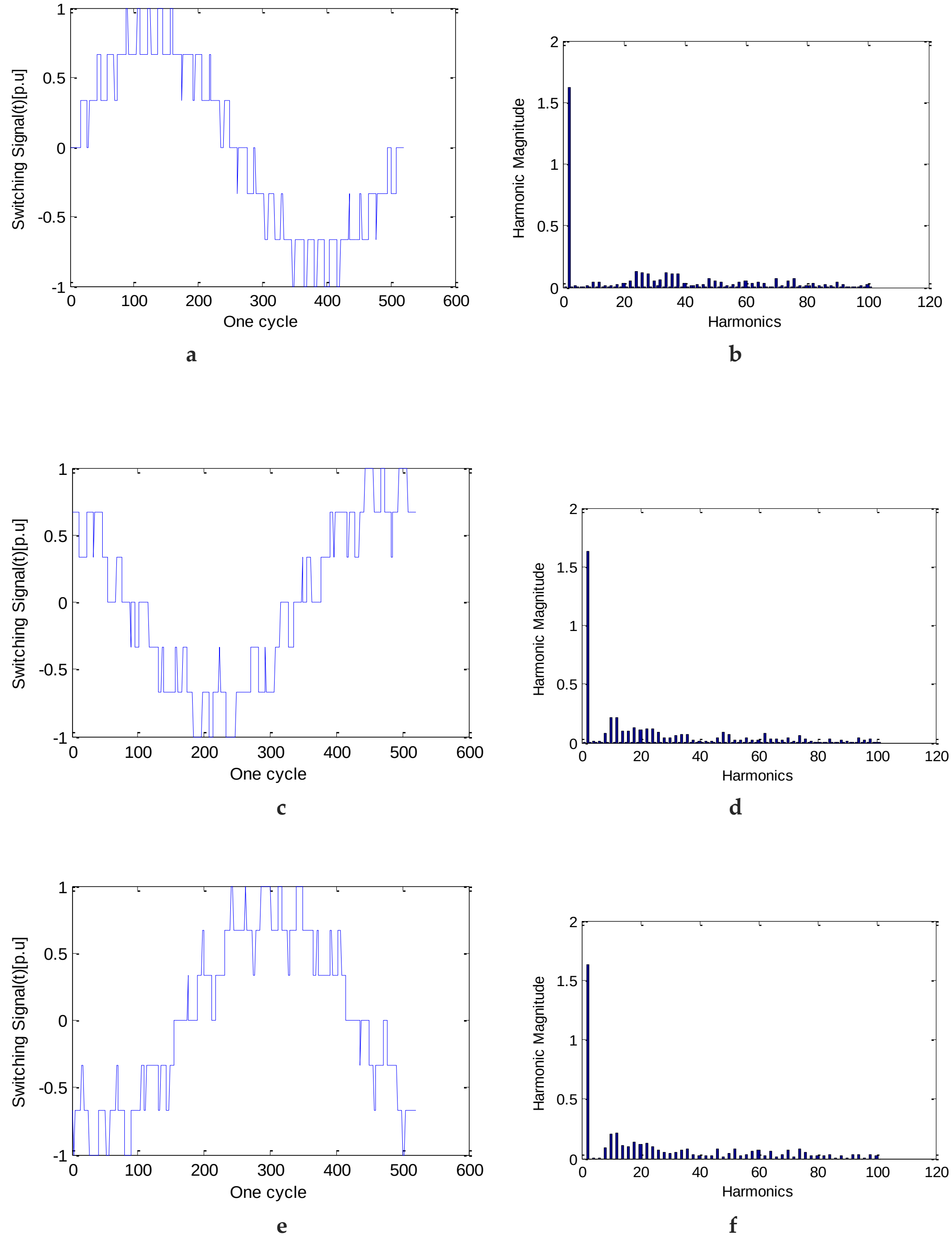
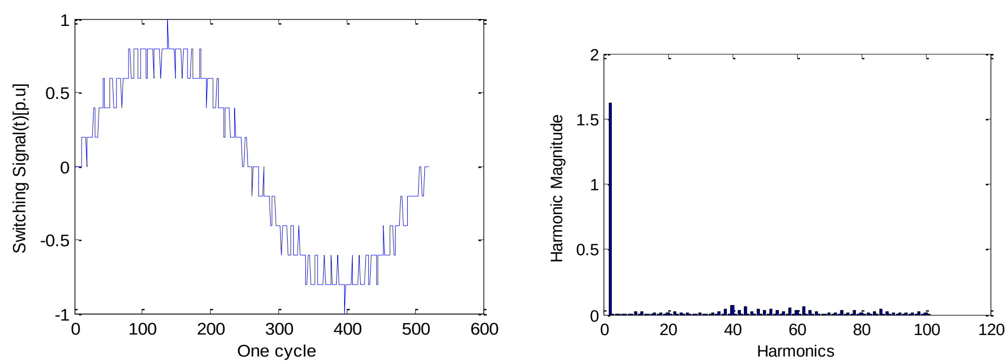


Fig. 5: Three-phase seven Level PWM-Unipolar Converter (a, c, e) output voltage waveform per phase (b, d, f) harmonic spectrum



a **b**

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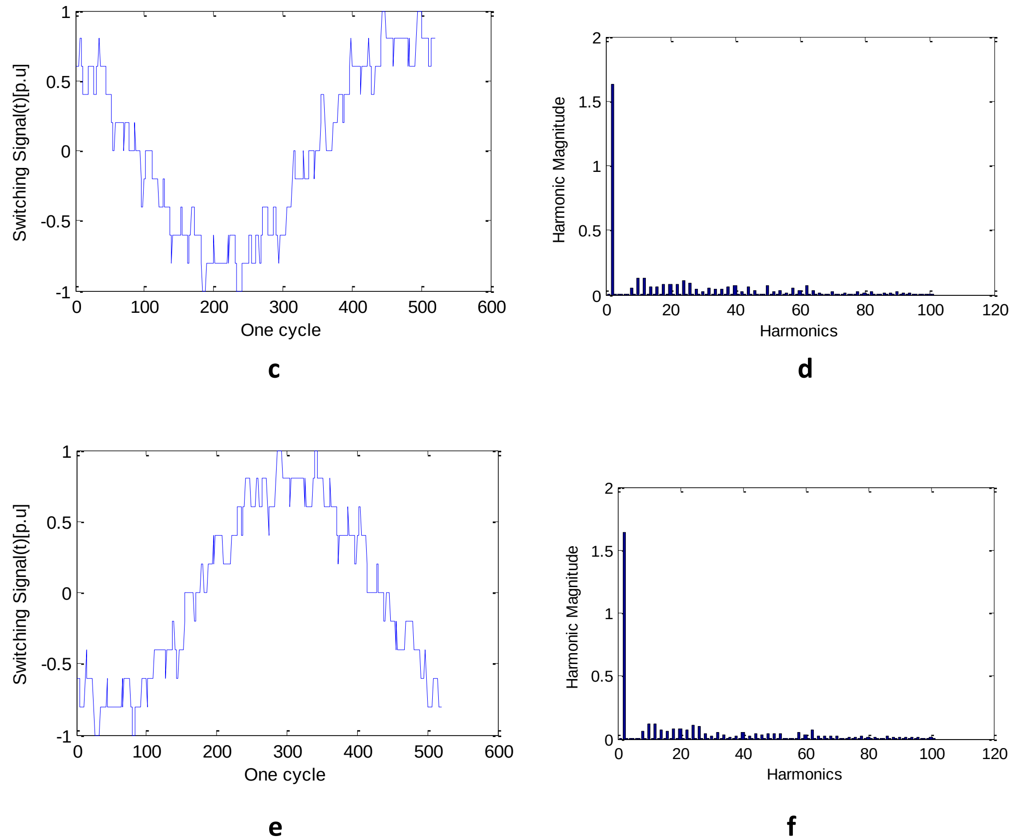

Fig. 6: Three-phase eleven Level PWM-Unipolar Converter (a, c, e) output voltage waveform per phase (b, d, f) harmonic spectrum

When converters are in operation they furnish electromagnetic interface with harmonic contents, thus reducing power quality. This means PWM-unipolar can be used to eliminate these harmonic contents and permit additional submodule to be added to existing facility. The achievement of power quality by PWM-unipolar control has become an interesting issue to transmission and distribution engineers.

The reduction in the switching losses varies from lower number of submodule to higher number submodule of the total PWM-unipolar converters. The switching losses are proportional to the voltage and current output waveforms reduced harmonic distortion.

The three-phase MMC under consideration provide high power drives at electromagnetic interface to high voltage system using VSC PWM-unipolar technology. Different device switching frequencies (50Hz, 1kHz, 1.5kHz, 2kHz, 2.5kHz, 5kHz, 10kHz) are employed to access the generation of output voltage levels waveforms with reduced harmonic content and the capability of PWM-unipolar controllability. At the end search, each arm produced high quality waveforms with lower switching stress. Also, each level harmonic spectrum was compared as the submodules increases, as observed harmonic contents reduce more as submodules increases by cascaded connection. The topology operation provides input current of low harmonic content which will bring smile to the end users.

All submodules are identical and inculcate both input and output circuitry that permit easy fault location finding and maintenance. The topology under discussion has provision for renewable energy source. The major drawback is that it required phase shifting transformer at the input, which attract huge procurement cost.

9. CONCLUSIONS

A new topology, modular multi-level converter using PWM-unipolar switching technique for harmonic content reduction is developed. The output voltage waveforms of the IGBTs are controlled using PWM-unipolar technique to achieve the minimum harmonic reduction. The MMC is suitable for reducing direct drive wave power harmonic voltage to extremely minimum level.

The switching functions, based on Complex Fourier Series, are used effectively to demonstrate the operation of the MMC. The optimum harmonic reductions of this model are proportional to the increase in the YSC submodule. However, comparison reveals that the MMC cascaded H-bridge with more SM generates higher level output voltage waveform with greater harmonic reduction. Reducing harmonic contents using a PWM-unipolar control, not only reduces both lower and higher harmonic contents to the best minimum, but also improves voltage profiles and reduces converter losses.

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Conflict of Interest

The author declares that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

REFERENCES AND NOTES

1. H. Akagi, "Classification, Terminology, and Application of the Modular Multilevel Cascade Converter (MMCC)". IEEE International Power Electronics Conference, 2010.
2. F.Z. Peng, J. W. McKeever, D. J. Adams, "Cascade Multilevel Inverters for Utility Applications." IEEE Industrial Electronics, Control and Instrumentation Conference (IECON), 1997.
3. F.Z. Peng. J. S. Lai, "Dynamic Performance and Control of a Static Var Generator using Multilevel Inverters." IEEE Transactions on Industrial Applications, vol. 33, May/June 1997.
4. L.M. Tolbert and F. Z. Peng, "Multilevel Converters as a Utility Interface for Renewable Energy Systems." IEEE 2000.
5. S. Sirisukprasert, A.Q. 1-luang and J.S. Lai, " Modelling, Analysis and Control of Cascaded-Multilevel Converter-Based STATCOM". IEEE 2003.
6. J. Rodriguez, J.-S. Lai, and F.Z. Peng, "Multilevel Inverters: A Survey of Topologies, Controls, and Applications." IEEE Trans. md. Electronics, vol. 49, Aug. 2002.
7. J. Wang, R. Wei, Q. Ge and Y. Li, "The Harmonic Selection Elimination of Multi-level Converters".
8. Q. Tu, Z. Xu, H. Huang and J. Zhang, "Parameter Design Principle of the Arm Induction in Modular Multilevel Converter based HVDC". International Conference on Power System Technology, 2010 IEEE.
9. A.L.P. de Oliveira, C.E. Tiburcio, M.N. Lemes and D. Retzmann, "Prospects of Voltage-Sourced Converters (VSC) Application in Power Transmission Systems". IEEE ANDESCON 2010.
10. Lesnicar and R. Marquardt, "An Innovative Modular Multilevel Converter Topology Suitable for a Wide Power Range". PowerTech Conference. 2003 IEEE.
11. K. Li and C. Zhao, "New Technologies of Modular Multilevel Converter for VSC-HVDC Application". 2010 IEEE.
12. Rasic, U. Krebs and H. Leu, "Optimization of the Modular Multilevel Converters Performance using the Second Harmonic of the Module Current". URL: http://www.siemens.com
13. X. Luo, G.F. Tang, K.P. Zha, Z.Y. He, and Y.N. Wu, "Study on the Design and Equivalence Test Methods of VSC-HVDC Valves". International Conference on Power System Technolgy, 2010 IEEE.
14. J. Rodrigues, S. Bernet, B. Wu, J. 0. Pontt and S. Kouro," Multilevel Voltage-Source-Converter Topologies for Industrial Medium-Voltage Drives". IEEE Transactions on Industrial Electronics, VOL. 54. 2007.
15. M. Saeedifard and R. Lravani, "Dynamic Performance of a Modular Multilevel Back-to-Back HVDC System". IEEE Transactions on Power Delivery, VOL. 25. 2010
16. J.S. Lai, F. Z. Peng, "Multilevel Converter-A New Breed of Power Converter". IEEE Transactions on Industrial Applications. Vol. 32. 1996.
17. C. Casablanca and J. Sun, "Interleaving and Harmonic Cancellation Effects in Modular Three-Phase Voltage-Sourced Converters". IEEE COMPEL Workshop, July 16-19, 2006.
18. N.A. Azli, and Y.C. Choong, "Analysis on the Performance of a Three-phase Cascaded H-Bridge Multilevel Inverter". IEEE PECon 2006.
19. E. Acha and M Madrigal," Power Systems Harmonics Computing Modelling and Analysis" WILEY January 2002.
20. S. Laali, K. Abbaszade and H. Lesani, "New Hybrid Control Methods Based on Multi-Carrier PWM Techniques and Charge Balance Control Methods for Cascaded Multilevel Converters." IEEE CCECE2O 11.

21. E. Acha and M Madrigal,"Harmonic Modelling of Voltage' Source Converters for HVDC Stations". CERPD, AC-DC Power Transmission, lEE 2001.
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