Mathematical Analysis for Power Loss Analysis of a Seven Level Aligned Multilevel Inverter

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Abstract: Multilevel inverters are widely used in many applications due to their superior performance over conventional inverter. However, due to increasing number of switches in existed multilevel inverts, the cost, size and losses are increasing continuously and these factors are directly proportional to number of inverter level. Hence, aligned multilevel invert is developed and enhanced the analysis on power loses is presented in this paper. The number of switches are used in aligned multilevel inverter is very less compared to existing multilevel inverters. Moreover, space vector pulse width modulation technique is developed for generating pulses to inverter. The mathematical calculation of power loss analysis for 7 level aligned multilevel inverteris evaluated and presented in this paper.

Keywords: Multilevel inverter, aligned multilevel inverter, power loss analysis, SVPWM, 7 level inverter.

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1. Introduction

Continuous improvements in power electronics introduced multilevel inverter technology for many applications including controlling of drives, FACTS devices, voltage controllers, renewable applications, grid connected devices etc [1-3]. The developments of multilevel inverters are introducing the concept of reduced number of switches. More number of switches leads to many problems including increasing cost, size, losses, complexity, required more cooling devises and weight. To overcome these problems, authors in [4] introduced aligned multilevel inverter with very less number of switches. The model configuration of a 7 level aligned inverter is shown in Fig. 1.

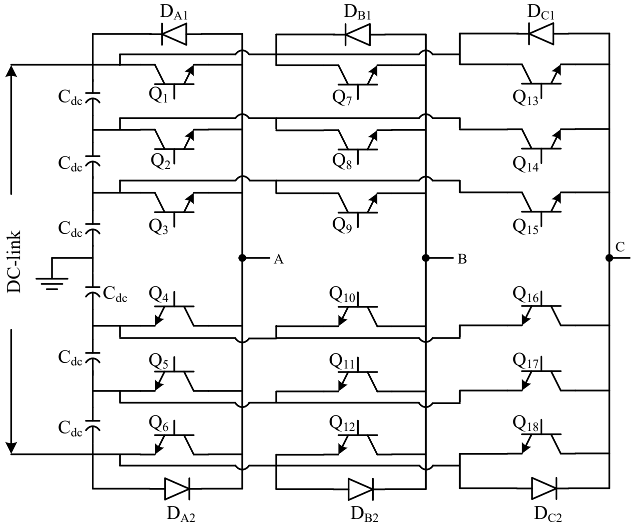

Fig. 1: configuration of 7 level aligned inverter.

Number of switches and ON time period are very less in aligned multilevel inverter compared with existing configurations. Generally multilevel inverters are widely used for many application, hence the aligned multilevel inverter are having significant priority to use in many places. Therefore, it is necessary to evaluate the power losses in aligned multilevel inverter which is considered a very important measure for cost, size, overall efficiency and system reliability. However, loss evaluation in aligned multilevel inverter is not an easy task due to involving many aspects like, switching time, voltage and current are differ for every switch in inverter. For calculation of average power loss the current and voltage are multiplied for calculation of average power loss in inverter at every stage. Unfortunately, the current flowing through switches is absurd to measure instantaneously, butmeasurement of instantaneous voltage is also impossible [5]. Therefore, the analysis of average power loss is a very complicated task especially in multilevel inverters. Generally there are two kinds of power losses analysis are using such as measurement of conduction and switching loss.

2. Literature review on Power loss analysis and SVPWM

Many scholars are examined power loss analysis of different configurations of inverters and few of them listed in this paper. Authors [6], introduced a general scheme for analyzing switching and conduction losses of powersemiconductors devises which are using in inverters based on online simulation. Authors in [7-9] developed different kinds of approaches to evaluate power losses for modular multilevel inverters. Authors in [10] investigated power losses in cascaded H-bridge inverter for HVDC application. However, no one till analyze power losses analysis for aligned multilevel inverter. The conduction and switching losses in three-level inverter are presented by authors in [9-10] respectively. The new approach of analysis and mathematical calculation of inverter power loss is introduced by authors in [11]. However, many of them neglect the effect of ripple current on power loss of inverter and also no one done the analysis of aligned multilevel inverter.Before approaching power losses analysis of aligned multilevel inverter, Space vector pulse width modulation technique is developed for switching pulses of IGBT's. The generalized space vector technology of a seven level aligned inverter (which is shown in Fig. 1) depicted in Fig. 2.

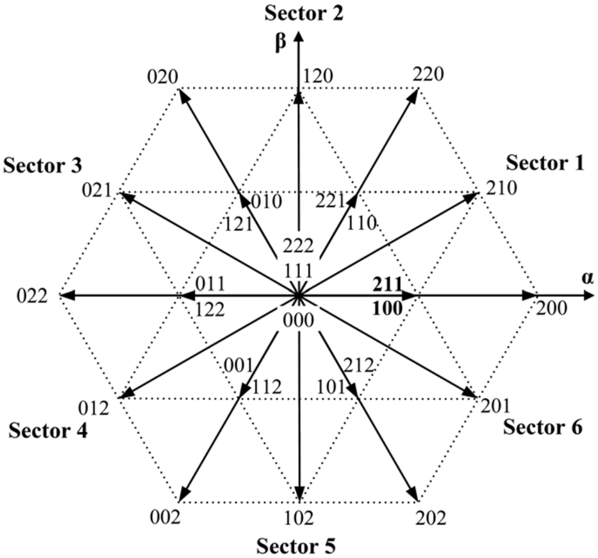

Fig. 2: SVPWM for aligned multilevel inverter.

3. Mathematical Analysis

The loss occurs in inverter is determined by the number of ON time period of each switching device and the conduction current. In SVPWM modulation method, the switching times of each switch is obtained and for aligned multilevel inverter has facility that ON time period of each switch is very less compared to other configurations. The total power loss is mainly affected by the current impact. The inverter loss generated in IGBT and freewheeling diode, total loss is equal to sum of six IGBTs and two freewheeling diodes loss per phase as shown in Fig. 1.

The conduction loss can be expressed as:

$$\begin{aligned} P &= \frac{M}{2\pi}\int_{0}^{2\pi}\left[P(t)d(\omega t)\right] \\ &= \frac{M}{2\pi}\int\left[v(t)\times i(t)+R\times i^{2}\right] \qquad (1) \\ &= M\left[v_{g}I_{avg}+RI_{rms}^{2}\right] \end{aligned}$$

Where, I_{avg} and I_{rms} are the switch's average and rms current when it is in conduction period. The term 'M' is used for modulation index.

The power loss due to diode is expressed by

$$P_{d}=M\frac{1}{2}\left[V_{dc}\times I_{dc(avg)}+R_{d}\times I_{rms}^{2}\right] \qquad (2)$$

Fromeq(1) and (2), total power loss can be expressed for generalized aligned multilevel inverter for level 'N' as:

$$\begin{aligned} P_{total} &= \sum_{n=1}^{N}P(totalswitch) \\ &\quad +2\times M\frac{1}{2}\left[V_{dc}\times I_{dc(avg)}+R_{d}\times I_{rms}^{2}\right] \end{aligned} \qquad (3)$$

Since total number of diodes per phase are only 2 for any number of levels. Moreover, the switching time is also very less.

Apart from this, the switching losses can be obtained by below equation when switch is in ON period.

For each switch,

$$P_{s}=\frac{1}{T_{f}}\frac{V_{\min}}{V_{nom}}\sum_{n=1}^{N}\left[E_{ON}+E_{Off}\right] \qquad (4)$$

For diode

$$P_{s}=\frac{1}{T_{f}}\frac{V_{\min}}{V_{nom}}\sum_{n=1}^{2}E_{diode} \qquad (5)$$

However, the duty cycle expression for 6 sectors needs to be evaluated.

$$D(t)=\begin{cases} =\frac{\sqrt{3}}{2}M\cos\left(\theta-\frac{\pi}{6}+\phi\right) & \left(0\le\theta+\phi\le\frac{\pi}{3}\right)\\ \frac{3}{2}M\cos(\theta+\phi) & \left(\frac{\pi}{3}\le\theta+\phi\le\frac{2\pi}{3}\right)\\ \frac{\sqrt{3}}{2}M\cos\left(\theta+\frac{\pi}{6}+\phi\right) & \left(\frac{2\pi}{3}\le\theta+\phi\le\pi\right)\\ \frac{\sqrt{3}}{2}M\cos\left(\theta-\frac{\pi}{6}+\phi\right) & \left(\pi\le\theta+\phi\le\frac{4\pi}{3}\right)\\ \frac{3}{2}M\cos(\theta+\phi) & \left(\frac{4\pi}{3}\le\theta+\phi\le\frac{5\pi}{3}\right)\\ \frac{\sqrt{3}}{2}M\cos\left(\theta+\frac{\pi}{6}+\phi\right) & \left(\frac{5\pi}{3}\le\theta+\phi\le 2\pi\right) \end{cases} \tag{6}$$

Therefore,

$$P_{IGBT}=\frac{MV}{2\pi}\left(\begin{array}{l} \int_{\frac{-\pi}{2}}^{\frac{-\pi}{3}}\frac{3}{2}\cos(\theta+\phi)I\cos(\theta)d\theta+\\ \int_{\frac{-\pi}{3}}^{0}\frac{\sqrt{3}}{2}\cos\left(\theta+\frac{\pi}{6}+\phi\right)I\cos(\theta)d\theta+\\ \int_{0}^{\frac{\pi}{3}}\frac{\sqrt{3}}{2}\cos\left(\theta-\frac{\pi}{6}+\phi\right)I\cos(\theta)d\theta+\\ \int_{\frac{\pi}{3}}^{\frac{\pi}{2}}\frac{3}{2}\cos(\theta+\phi)I\cos(\theta)d\theta+ \end{array}\right)=\frac{1}{4}MI_{\phi}V\cos\phi \tag{7}$$

$$P_{IGBT-Rf}=\left(\frac{24-5\sqrt{3}}{24}\right)\frac{MR_{co}I^{2}}{\pi}\cos\phi \tag{8}$$

$$P_{IGBT}=P_{IGBT}+p_{IGBT-Rf=\frac{1}{4}MIV\cos\phi+\left(\frac{24-5\sqrt{3}}{24}\right)\frac{MRI^{2}}{\pi}\cos\phi} \tag{9}$$

$$V_{f}(t)=V_{fo+}RI_{f}(t) \tag{10}$$

$$P_{diode} = P + P = \frac{VI}{\pi}\left(\frac{4 - M\pi\cos\phi}{4}\right) + \frac{RI^2}{\pi}\left(\frac{5\sqrt{3M}\ \cos\phi + 6\pi - 24M\cos\phi}{24}\right) \tag{11}$$

$$P = \frac{1}{N}\sum_{n-1}^{N}\left(\frac{E(nT)}{T} + \frac{E(nT)}{T}\right) \tag{12}$$

$$E(nT) = E\frac{V_{DC}}{V_{DON}}\frac{I(nT)}{I} \tag{13}$$

$$E(nT) = E\frac{V_{DC}}{V_{DON}}\frac{I(nT)}{I} \tag{14}$$

$$P = \frac{1}{NT}\sum_{n=1}^{N}\left(E\frac{V_{DC}I(nT)}{V_{DCON}I} + E\frac{V_{DC}}{V_{DCoff}}\frac{I_{Coff(nT)}}{I}\right) \tag{15}$$

$$P = \begin{pmatrix} E\dfrac{V_{DC}}{V_{DCON}}\dfrac{I_{\phi}}{I_C} + \\ E\dfrac{V_{DC}}{V_{DCON}}\dfrac{I_{\phi}}{I_C} \end{pmatrix}\frac{F}{T}\int_{0}^{\frac{T_n}{2}}\cos(\omega_s t)dt \tag{16}$$

$$P = 6^{*}\left(P_{IGBT} + P_{Diode} + P_{sw}\right) \tag{17}$$

$$D_n = m\sin\left(2\pi f_g . \frac{n}{f_k}\right) \tag{18}$$

$$P = \frac{F}{\pi}\begin{pmatrix} E\dfrac{V_{DC}}{V_{DCON}}\dfrac{I_{\phi}}{I_C} + \\ E\dfrac{V_{DC}}{V_{DCON}}\dfrac{I_{\phi}}{I_C} \end{pmatrix} \tag{19}$$

$$V_{VT} = \left(V_{CEN} - V_{CEO}\right).\frac{i_c}{I_{CN}} + V_{CEO} \tag{20}$$

$$V_{VD} = \left(V_{FN} - V_{FO}\right).\frac{i_c}{I_{CN}} + V_{FO} \tag{21}$$

$$i(\omega t) = I_m . \sin(\omega t) \tag{22}$$

$$i(\omega t) = \frac{V.m.\sin(\omega t)(1 - m.\sin(\omega t))}{4 f_k . L} \tag{23}$$

$$\begin{cases} i(n) = I_m \sin\alpha_n = I_m \sin\left(\dfrac{2\pi f_{g.n}}{f_k}\right) \\ i(n) = V.m.\sin\left(\dfrac{2\pi f_{g.n}}{f_k}\right)\left(1 - m\cdot\sin\left(\dfrac{2\pi f_{g.n}}{f_k}\right)\right)\Big/ 4f_{k\cdot L} \end{cases} \tag{24}$$

$$v_{CE} = \frac{V_{CEN} - V_{CEO}}{I_{CN}} i_c + V_{CEO} \tag{25}$$

$$V_{CE} = a_1 I_c^2 + a_2 I_c + a_3 = l_{(1)} V_{CE(1)} + l_{(2)} V_{CE(2)} + l_{(3)} V_{CE(3)} \tag{26}$$

$$\begin{cases} l_{(1)} = \dfrac{\left(I_c - I_{c(2)}\right)\left(I_c - I_{c(3)}\right)}{\left(I_{c(1)} - I_{c(2)}\right)\left(I_{c(1)} - I_{c(3)}\right)} \\ l_{(2)} = \dfrac{\left(I_c - I_{c(1)}\right)\left(I_c - I_{c(3)}\right)}{\left(I_{c(2)} - I_{c(1)}\right)\left(I_{c(1)} - I_{c(3)}\right)} \\ l_{(3)} = \dfrac{\left(I_c - I_{c(1)}\right)\left(I_c - I_{c(2)}\right)}{\left(I_{c(3)} - I_{c(1)}\right)\left(I_{c(3)} - I_{c(2)}\right)} \end{cases}$$

The harmonic analysis needs to be implemented to extract loses when converting DC to AC through inverter. All the triplen harmonics are generally zero when producing balanced three-phase output from inverter,:

$$\frac{4V_{dc}}{\pi}\left[\cos\alpha_1 + \cos\alpha_2 + \cos\alpha_3 + \cos\alpha_4 + \cos\alpha_5 + \cos\alpha_6 + \cos\alpha_7\right] = f_1(\alpha) = M$$

$$\frac{4V_{dc}}{5\pi}\left[\cos5\alpha_1 + \cos5\alpha_2 + \cos5\alpha_3 + \cos5\alpha_4 + \cos5\alpha_5 + \cos5\alpha_6 + \cos5\alpha_7\right] = f_2(\alpha) = 0$$

$$\frac{4V_{dc}}{7\pi}\left[\cos7\alpha_1 + \cos7\alpha_2 + \cos7\alpha_3 + \cos7\alpha_4 + \cos7\alpha_5 + \cos7\alpha_6 + \cos7\alpha_7\right] = f_3(\alpha) = 0$$

$$\frac{4V_{dc}}{11\pi}\left[\cos11\alpha_1 + \cos11\alpha_2 + \cos11\alpha_3 + \cos11\alpha_4 + \cos11\alpha_5 + \cos11\alpha_6 + \cos11\alpha_7\right] = f_4(\alpha) = 0$$

$$\frac{4V_{dc}}{13\pi}\left[\cos13\alpha_1 + \cos13\alpha_2 + \cos13\alpha_3 + \cos13\alpha_4 + \cos13\alpha_5 + \cos13\alpha_6 + \cos13\alpha_7\right] = f_5(\alpha) = 0$$

$$\frac{4V_{dc}}{17\pi}\left[\cos17\alpha_1 + \cos17\alpha_2 + \cos17\alpha_3 + \cos17\alpha_4 + \cos17\alpha_5 + \cos17\alpha_6 + \cos17\alpha_7\right] = f_6(\alpha) = 0$$

$$\frac{4V_{dc}}{19\pi}\left[\cos19\alpha_1 + \cos19\alpha_2 + \cos19\alpha_3 + \cos19\alpha_4 + \cos19\alpha_5 + \cos19\alpha_6 + \cos19\alpha_7\right] = f_7(\alpha) = 0$$

Where M is modulation index.

The total conduction losses can be expressed by(for 7 level inverter)

$$P_{con} = N\frac{T_{on}}{T} f_g \left[2 \times \sum_{n=1}^{f_k/2f_g} \begin{pmatrix} P_{S1} + P_{S2} + P_{S3} \\ + P_{S4} + P_{S5} + P_{S6} \\ + P_{D1} + P_{D2} \end{pmatrix} \right]$$

4. Conclusions:

The power loss analysis of aligned multilevel inverter is done with the help of switching losses and conduction losses. The harmonic content also included to enhance more realistic system. The analysis is made for a seven level aligned inverter with SVPWM technique. The switching time period is very less compare to other configurations, hence total conduction losses are reduced. The switching losses also minimized due to less number of switches. Moreover, only two diodes are required for each phase. This implied fewer losses due to diodes.

References:

[1]. S. K. Baksi, et al., "Reduced Switch Count Three-Phase Five-Level Boosted ANPC Inverter with Unipolar PWM Scheme for Electric Vehicle Propulsion Drive," *IECON 2021 – 47th Annual Conference of the IEEE Industrial Electronics Society*, 2021, pp. 1-6, doi: 10.1109/IECON48115.2021.9589916.

[2]. U. R. Muduli, B. Chikondra and R. K. Behera, "Continuous and Discontinuous SVPWM with Switching Loss Control for Five-Phase Two-Level VSI fed Induction Motor Drive," *2020 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2020, pp. 1-6, doi: 10.1109/PEDES49360.2020.9379717.

[3]. B. Ch, U. R. Muduli and R. K. Behera, "Performance Comparison of Five-Phase Three-Level NPC to Five-Phase Two-Level Voltage Source Inverter," *2018 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, 2018, pp. 1-6, doi: 10.1109/PEDES.2018.8707510.

[4]. Motaparthi Nagaraju and Kiran Kumar Malligunta, Grid integration of hybrid renewable energy source using Aligned Multilevel Inverter, journal International Journal of Emerging Electric Power Systems, Vol. 23, Issue 5, 2021, https://doi.org/10.1515/ijeeps-2021-0366

[5]. Tania Annur, "An analytical method for the loss calculation of an inverter with THPWM modulation technique", American Journal of Engineering Research (AJER), Volume-8, Issue-2, pp-53-63, 2019.

[6]. Alamri, B., &Darwish, M. (2014). Precise modelling of switching and conduction losses in cascaded h-bridge multilevel inverters.

[7]. Tu, Q., & Xu, Z. (2011, July). Power losses evaluation for modular multilevel converter with junction temperature feedback. In Power and Energy Society General Meeting, 2011 IEEE (pp. 1-7). IEEE..

[8]. Huang, S., Liao, W., Liu, P., Tang, W., & Huang, S. (2016). Analysis and calculation on switching frequency and switching losses of modular multilevel converter with maximum sub-module capacitor voltage deviation. IET Power Electronics, 9(2), 188-197.

[9]. Stringfellow, J. D., Summers, T. J., & Betz, R. E. (2016, December). Control of the modular multilevel converter as a photovoltaic interface under unbalanced irradiance conditions with MPPT of each PV array.In Power Electronics Conference (SPEC), IEEE Annual Southern (pp. 1-6).IEEE.

[10]. Alamri, B., &Darwish, M. (2015, June). Power loss investigation in HVDC for cascaded H-bridge multilevel inverters (CHB-MLI). In PowerTech, 2015 IEEE Eindhoven(pp. 1-7). IEEE.

[11] de Andrade, F.C., Bradaschia, F., Limongi, L.R., Cavalcanti, M.C. (2017). A reduced switching loss technique based on generalized scalar PWM for nine-switch inverters. IEEE Transactions on Industrial Electronics, 65(1): 38-48. https://doi.org/10.1109/TIE.2017.2721906

[12] Alamri, B., Darwish, M. (2014). Precise modelling of switching and conduction losses in cascaded h-bridge multilevel inverters.In 2014 49th International Universities Power Engineering Conference (UPEC), pp. 1-6. https://doi.org/10.1109/UPEC.2014.6934613

[13] Kumar, D., Pattnaik, S., Singh, V. (2012). Genetic algorithm based approach for optimization of conducting angles in cascaded multilevel inverter. IJERA, 2(3): 2389-2395. https://doi.org/10.1.1.449.8385