Comparative analysis of 3L-NPC converter output voltage with selective harmonic elimination PWM

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Abstract. The main purpose of this article is to show the importance of a comparative analysis of a three-level neutral point clamped (3L-NPC) output voltage with selective harmonic elimination PWM (SHEPWM). As compared to other PWM technique, the SHEPWM method has a lower dynamic power loss and a better THD at the same switching frequency. The objective of this analysis is to provide a modelling results of THD and a voltage/current spectrum of the output voltage with a various SHEPWM implementation for the 3L-NPC converter. A mathematical model for this research was developed in Matlab/Simulink. A practical use of the comparative analysis results can be applied to power electronic systems of high power wind generators.

1. Introduction
An improvement and a development of new pulse width modulation (PWM) algorithms are the priority research for power conversion by power semiconductor converters. The common topologies of the power converters are applied into energy and industrial applications, such as high voltage dc transmission (HVDC) and flexible ac transmission system (FACTS), renewable energy sources (RES) and electric drives. The utilising of the identical topologies leads to a non-effective use of PWM methods, as this depends on load or grid connection performances, especially at different electromagnetic compatibility requirements [1]. There are several variants for implementation of one PWM method, and at the selection of an optimal PWM method, it is possible to achieve the current/voltage THD, which will correspond to the THD reference requirements [2].

Neutral-point clamped (NPC) converter is an essential part of high-power energy applications. The specific purpose of NPC is to solve the problems of the voltage limit capability of semiconductor devices, and they are attractive for high-power energy control due to their superior performance in power semiconductor technology [3]. High quality of the current and voltage waveforms both at the input and output terminals of the converter are needed to be improved as much as possible, and this requirement is affected by the topology we used, the control algorithm and the actual application [4]. NPC converters are the most established and commercialized topology. New means of boosting the three level NPC converter energy efficiency are required to develop and study applied power circuits, modulation algorithms and control systems [5-7]. Figure 1 shows a typical power circuit of high-power drive system based on the NPC converters.

Currently there are a lot of scientific research focuses on selective harmonic elimination (SHE) and space vector pulse width modulation (SVPWM) for 3L-NPC converters. The article [8] describes hybrid PWM based on sinusoidal (SPWM) and SHEPWM, which provides comparative analysis and algorithm of a smooth transition between them for power quality improving. The article [9] presents a
performance of hybrid PWM with a transition between SV and SHEPWM, which allows to make the power losses less.

Figure 1. Typical industrial circuits are based on 3L-NPC converters.

2. Problem definition
The amount of dynamic losses, which depend on the sample frequency of switching, is the main indicator reducing the efficiency of the power converters. Reduction in the number of switching of the converter allows increasing power, reliability and efficiency, but it can provide a significant effect on the quality of the converted current and voltage. Using one method of modulation over the full frequency range and the output voltage and current magnitudes has not able to achieve the maximum efficiency of the converter and maintain the required power quality. The comparative analysis of converter output voltage with selective harmonic elimination PWM is needed to solve this task. It can assess voltage/current THD and spectrum for several SHE patterns and provide the information about an optimal pattern.

The objective of this analysis is to provide a modelling results of THD and a voltage/current spectrum of the output voltage with a various SHEPWM implementation for the 3L-NPC converter.

3. Mathematical description of 3L-NPC converter
The NPC has already applied in many conventional high-power ac motor drives, and a back-to-back topology for NPC makes it successfully used in regenerative applications, like the grid interfacing of renewable energy sources. In addition, the topology can be extended to any level by adding more diodes and capacitors, but the main problem of the topology is how the neutral point voltage balanced or maintained on the DC-link, that is, to keep DC-side voltage stable [10,11].

A mathematical model of three level NPC (Figure 2) was developed via discrete switching functions $S_{abc/lcrv}$ of power modules for grid side:

$$
\gamma_{abc} = \begin{cases} 
1, \ (S_{abc1} \ and \ S_{abc2}) = 1 \ and \ (S_{abc3} \ and \ S_{abc4}) = 0 \\
0, \ (S_{abc2} \ and \ S_{abc3}) = 1 \ and \ (S_{abc1} \ or \ S_{abc4}) = 0 \\
-1, (S_{abc3} \ and \ S_{abc4}) = 1 \ and \ (S_{abc1} \ and \ S_{abc2}) = 0 
\end{cases}
$$

These switching states $\gamma_{abc/lcrv}$ create the discrete logic functions $F$. 


Using the functions \( F \) and Kirchhoff’s laws, an equation system describing the electromagnetic processes of 3L-NPC was written as:

\[
\begin{align*}
\begin{bmatrix}
F_{abc1} = \gamma_{abc} \cdot (\gamma_{abc} + 1) \\
F_{abc2} = \gamma_{abc} \cdot (\gamma_{abc} - 1)
\end{bmatrix},
\end{align*}
\]

(2)

where \( i_a, i_b \) and \( i_c \) are 3L-NPC converter phase currents.

4. Description of SHE pulse-with modulation

The selective harmonic elimination PWM has able to eliminate the defined harmonics from 3L-NPC converter output phase voltage. And the total amount of eliminated harmonics is limited the switching frequency of the power modules as

\[
k = \frac{f_{ov,\text{max}}}{2 \cdot f_1} - 1 = N - 1
\]

(4)

where \( f_{ov,\text{max}} \) is the max. switching frequency; \( N \) – is amount of the power module switching in per quarter of the voltage time period, \( k \) – is amount of the eliminated harmonics.

A typical phase voltage of SHE this a quarter-wave symmetry [12], as shown in Figure 3.
The switching angles and the spectrum of the 3L-NPC converter output voltage with the SHE by means of a system of nonlinear equations [13]

\[
\begin{align*}
\sum_{k=1}^{N} (-1)^{k} \cdot \cos(n \cdot \alpha_k) &= \frac{\pi}{4} \cdot \frac{2}{U_{dc}} \cdot U_n \\
\sum_{k=1}^{N} (-1)^{k} \cdot \cos(n \cdot \alpha_k) &= 0, n = 5, 7, 11, ...
\end{align*}
\]  

where the pick voltage \( U_n \) is calculated [14, 15] by

\[
U_n = \frac{4}{\pi} \int_{0}^{\pi} u(o\tau) \cdot \sin(n \cdot o\tau) d(o\tau) = \frac{4}{\pi} \cdot \frac{U_{dc}}{2} \cdot \sum_{k=1}^{N} (-1)^{k} \cdot \cos(n \cdot \alpha_k)
\]  

where \( u(o\tau) = \sum_{n=1,3,5,...}^{\infty} \frac{2 \cdot U_{dc}}{\pi \cdot n} \left[ \sum_{k=1}^{N} (-1)^{k+1} \cdot \cos(n \cdot \alpha_k) \right] \cdot \sin(o\tau \cdot n) \), in which \( \alpha_k \) – a switching angle at elimination of \( k \) harmonics [16].

5. Modelling results

Using the mathematical descriptions of the three-level converter and the SHE modulation algorithm, a research model was developed in the Matlab/Simulink. For the comparative analysis, presented in Table 1 four patterns of the SHE implementation were calculated. The results of calculation of the switching angles from the modulation factor are shown in Figure 4. The dependences of the THD voltage and current of the converter for the SHE patterns are shown in Figure 5.

The simulation results determined the non-linear dependence of voltage and current THD on the modulation factor for different patterns of SHEPWM. The analysis of the obtained results in Figure 5 shows that the voltage THD depends strongly on a converter modulation factor. At the maximum values of the modulation factor, the voltage THD becomes equal, therefore, it will be optimal using of the SHE pattern with a low switching. However, a comparative analysis of the current THD provides better results at the SHE pattern with a high switching.

| SHE | \( k \) | Patterns |
|-----|-----|----------|
| SHE1 | 6 | 5, 7, 11, 13, 17 and 19 |
| SHE2 | 8 | 5, 7, 11, 13, 17, 19, 23 and 25 |
| SHE3 | 10 | 5, 7, 11, 13, 17, 19, 23, 25, 29 and 31 |
| SHE4 | 12 | 5, 7, 11, 13, 17, 19, 23, 25, 29, 31, 35 and 37 |
Figure 4. Switching angles for SHE₁(a), SHE₂(b), SHE₃(c), SHE₄(d).

Figure 5. Comparative analysis of voltage(a) and current(b) THDs.

6. Conclusion
In this paper the comparative analysis of 3L-NPC converter output voltage with selective harmonic elimination PWM has been considered. Mathematical description and of 3L-NPC converter and selective harmonics elimination method were provided. The calculation results of voltage and current THDs at the four patterns of the SHE implementations were obtained. The results show a possibility of using a low switching SHE pattern at a high modulation factor for a voltage THD.
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