Analysis of three-level neutral point piloted power converter topology

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Abstract – **This paper deals with three-level topology of neutral point piloted converters (3L-NPP). These converters can be realized in two variants. The first one is represented by one power semiconductor switch only placed in the top and bottom part of an output leg of a half bridge representing a phase of a three phase converter; the second one is represented by two serial connected semiconductor switches in top and bottom part of the converter leg. These topologies are often compared with neutral point clamped converters but not between themselves. Therefore, the analysis of those topologies is performed in detail in this paper and furthermore, they are compared with a standard two level voltage source converter (2L-VSC) in the point of view of converter losses and output quantities distortion.**

Keywords-power converter; neutral point piloted; three-level voltage; soft switching; dc-link;

I. Introduction

The multilevel converters are intended for medium and high voltage applications where conventional two-level voltage source converters cannot be used because of insufficient blocking voltage of semiconductor switches. The multilevel converters solve this problem using a system of serial-like connection of the semiconductor switches. Furthermore, the output voltage waveform is better in comparison with standard two-level voltage source converters [1]. The 3L-NPP is a type of multilevel converters. This topology is not usually used in industrial application in comparison with widely spread converters as three-level neutral point clamped or active neutral point clamped converters, flying capacitor converters or modular multilevel converters [1]-[4]. The NPP topology brings some interesting features, which should be deeply investigated.

II. Topology of Three-Level NPP

The 3L-NPP topology can be realized in two variants. First of them is shown in Figure 1 and the second one is shown in Figure 2. These variants are different in number of switches in top and bottom part of the converter leg (one as T1 or two as T1 and T2 connected in series). There is one bidirectional switch which connects the middle of the dc-link to the output of each phase. Then the maximum voltage for each upper and bottom part of the leg is strictly defined. This switch can be realized in two ways: (I) use of two anti-serial transistors and reverse diodes (II) use of BR-IGBT [5].

A. Topology with one switch per leg

The 3L-NPP topology with one switch, sometimes called T-type converter, consist of four IGBT transistors and four reverse diodes in one phase. Because there is only one switch in top part of the leg (top branch) and one switch in bottom part of the leg (bottom branch), these inverters cannot be straightforward used for medium voltage applications. The topology with one switch is usually used in applications of low or medium power as small photovoltaic systems [6].

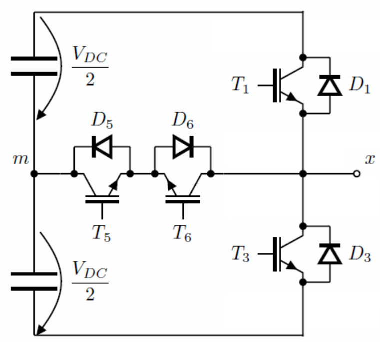

Figure 1. Three level NPP topology with one switch per leg

B. Topology with two switches per leg

This topology is shown in Figure 2. It contains two more transistors and two more diodes in one phase in comparison with the previous variant from Figure 1. The switches in top and bottom branches are connected in series. Transistors T_1 and T_2 form the top branch which connects voltage level $V_{DC}/2$ to the load when these transistors are turned on. Transistors T_3 and T_4 form bottom branch which connects voltage level -$V_{DC}/2$ to the load. Transistors T_5 and T_6 form the bidirectional switch which connect middle point of capacitors to the output terminal of one converter phase.

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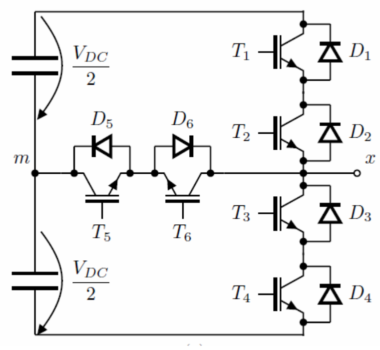

Figure 2. Three-level NPP topology with two switches per leg

The 3L-NPP topology with two switches in series has some advantages in comparison with 3L-NPP topology with one switch. This topology can work with higher voltage levels because there are two switches in series. The switching losses of transistor T_1 are half in comparison with previous topology because transistor T_1 switches with half voltage level. It leads to possibility to significantly increase the switching frequency. The switching and blocking voltages are shown in TABLE I. The switching voltage appears on a switch when it is turning on or off. This voltage with the current creates switching losses. The blocking voltage is a voltage level which has to be blocked by a switch when it is turned off.

TABLE I. BLOCKING AND SWITCHING VOLTAGES

Switch	3L-NPP with 1 switch		3L-NPP with 2 switches	
	Blocking voltage	***Switching voltage***	***Blocking voltage***	***Switching voltage***
T_1	V_{DC}	$V_{DC}/2$	$V_{DC}/2$	$V_{DC}/4$
T_2	---	---	$V_{DC}/2$	$V_{DC}/4$
T_3	V_{DC}	$V_{DC}/2$	$V_{DC}/2$	$V_{DC}/4$
T_4	---	---	$V_{DC}/2$	$V_{DC}/4$
T_5	$V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$
T_6	$V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$	$V_{DC}/2$

III. PRINCIPLE OF BIDIRECTIONAL SWITCH

The bidirectional switch consists of anti-serial connection of two transistors and reverse diodes. The elements of bidirectional switch can be used in soft switching mode in some cases. These cases depend on operating mode of the converter and furthermore, proper control conditions have to be fulfilled. This leads to design of a new PWM modulator which fulfil conditions in Table II.

TABLE II. SWITCHING STATES OF ONE PHASE 3L-NPP

Output voltage level		$\mathbf{V_{DC}/2}$	**0**	$\mathbf{-V_{DC}/2}$
Switching signals sending on		T_1, T_2, T_5	T_5, T_6	T_3, T_4, T_6
Current is leaded by	$i_L > 0$	T_1, T_2	T_5, D_6	D_3, D_4
	$i_L < 0$	D_1, D_2	D_5, T_6	T_3, T_4

Cases with soft switching are indicated in TABLE III. It can be seen that the soft switching appears in case when the output voltage comes from Vdc/2 or -Vdc/2 to zero or vice versa for defined current polarities.

TABLE III. CASES OF SOFT SWITCHING

Working mode of NPP	**Current orientation**	**Soft switching**
$V_{DC}/2 \leftrightarrow 0$	$i_L > 0$	T_5
$V_{DC}/2 \leftrightarrow 0$	$i_L < 0$	does not occur
$-V_{DC}/2 \leftrightarrow 0$	$i_L > 0$	does not occur
$-V_{DC}/2 \leftrightarrow 0$	$i_L < 0$	T_6

A. Principle of soft switching transistor T_5

The soft switching principle of transistor T_5 is explained in Figures 3 and 4. Let us suppose the operation mode where the output voltage is changed between level $V_{DC}/2$ and zero voltage. The current is assumed positive. This means that the current flows toward to the load. The switching signals are sent to transistors T_1, T_2 and T_5. The current flows through T_1 and T_2. There is no current flowing through transistor T_5 in this mode. However, as mentioned above, transistor T_5 gets also the switching signal. It causes preparation of transistor T_5 to turn on.

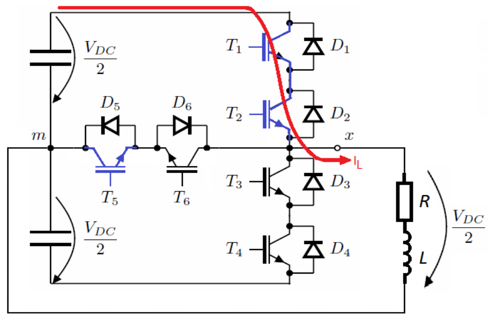

Figure 3. Positive output voltage operation mode

In following mode, the transistors T_1 and T_2 are turned off and the output voltage should be zero. The current does not flow through these transistors. Top branch is closed and the bidirectional switch starts lead the current. Transistor T_5 is prepared from previous mode and whole commutation takes place at diode D_6. There are not any switching losses at T_5 at this moment. The bidirectional switch is activated. This mode is shown in Figure 4. The operation modes for transistor T_6 can be derived similarly.

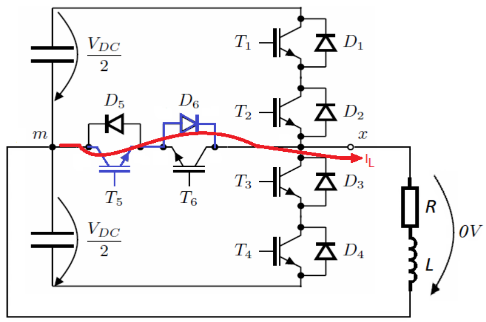

Figure 4. Zero voltage voltage operating mode.

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B. Simulation of soft switching transistor T_5

Previous theoretical assumptions were verified by simulation of the soft switching operation mode. The simulation model was built using Matlab/Simulink with PLECS toolbox. Only one phase of the 3L-NPP converter was simulated. The converter was controlled by the carrier based PWM. Duty cycle was set up 50%. The parameters of the load are: R = 1.5 Ω and L = 5 mH. The DC link voltage was of 3kV. The switching frequency was of f_s = 1000 Hz. There were used Infineon FZ1000R33HE3 transistors with reverse diodes. These components have blocking voltage 3300 V and nominal forward current 1000 A. The whole phase of the converter was placed on a heat sink. A thermal library was created for all power semiconductor components using manufacturer data [7].

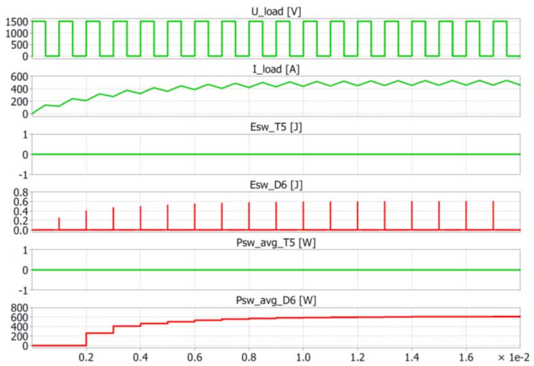

Figure 5. Power losses of bidirectional switch analysis

The simulation results for start-up and steady state of the converter are shown in Figure 5. The lost switching energy is detected only at diode D_6. This lost energy is caused by diode recovery charge. The waveform named Psw_avg_D6 represents the mean value of D_6 switching losses. The value of switching losses is stabilized on 600W for this converter state after a while.

IV. Simulation of Three-Phases 3L-NPP

This paragraph is focused on simulations of three-phase 3L-NPP converter and three-phase 2L-VSC converter. There will be compared harmonic distortion of output voltages and currents. Total harmonic voltage distortion (THD_U) is defined by equation (1). Total harmonic current distortion (THD_I) is defined the same way as THD_U. Fourier analysis is performed for basic frequency 50Hz in measuring window ten periods of basic frequency.

$$THD_U = \frac{\sqrt{\sum_{h=2}^{40} U_h^2}}{U_1} \cdot 100 \quad [\%] \tag{1}$$

The simulation parameters are: RL load where R = 1.5 Ω and L = 5 mH. The DC link voltage was 3kV. The switching frequency was f_s = 1000 Hz. The modulation frequency was f_m = 50 Hz. There were used Infineon FZ1000R33HE3 transistors with reverse diodes.

In Figure 6, there are shown output voltage and current in one phase 3L-NPP converter for modulation depth m=1. The phase converter voltage has three levels but phase load voltage has five levels which is significantly advantageous because of lower dv/dt and lower current ripple comparing to a standard two level converter (2L-VSC).

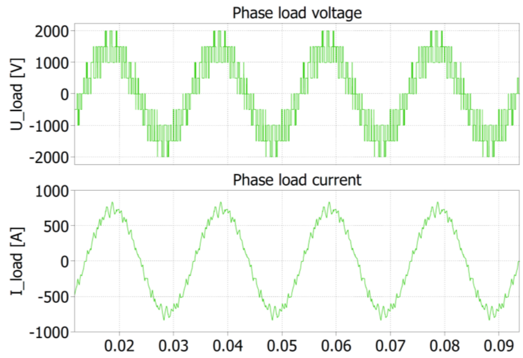

Figure 6. Output voltage and output current of 3L-NPP converter

In TABLE IV are shown simulation results of total harmonics distortion of output voltages and currents (THD_U and THD_I). Total harmonics distortions were computed for depth modulations m = 1 and m = 0.1 respectively.

TABLE IV. Blocking ltages

	Modulation depth m=1		**Modulation depth m=0.1**	
	3L-NPP	***2L-VSC***	***3L-NPP***	***2L-VSC***
THD_U [%]	25.5	48.8	117.6	101.4
THD_I [%]	7.2	14.4	13	16.7

THD_I of 3L-NPP converter is lower for both operation points in comparison with 2L-VSC. THD_U is a bit different in selected operation modes. THD_U is significantly lower in 3L-NPP for m=1. This is caused by number of output voltage levels. Nevertheless, for modulation depth m=0.1 are the THD_U comparable because of similar output waveform of voltage levels (see Fig. 14 for 3L-NPP). The higher THD_U is caused by relatively small value of the fundamental harmonic. Frequency spectra of output voltage and output current of the 3L-NPP for both modulation depths are show in Figure 7.

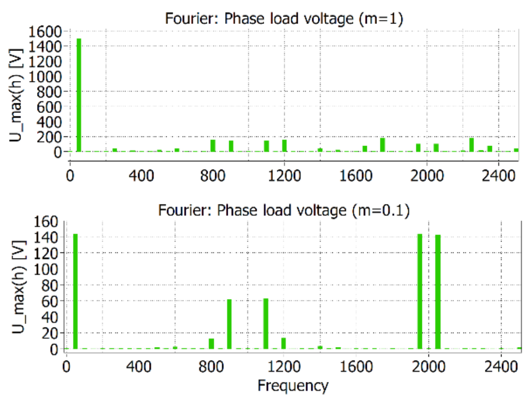

Figure 7. Frequency spectra of 3L-NPP for m = 1

Occurrence of high values of voltage harmonics around multiples of switching frequency in operation mode with depth of modulation m = 0.1 is caused by

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thin pulses of output voltage. Fourier analysis of this waveform leads to high values of higher harmonics. Detail of output voltage and output current of 3L-NPP in operation mode with depth of modulation m = 0.1 is shown in Figure 8.

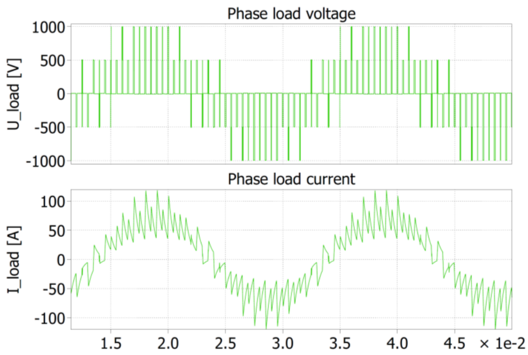

Figure 8. Output voltage and output current of 3L-NPP for m = 0,1

V. COMPARISON OF POWER LOSSES

This paragraph is focus on comparing of power losses. These topologies were simulated: 3L-NPP with one switch per leg, 3L-NPP with two switches per leg and 2L-VSC converter. Simulation parameters were same as in Chapter IV. All topologies were tested for modulation depths m = 1 and m = 0.1. Conduction losses, switching losses and total losses were observed. The results are shown in Figures 9 and 10.

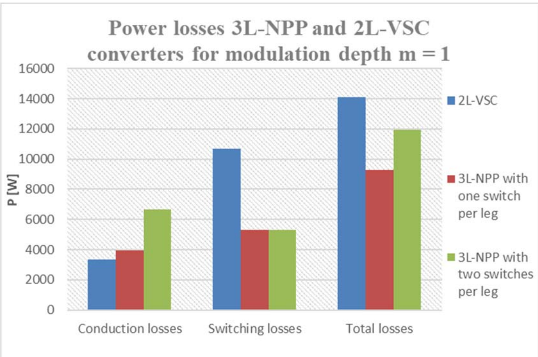

Figure 9. Power losses of 3L-NPP and 2L-VSC for modulation depth m = 1

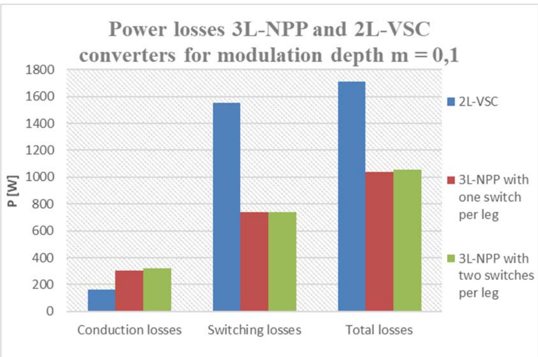

Figure 10. Power losses of 3L-NPP and 2L-VSC for modulation depth m = 0.1

The topology 2L-VSC has the lower conduction losses of all converters for both modulation depths. It is caused by number of switches per leg. 2L-VSC converter has only two switches per leg. 3L-NPP converters have four or six switches per leg depending on the selected topology. Both 3L-NPP topologies have lower switching losses in comparison with 2L-VSC converters. There are the same values of switching losses for 3L-NPP with one switch per leg and 3L-NPP with two switches per leg. This is caused by half switching voltage which is at serial connected switches.

Total losses of both 3L-NPP topologies are lower in comparison with the 2L-VSC converter. The 3L-NPP topology with one switch per leg has the lowest total losses

VI. CONCLUSION

This paper presents a description of two variants of so called three-level neutral point piloted converters (3L-NPP) with one and two serial connected transistors in one branch. The possibility of soft switching of selected transistor is analyzed. Then an analysis of output voltage and current is performed and compared with a standard two-level converter topology (2L-VSC). It is shown that the 3L-NPP topology achieves better performance in point of view of total harmonic distortion for higher modulation depths because of higher number of output voltage levels, unfortunately it contains higher number of semiconductor switches. Furthermore, the conducting, switching and total converter losses were analyzed. The lowest losses ha the 3L-NPP topology with one switch per branch. The theoretical assumptions are proven by simulations of selected transient and steady states of both converter types.

REFERENCES

[1] H. Akagi, "Multilevel Converters: Fundamental Circuits and Systems," in Proceedings of the IEEE, vol. 105, no. 11, pp. 2048-2065, Nov. 2017.

[2] H. A. B. Siddique, A. R. Lakshminarasimhan, C. I. Odeh and R. W. De Doncker, "Comparison of modular multilevel and neutral-point-clamped converters for medium-voltage grid-connected applications," 2016 IEEE International Conference on Renewable Energy Research and Applications (ICRERA), Birmingham, 2016, pp. 297-304.

[3] Wilson and S. Bernet, "Comparative evaluation of three-level converters using 4.5 kV, 1.2 kA IGBT modules," 2015 IEEE International Conference on Industrial Technology (ICIT), Seville, 2015, pp. 3040-3045.doi: 10.1109/ICIT.2015.7125547

[4] V. Guennegues, B. Gollentz, F. Meibody-Tabar, S. Rael and L. Leclere, "A converter topology for high speed motor drive applications," 2009 13th European Conference on Power Electronics and Applications, Barcelona, 2009, pp. 1-8.

[5] S. Vazquez, C. Mohan, L. G. Franquelo, A. Marquez and J. I. Leon, "A Generalized Predictive control for T-type power inverters with output LC filter," 2015 9th International Conference on Compatibility and Power Electronics (CPE), Costa da Caparica, 2015, pp. 20-24.

[6] C. Verdugo, S. Kouro, C. Rojas and T. Meynard, "Comparison of single-phase T-type multilevel converters for grid-connected PV systems," 2015 IEEE Energy Conversion Congress and Exposition (ECCE), Montreal, QC, 2015, pp. 3319-3325.

[7] IGBT model FZ1000R33HE3 datasheet. [Online]. Available: https://www.infineon.com/dgdl/Infineon-FZ1000R33HE3-DS-v03_02-EN.pdf?fileId=db3a30431ce5fb52011d760f30227290

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