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THD analysis of converter power station 25 kV 50 Hz

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Abstract—The article deals with the waveform total harmonic distortion (THD) analysis at the multilevel converter output under selected conditions. The simulation results take into account the influence of the converter topology, the number of converter levels and the phase shift in the individual branches of single-phase multilevel converters, the switching frequency and the type of PWM. The converter simulation also considers specific traffic situations with a subsequent evaluation of the investigated quantities influence. The analysis aim can be summarized in finding the ideal configuration of the output converter from the THD point of view.

1. INTRODUCTION

The technology of converter power stations 25 kV 50 Hz is another option for the currently constructed unified railway power supply system. The most common topology of 25 kV 50 Hz converter power stations is a system consisting of the following components: input three-phase isolation transformer, indirect frequency converter with voltage intermediate circuit, and single-phase output transformer. This concept was used for the first time in the Czech Republic at the Otrokovice and Říkovice substations on the II. transit corridor from Austria to Poland. At the same time, it is currently the second application of inverter power supply of a 25 kV 50 Hz catenary in the world after the application at Wulkuraka substation in Australia.

The converter technology offers several important features to address the significant negatives of conventional 25 kV 50 Hz transformer substations. Converter technologies allow unlimited recuperation to the power supply grid, definition of the spectrum of current drawn from the parent power supply system, control the amount of reactive energy, and above all symmetrization of the energy consumption from the public distribution network. Continuous two-way power supply of track sections can be achieved by the cooperation of several converter power stations with coordinated control of power supply stations and the introduction of a single phase on the entire track (possibility of connecting neutral fields). This area of advantages and disadvantages of traction power systems with converters is discussed in [1], [7], [11], [14].

2. TOPOLOGIES OF MULTILEVEL CONVERTERS

The principles of the basic types of multilevel converters are generally known and are described in detail in, for example, [2], [3] and [13]. Multilevel converters are used for application in traction substations with clamping diodes (NPC – Neutral Point Clamped converter) together with IGCT switching elements and also multilevel modular converters (MMC) with IGBT switching elements. Converter structures of the NPC type are based on the use of several three-level NPC converters, with a switching frequency of approximately 500 Hz, connected to multi-winding transformers. On the other hand, MMC converter structures are created in which a single MMC converter is used on both the input and output side of the power supply with the number of levels in the order of units or lower tens and with the switching frequency in the order of low kHz units (1-2 kHz). The range of investigated converter topologies is also adapted to the mentioned practical implementations [12].

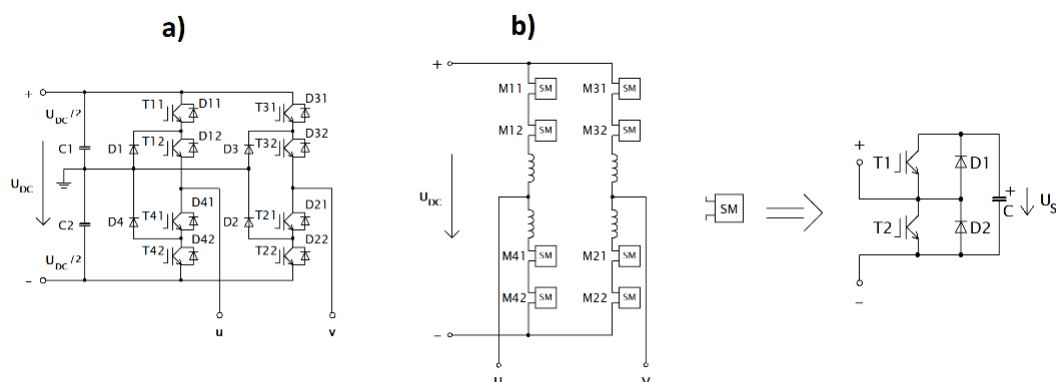


Figure 1 a) multilevel converter with clamping diodes (NPC), b) multilevel modular converter (MMC)

3. CONVERTER SIMULATIONS

The simulations are performed in Matlab Simulink [8] and [10]. Some simplifications are included in the simulation programs by replacing the submodule capacitors and the capacitive divider of the converters (see Figure 1) with ideal voltage sources. Due to these simplifications, there is no need to address balancing in the control of the converters, and furthermore, the inductors can be omitted in MMC circuits as there is no need to address the limitation of balancing currents at different real capacitor voltages [15].

This paper aims to analyze the output of a multilevel converter that operates as a single-phase inverter for the considered power flow. The input part of the substation, i.e. the transformer, the pulse rectifier (also a multilevel topology in real form) and the DC intermediate circuit were replaced by a simplification in the form of a DC voltage source. The analysis of the output converter consists of evaluating the quality of the output waveforms of current and voltage in terms of their harmonic distortion (THD_i and THD_u - see (1) and (2)) at different parameters of the output converter. Different parameters mean different inverter topology, number of levels, f_{SWITCH} switching frequency, PWM type, and especially phase shift of reference sinusoids in individual converter branches. For THD_i a THD_u the following applies:

$$THD_i = \sqrt{\sum_{n=2}^{n=40} \left(\frac{I_n}{I_1}\right)^2} \cdot 100 \quad [\%; A, A], \quad (1)$$

$$THD_u = \sqrt{\sum_{n=2}^{n=40} \left(\frac{U_n}{U_1}\right)^2} \cdot 100 \quad [\%; V, V], \quad (2)$$

where I₁, U₁ are the effective values of the basic harmonic components of the current and voltage and I_n, U_n are the effective values of the nth harmonic components of the current and voltage.

The presented results are performed for the method of PWM control using the POD PWM (Phase Opposition Disposition) method from the Level Shifted PWM category, subcategory of Multicarrier PWM, which was chosen based on previous analysis focused on the effect of PWM control on the values of THD_u and the investigated variables [9]. PWM control methods for multilevel converters are discussed in detail in, for example, [4], [5] and [6]. The presented results are made for the load designated as "load A". This is a consideration of a single-sided powered section with one vehicle moving away from the substation. A modern vehicle of 3rd generation (P = 3.43 MW) is considered in the simulations, which has a power factor cosφ = 0.99 due to the input pulse rectifier. In the simulation models, the output transformer is represented by the short-circuit reactance of conventional transformers (X_k = 7.5 Ω) and the traction circuit impedance is considered to be (Z_{trm} = 0.26 + 0.55j Ω/km) according to [16].

The primary task of the analysis is to compare two realistic traction topologies or 4x 3L NPC topology with shifted control by 1/n period (n = number of sorted 3L NPCs; and f_{SWITCH} = 500 Hz) and 9L MMC topology with f_{SWITCH} = 2 kHz. The simulation of two, three and four three-level NPC inverters, connected to several primary windings of the output transformer, was carried out with shifted control to achieve the desired reduction in the content of higher harmonic components in the waveforms of the output quantities.

Table 1 - Comparison of practically used topologies - 9L MMC (f_{SWITCH} = 2 kHz) and 4x 3L NPC with shifted control (f_{SWITCH} = 500 Hz)

1x 3L NPC (without overlap control)				2x 3L NPC (without overlap control)				3x 3L NPC (without overlap control)				4x 3L NPC (without overlap control)			
THD [%]	I _z	U _z	U _{nap}	THD [%]	I _z	U _z	U _{nap}	THD [%]	I _z	U _z	U _{nap}	THD [%]	I _z	U _z	U _{nap}
P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99				P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99				P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99				P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99			
S _{1,train} [km]				S _{1,train} [km]				S _{1,train} [km]				S _{1,train} [km]			
6	19,02	34,74	37,63	6	19,02	34,7	37,59	6	19,02	34,73	37,62	6	19,02	34,72	37,61
60	12,77	22,79	40,62	60	12,77	22,77	40,59	60	12,77	22,79	40,63	60	12,77	22,78	40,60
2x 3L NPC (with overlap control: T/2)				3x 3L NPC (with overlap control: T/3)				4x 3L NPC (with overlap control: T/4)				5x 3L NPC (with overlap control: T/5)			
THD [%]	I _z	U _z	U _{nap}	THD [%]	I _z	U _z	U _{nap}	THD [%]	I _z	U _z	U _{nap}	THD [%]	I _z	U _z	U _{nap}
P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99				P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99				P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99				P = 3,43 MW, f _{switch} = 500 Hz, cosφ = 0,99			
S _{1,train} [km]				S _{1,train} [km]				S _{1,train} [km]				S _{1,train} [km]			
6	5,45	15,29	16,86	6	2,49	9,86	10,95	6	1,51	5,48	6,08	6	0,64	3,29	3,66
60	3,44	9,59	18,61	60	1,55	6,12	12,19	60	0,97	3,41	6,76	60	0,39	2,03	4,09
9L MMC															
THD [%]	I _z	U _z	U _{nap}												
P = 3,43 MW, f _{switch} = 2 kHz, cosφ = 0,99															
S _{1,train} [km]															
6	0,64	3,29	3,66												
60	0,39	2,03	4,09												

The results without shifted control (see Table 1) are used to check the correctness of the simulation model (the THDi and THDu values for 1x, 2x and 3x 3L NPCs are identical, which verifies the correctness of the model). It can be seen that with the addition of additional 3L NPCs connected in series and at the same time with their shifted control, both THDi and THDu are reduced, which makes it possible to achieve lower THD values even without the need to increase the number of levels of a single inverter.

When comparing the chosen MMC topology (9L MMC, $f_{\text{SWITCH}} = 2 \text{ kHz}$) and the variant with 4x 3L NPC with shifted control by $\frac{1}{4}$ period (see table 1), it can be seen that the values of THDi_z (current through the load), THDu_z (voltage on the load) and THDu_{nap} (voltage at the output of the power station) came out lower for the 9L MMC variant with $f_{\text{SWITCH}} = 2 \text{ kHz}$. The largest difference in values between the investigated topologies is for THDi_z.

The second objective of the analysis is to determine the effect of the mutual phase shift of the reference sinusoids of the first and second branch potential of the inverter on the THDu values, and the effective value of the first harmonic of the output voltage of the substation.

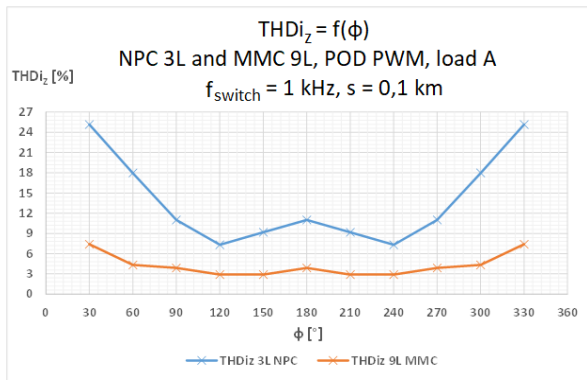


Figure 2 - Dependence of THDi_z on the phase shift of the reference sinusoids of the 1st and 2nd branch of the converter

Table 2 - Dependence of THDi_z on the phase shift of the reference sinusoids of the 1st and 2nd branch of the converter (values)

load A, s = 0,1 km, $f_{\text{NPC}} = 500 \text{ Hz}$, $f_{3-7\text{MMC}} = 1 \text{ kHz}$, $f_{9\text{MMC}} = 2 \text{ kHz}$					
ϕ [°]	NPC 3L	MMC 3L	MMC 5L	MMC 7L	MMC 9L
	THDi _z [%]	THDi _z [%]	THDi _z [%]	THDi _z [%]	THDi _z [%]
30	25,16	25,16	14,15	9,80	7,40
60	17,97	17,98	9,01	6,82	4,33
90	10,99	10,99	5,81	4,43	3,88
120	7,31	7,33	4,60	3,50	2,89
150	9,17	9,17	5,00	3,87	2,89
180	10,99	10,99	5,81	4,43	3,88
210	9,17	9,17	5,00	3,87	2,89
240	7,31	7,31	4,60	3,50	2,89
270	10,99	10,99	5,81	4,43	3,88
300	17,97	17,98	9,01	6,82	4,33
330	25,16	25,16	14,15	9,80	7,40

It can be seen from the data in Table 2 that the 3L NPC and 3L MMC inverters have similar THDu and THDi values and their circuits are interchangeable. Another finding is the reduction of THD values with an increase in the number of levels, which, however, gradually decreases in intensity with the use of converters with a higher and higher number of levels.

All the converters tested are supplied from the DC side by voltage source of 38.53 kV. The effective values of the first harmonic voltage at the U_Z load at a given angle ϕ are similar for all converter variants investigated. An example is given for a 5L MMC to compare the magnitudes of U_Z with variable ϕ . For example, at $\phi = 30^\circ$, 5L MMC U_Z = 6,900 V, further at $\phi = 120^\circ$, U_Z = 23,395 V and at $\phi = 180^\circ$, U_Z = 27,045 V. It can be seen from the results that both THDu and THDi values are lowest at $\phi = 120^\circ$, while when running with a lower shift of ϕ , there is an increase in THD, and when running with a higher shift up to $\phi = 180^\circ$, there is also an increase in THD values. The magnitude of the first harmonic voltage on the load is largest at $\phi = 180^\circ$ and decreases with any change in the shift of ϕ . Therefore, although the lowest THD values are achieved at $\phi = 120^\circ$, only 0.865·U_Z (180°) is achieved. If $\phi = 180^\circ$, then the voltage and current waveforms in the simulation circuits are much "less affected" by the multilevel nature of the converters.

4. CONCLUSION

The interchangeability of 3L NPC and 3L MMC topologies (with respect to THDi, u values) was verified by simulations, as well as the effect of increasing the number of levels on decreasing THDi, u. While the reducing effect decreases with the growth of the number of levels. Using a series connection of several 3L NPCs with shifted control is a second option for THD reduction. Comparing the 9L MMC with $f_{\text{SWITCH}} = 2 \text{ kHz}$ and the 4x 3L NPC with shifted control and $f_{\text{SWITCH}} = 500 \text{ Hz}$, or comparing two practically feasible designs, the THDi, u of the 9L MMC is lower (see Table 1). It was further verified that at $\phi = 180^\circ$ the highest effective value of the first harmonic component of the voltage at the output terminals of the substation is obtained. THDi, u values are reduced by 25 to 50% by applying $\phi = 120^\circ$ (see Table 2), but at the same time the effective value of the first harmonic of the output voltage is reduced to 0.865·U_Z (180°). Therefore, the question arises regarding the compromise between a low THD value and the size of the first harmonic component of the voltage on the U_Z load, which will vary according to the specific application. Research is now focusing on the possibility of obtaining data from the real operation of the substations.

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