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Centralized normalization of voltage harmonics in the network with distributed nonlinear loads by the third-order filters

***Abstract**. Problem of centralized normalization of harmonic voltages in a network with distributed nonlinear loads by passive third-order filters is studied in the paper. It includes: the choice of the node for filter installation, calculation of filter parameters; efficiency evaluation of chosen filters for centralized normalization of harmonic voltages at the network nodes. An example of choosing filters for a real 220 kV network supplying power to traction loads is given.*

***Streszczenie.** W artykule przedstawiono problem scentralizowanej normalizacji harmonicznych napięcia w sieci z rozłożonymi nieliniowymi obciążeniami z wykorzystaniem pasywnego filtru trzeciego rzędu. Rozważania dotyczą wyboru węzła dla instalacji filtra, obliczenia parametrów filtra oraz ocenę skuteczności wybranych filtrów do scentralizowanej normalizacji harmonicznych napięcia w węzłach sieci. Jako przykład przedstawiono wybór filtra dla rzeczywistej sieci 220kV **(Scentralizowana normalizacja harmonicznych napięcia filtrami trzeciego rzędu w sieciach z rozłożonymi obciążeniami nieliniowymi)**.*

Keywords: harmonic measurement, harmonic distortion, harmonic limits, centralized normalization, passive filter
Słowa kluczowe: pomiar harmonicznych, odkształcenia harmoniczne, dopuszczalny poziom harmonicznych, scentralizowana normalizacja harmonicznych, filtry pasywne.

Introduction

The network with distributed nonlinear loads is the 110-220 kV public electric network with a frequency of 50 Hz, that feeds railway traction substations. Railway is thousands of kilometers long. Traction substations are connected to the supply network at a distance of 40-60 km from one another. Normally each substation has two three-phase three-winding transformers with a capacity of 40 MW. The 27.5 kV transformer winding feeds traction network that supplies power to electric locomotives. In the normal condition only one transformer is in operation. The second transformer is switched off. In the event of some emergency or maintenance the second transformer is switched on. Every traction substation is fed by two sources, as a rule, by two-circuit transmission lines. Electric locomotives operate with direct current motors that receive power through one-phase two-pulse rectification circuits. These motors are nonlinear loads that cause distortion of voltage waveform at the nodes connecting traction substations to supply network. An average power of traction load is 4-8 MW. The maximum power is up to 20 MW.

The voltage nonsinusoidality according to the Russian standard [1] is characterized by two indices: $K_{U(h)} = 100U_h / U_{nom}$ [%] – a h-th harmonic factor and $K_U = 100\sqrt{\sum_{h=2}^{H} U_h^2} / U_{nom}$ [%] – a total harmonic distortion, h - a harmonic number.

Measurements show that voltage nonsinusoidality at the points of connecting traction substations to the supply network exceeds the limits set according to [1].

The studies have revealed that centralized normalization of the indices may become an efficient method of decreasing the values of $K_{U(h)}$ and K_U at the nodes connecting traction substations to the supply network. With centralized normalization in the network with distributed nonlinear loads it will be sufficient to install filters only at some nodes.

Centralized normalization of harmonic voltages was already considered in [2-5]. It concerned radial networks of low and medium voltages with numerous nonlinear low-power loads. Single-tuned passive shunt filters consisting of a reactor and a capacitor connected in series were applied for harmonic filtering. The work [3] also underlines essential advantages of the centralized approach which are difficult to deny.

This paper studies the possibility of centralized normalization of harmonic voltages in an extended HV network by the third-order filters. In [6] such a problem was solved by the C-type filters. The authors in [7] point out that the C-type filter is more sensitive to changes in frequency and variations in parameters of elements than the third-order filter. It is also noted that the third-order filter has a great advantage – low losses at the fundamental frequency. Calculation of the third-order filter parameters poses difficulty. In [8] expressions for calculation of the filter parameters are derived for the condition of equal capacitance of two capacitors used in the filters, i.e. $C_1 = C_2$. In [7] the authors indicate that in the third-order filter there should be a relation $C_1 >> C_2$. In this paper the expressions for calculation of the filter parameters if $C_1 \neq C_2$ are obtained and possible relations between C_1 and C_2 are studied.

The choice of network node for filter installation is the most difficult problem for the centralized approach [4-5]. The authors of the mentioned works suggest rather sophisticated methods for determination of the preferred node for filter installation. This paper offers a very simple approach for present purposes that reflects the essence of a real filter at the tuned frequency. In [6] the approach is called a "test filter".

The paper gives an example of choosing the third-order filter of the 5-th harmonic for the 220 kV network supplying traction substations with power.

Main stages of choosing filters for centralized normalization of harmonic voltages

The main stages of choosing filters may be the following:

- analysis of harmonic modes in the network;
- choice of node for installation of filter;
- calculation of the harmonic filter parameters;
- evaluation of the efficiency of the selected harmonic filters in the considered network.

A. Analysis of harmonic modes in the network

The necessity of exact information about harmonic parameters in the network for choosing filters has been underlined in extensive publications. The information is needed for choosing the nodes for filter installation and calculating the filter parameters.

In the extended network special features of harmonic modes manifest themselves, for example, ripple effect, besides with a large number of nonlinear loads the harmonic currents are compensated.

When choosing filters it is also necessary to take into account the changes in the network. The changes can be so large that filters may fail to operate in accordance with their purpose. Changes in the network, for example, when disconnecting transmission lines, cause changes in the harmonic voltages in the nodes. They may both decrease and increase. When the network configuration is changed the values of harmonic voltages at the nodes can change since impedances of paths, on which currents flow, vary and therefore currents are redistributed.

The network configuration and its state parameters change during operation therefore it is important to choose the most suitable rated condition for choosing the node for installation of filter in order to provide later the filter's effective work at network changes.

B. Choice of node for installation of filter

In the centralized approach correct choice of node for installation of filter is the major task. The node should be chosen in such a way that the harmonic voltages are decreased in the largest number of nodes and by the highest value.

The work [2] suggests installation of filter at the node with the highest harmonic voltages at the end or near the end of the feeder. In [4] the best node for filter installation is determined by the sensitivity analysis method that allows the siting indices to be obtained. In [5] the best node for filter installation is sought by applying the normalized sensitivity index obtained by the admittance matrix in terms of its eigenvalues and eigenvectors, account being taken of harmonic current injections. The approaches suggested in [4-5] are complicated and require much effort. In [6] the search for the node for filter installation is carried out on the basis of the "test filter" that is a resistance of 10 or 100 Ohm and even more. The idea of the approach is that any passive filter at the tuned harmonic is a resistance. Placement of resistance as a filter at each node that is a candidate for filter installation and calculation of harmonic voltages at the nodes reveal the tendency of change in harmonic voltages at the nodes, for which the filter is chosen. After analysis and comparison of the results it is possible to determine the node preferred for filter installation. The example of node choice by the "test filter" is given below.

C. Determination of the third-order filter parameters

Let the n-th harmonic denote the harmonic to be tuned to. The filter parameters should be chosen so that the filter can provide desirable nodal voltage at the n-th harmonic U_{nf} or the desirable value of the index that will be denoted by $K_{U(n)f}$. If with respect to some node the electric network at the n-th harmonic is represented as current source with admittance, the nodal voltage $\dot{U}_n$ will be determined from the expression

(1) $$\dot{U}_n = \frac{\dot{I}_{nS}}{Y_{nS}},$$

where $\dot{I}_{nS}$ is the current of the current source of the network $Y_{nS} = g_{nS} + jb_{nS}$ is the admittance of current source of the network.

The voltage can be reduced by increasing the denominator, what in turn can be achieved by the filter admittance Y_{nf}

(2) $$\dot{U}_{nf} = \frac{\dot{I}_{nS}}{Y_{nS} + Y_{nf}}.$$

In [9] it is suggested the use of conductance as such an admittance. Then the filter for the n-th harmonic should have the value of the input resistance R_{nf} that will provide decrease of the tuned harmonic voltage. The resistance value R_{nf} can be determined accurately enough, when expressions (1) and (2) are applied jointly

(3) $$R_{nf} = \frac{K_{U(n)f}}{(K_{U(n)} - K_{U(n)f})\sqrt{g_{nS}^2 + b_{nS}^2}},$$

where $K_{U(n)}$, $K_{U(n)f}$ - values of indices at the node without the filter and with it.

The scheme of the third-order filter is given in Fig.1. It is necessary to determine the parameters X_{C1}, X_{C2}, R, X_L at the fundamental frequency. The value of R is assumed to be invariable with change in the frequency. Resistance of reactor is not taken into account.

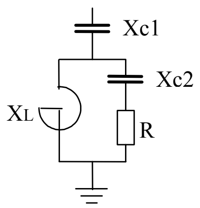

Fig.1. Schematic diagram of the third-order filter

The filter parameters should meet the following conditions:

1) reactive power of filter at the fundamental frequency equals $Q_{(1)}$,

2) reactance of filter at the n-th harmonic equals zero,

3) resistance of filter at the n-th harmonic equals R_{nf},

4) $X_{C2} = mX_{C1}$, where m – a coefficient taking into account relation between X_{C1} and X_{C2}.

Impedance of the third-order filter at the n-th harmonic can be written as

$$Z_n = \frac{jX_{Ln}(R - jX_{C2n})}{R + j(X_{Ln} - X_{C2n})} - jX_{C1n}.$$

Transform Z_n, by separating real and imaginary parts

$$Z_n = \frac{RX_{Ln}^2}{R^2 + X_{LC2n}^2} + j\frac{R^2 X_{LC1n} - X_{Ln}X_{C2n}X_{LC2n} - X_{C1n}X_{LC2n}^2}{R^2 + X_{LC2n}^2},$$

where

(4) $$X_{LC1n} = X_{Ln} - X_{C1n},$$
$$X_{LC2n} = X_{Ln} - X_{C2n}.$$

According to conditions 2) and 3) imaginary part Z_n at the n-th harmonic is equal to zero, real - to R_{nf}. After the transformations real and imaginary part Z_n can be represented as a system of two equations

$$RX_{Ln}^2 - R_{nf}R^2 - R_{nf}X_{LC2n}^2 = 0,$$

$$R^2X_{LC1n} - X_{Ln}X_{C2n}X_{LC2n} - X_{C1n}X_{LC2n}^2 = 0.$$

Having solved the system of equations, considering that $X_{C2} = mX_{C1}$, we obtain the expressions for X_{Ln} and R

(5) $$X_{Ln} = (-B + \sqrt{B^2 - 4AC})/(2A),$$

(6) $$R = R_{nf}(X_{Ln} - mX_{C1n})/X_{LC1n},$$

where

(7) $$A = -X_{C1n}(1+m),$$

(8) $$B = R_{nf}^2 + X_{C1n}^2(1+2m),$$

(9) $$C = -R_{nf}^2 mX_{C1n}(1 + X_{C1n}^2).$$

The value of m is unknown in the obtained expressions. In order to determine the admissible values of m we use the conditions that $C_1 >> C_2$ and the expression under the root sign in (5) should be positive, i.e.

$$B^2 - 4AC > 0.$$

Solving the inequality we obtain the value of m lying in the interval

(10) $$1 < m \le \frac{R_{nf}^2 + X_{C1n}^2}{2R_{nf}X_{C1n}}.$$

Expression (10) shows that the relation between X_{C1} and X_{C2} is determined by the values X_{C1} and R_{nf} at the harmonic for which the filter is chosen. Thus, the parameters of the third-order filter on the basis of (4), (5-10) can be calculated by the expressions:

$$X_{C1} = \sqrt{3}U^2/Q_{C1},$$

$$X_{C2} = mX_{C1},$$

$$X_L = (-B + \sqrt{B^2 - 4AC})/(2An),$$

$$R = R_{nf}(X_L n^2 - mX_{C1})/(X_L n^2 - X_{C1}),$$

where U is the voltage at the fundamental frequency. Calculations show that the value of Q_{C1} may be set equal to (0.5-0.6) of the reactive power $Q_{(1)}$. The required value of $Q_{(1)}$ can be determined by calculating the condition at the fundamental frequency or by using the annual curves of reactive power consumed by loads. The power factor of traction load is about 0.85.

The filter parameters should be selected so that the total power losses in filter for all harmonics are minimal, i.e.

$$\sum_{h=1}^{H} P_{(h)} = min$$

subject to

$$K_{U(n)f\,min} \le K_{U(n)f} \le K_{U(n)f\,max},$$

$$Q_{(1)min} \le Q_{(1)} \le Q_{(1)max}.$$

D. Evaluation of the efficiency of the selected filters

After the filters are chosen, it is necessary to verify the efficiency of filter operation under all possible network states. This will make it possible to know when the filters can deteriorate operation and possibly disconnect them or consider another version of the filters.

An example of choosing filter

Choice of the third-order filter for the 5-th harmonic is presented as an example.

A. Analysis of harmonic mode in the considered network

The 220 kV network is 900 km long. It supplies power to 23 traction substations. Fig.2 shows the oscillograms of voltages that are drawn on the high voltage side of the transformer at one of the traction substations.

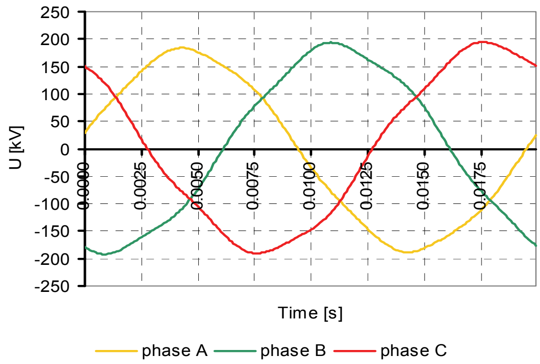

Fig. 2. Oscillograms of the phase voltages

The indices $K_{U(h)}$ and K_U were measured at seven traction substations. The measurement results are presented in Table 1. The same table shows admissible values of $K_{U(h)}$ and K_U determined in [1]. The measured values of indices that exceed the admissible values are given in bold type. The admissible values of $K_{U(h)}$ and K_U are exceeded at four network nodes, i.e. S6, S12, S13, S14.

Table 1. Measured $K_{U(h)}$ and K_U

Substation	K_U [%]	$K_{U(3)}$ [%]	$K_{U(5)}$ [%]	$K_{U(7)}$ [%]
S1	1.99	0.76	1.34	0.92
S2	1.92	0.84	1.13	0.81
S3	1.91	0.89	1.02	0.70
S6	**2.54**	1.00	**2.32**	0.76
S12	**2.01**	**1.71**	1.22	0.69
S13	**2.86**	**2.00**	**2.07**	0.82
S14	**3.09**	**2.06**	**2.27**	0.96
Norms	2.0	1.5	1.5	1.0

The values of indices at the other nodes of the considered network were calculated by the software HARMONICS. Fig. 3 presents the values of K_U, $K_{U(3)}$, $K_{U(5)}$, $K_{U(7)}$ at the nodes of the considered network without filters. The admissible values of $K_{U(3)}$ are exceeded at eight nodes, $K_{U(5)}$ - at twelve, $K_{U(7)}$ - at four, K_U - at twelve nodes and should be reduced with the help of filters. Normal operating condition was assumed as rated condition to choose filter for the considered network. The measurements of $K_{U(h)}$ and K_U were carried out for this condition. After calculations of $K_{U(h)}$ in the rated condition we form the groups of nodes at which the admissible value of index is exceeded and which will be considered as candidate nodes for filter installation.

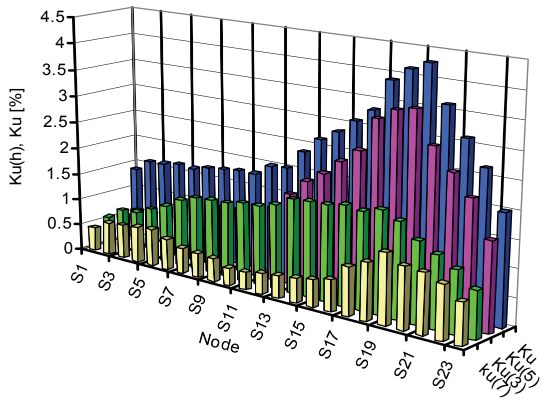

Fig. 3. $K_{U(h)}$ and K_U at network nodes without filters

B. Choice of node for the filter installation

The choice of node intended for filter installation is made with the help of a "test filter". A "test filter" with a resistance of 100 Ohm is installed at each of candidate nodes and the 5-th harmonic condition is calculated. In Fig. 4 the name of each curve indicates the node for installation of the "test filter" and the curves show the impact of filter on the value of $K_{U(5)}$. Curves show that the most suitable node for the 5-th harmonic filter is node S17. The filter decreases the value of $K_{U(5)}$ practically at all the nodes of the network. The curve of $K_{U(5)}$ changes along the entire trajectory of nodes without dramatic changes in the value.

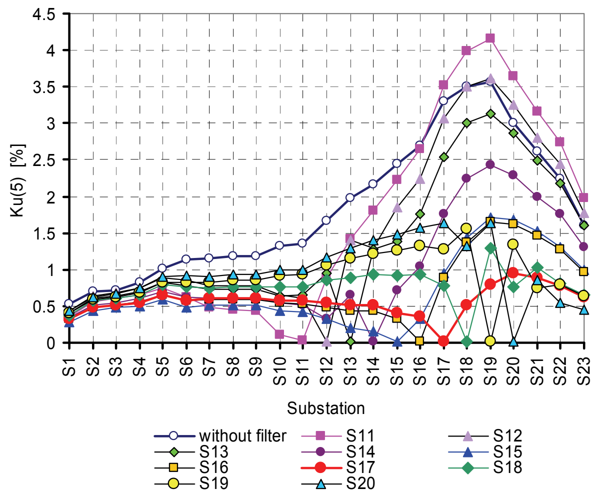

Fig.4. $K_{U(5)}$ at nodes of the network with test filter

C. Determination of parameters of the 5-th harmonic filter

The filter parameters of 5-th harmonic will be selected so that the values of $K_{U(5)f}$ at the network nodes are (0.7-1.2) %, the value of Q_{C1} of a filter can be (3-6) Mvar.

The values of the filter resistance $R_{(5)f}$ for the desired values of $K_{U(5)f}$ were calculated by expression (3). Fig. 5 presents curves of the resistance $R_{(5)f}$, and also the power losses P at the 5-th harmonic in the filter at the calculated values of $R_{(5)f}$.

As a result of analysis it was assumed to calculate the filter parameters for $K_{U(5)f}$ equal to 0.7%, which is achieved at $R_{(5)f}$ equal to 69.2 Ohm and the power losses of 34.3kW. For the 5-th harmonic filter it was assumed that Q_{C1} is equal to 3 Mvar.

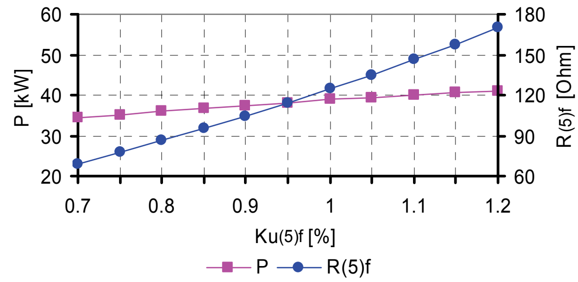

Fig. 5. $R_{(5)f}$ and P with change of $K_{U(5)f}$

The range of values of the parameter m was calculated by relation (10). Table 2 presents the minimum and maximum values of m. For example, for $R_{(5)f}$ equal to 69.2 Ohm and Q_{C1} equal to 3 Mvar the values of m must be in the range 2.33< m ≤20.99.

Table 2. Values of m

$K_{U(5)f}$ [%]	Q_{C1} [Mvar]			
	3	4	5	6
0.7	2.33	1.75	1.4	1.17
	20.99	15.75	12.65	10.51
0.8	1.87	1.40	1.12	0.94
	16.85	12.64	10.12	8.44
0.9	1.54	1.16	0.93	0.77
	13.89	10.43	8.35	6.97
1.0	1.30	0.97	0.78	0.65
	11.68	8.77	7.03	5.87
1.1	1.11	0.83	0.67	0.56
	9.96	7.48	6.00	5.01
1.2	0.95	0.72	0.57	0.48
	8.58	6.45	5.17	4.32

The filter parameters were calculated by applying 10 values of m with a step of Δm equal to 2.33. The input reactance of the filter for harmonics from 1 to 25 is presented in Fig.6.

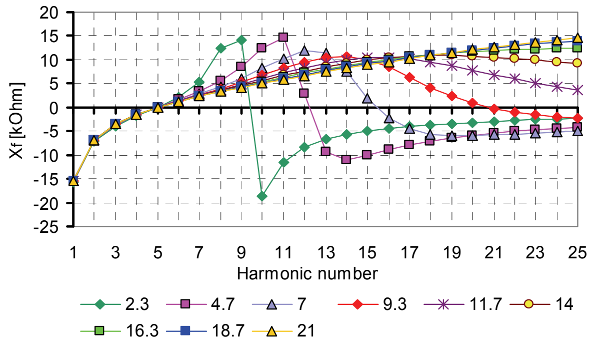

Fig. 6. Input filter reactance for different values of m

The choice of the filter parameters should provide impossibility for occurrence of resonant modes in the network at the harmonics above the tuned harmonic and the least power losses at both the fundamental and harmonic frequencies. The curves (Fig.6) show that for the harmonics below the 5-th one the filter reactance is capacitive. For the harmonics above the 5-th one for $m \leq 9.3$ the filter reactance is also capacitive for some harmonics, which can create resonance circuits with the network. Analysis of the curves shows that m equal to 20.99 is the most suitable for selecting the filter. The parameters corresponding to this value of m were selected for the 5-th harmonic filter.

The filter parameters of the 3-rd and 7-th harmonics were determined in a similar way. The filter parameters are presented in Table 3.

Table 3. Parameters of filters

Parameter	Harmonic number		
	3	5	7
Q_{C1} [Mvar]	4.	3.	3.
X_{C1} [Ohm]	12100.	16133.	16133.
X_{C2} [Ohm]	191181.	338639.	111166.
X_L [Ohm]	1287.	624.	299.
R [Ohm]	39941.	42447.	9954.

The curves of $K_{U(3)}$, $K_{U(5)}$, $K_{U(7)}$ at the network nodes with filters are shown in Fig. 7. At all the network nodes the filters decrease the values of indices to the desired values.

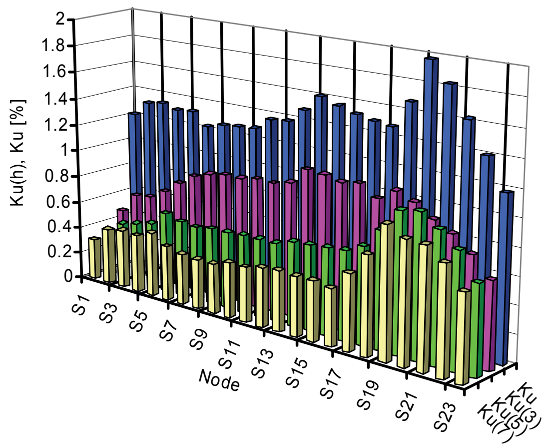

Fig.7. $K_{U(h)}$ and K_U at the network nodes with filters

D. Evaluation of the efficiency of selected filters

Eighteen special calculations were made to estimate the efficiency of filters of the 3-rd, 5-th and 7-th harmonics that were accommodated on the 220 kV buses of substation S17. In each of the calculations network configuration was changed by disconnecting the line feeding one of the traction substations and the values of indices $K_{U(3)}$, $K_{U(5)}$, $K_{U(7)}$ at the nodes throughout the network were calculated. For the 3-rd and 5-th harmonics only in 2 of 18 conditions the indices $K_{U(3)}$ and $K_{U(5)}$ did not decrease, for the 7-th harmonic one more condition was added to the previous two.

Besides, the impact of the selected filters on operating conditions of harmonics 11, 13, 17, 19, 23 and 25 was analyzed at all the nodes. Fig. 8 shows the curves of $K_{U(11)}$ and $K_{U(13)}$ without filters and with them. It is seen that the impact of selected filters on voltages of harmonics 11 and 13 at all the network nodes is negligible. There is practically no impact of filters for the remaining harmonics.

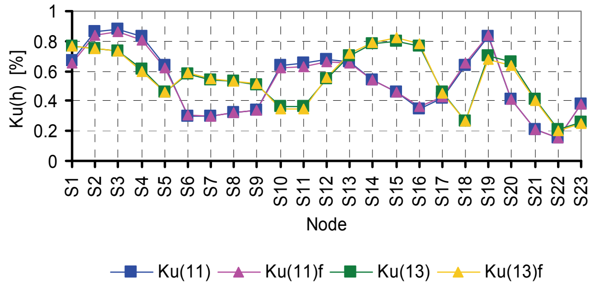

Fig.8. $K_{U(h)}$ at the nodes without filters and with filters

Conclusions

1. The possibility is shown to centrally normalize harmonic voltages with the third-order filter at the nodes of an extended high voltage network with distributed nonlinear loads.
2. The mathematical expressions are derived to determine the parameters of the third-order filter.
3. The "test filter" is suggested for choosing the network node to install a filter.
4. The example of filters of the 3-rd, 5-th and 7-th harmonics is given for the extended 220 kV network that feeds traction substations.

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