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Elimination of higher harmonics of voltage in the power systems supplying the rectifier circuits

***Abstract**. The paper presents the results of simulation of the power network composed of the main supplying point (PCC) of 15kV, 4km overhead supply line of middle voltage, filter of k^{th} harmonics and 6- and 12-pulse rectifier. In each case we have determined the impedance characteristics of the network as the function of frequency in steady state of AC analysis. The values of the voltage harmonics corresponding to the circuit before and after filter of k^{th} harmonic have been also calculated. The supplying line was simulated by a two-port of the distributed parameters. The numerical data used in experiments have been acquired from the real (physical) power system. All experiments have been performed using Micro-Cap 8 program. In the paper we have included the exemplary results of the numerical calculations..*

***Streszczenie.** W artykule przedstawiono wyniki badań symulacyjnych dotyczących współpracy odbiornika nieliniowego 6- i 12-pulsowego prostownika/ z systemem elektroenergetycznym z dołączonym filtrami wyższych harmonicznych. Dla poszczególnych przypadków przedstawiono zmiany modułów impedancji układu w zależności od częstotliwości wyznaczone przy wykorzystaniu analizy AC. Do obliczeń numerycznych przyjęto dane występujące w układach rzeczywistych a linie zasilające napowietrzne odwzorowano układami o parametrach skupionych . Dla różnych konfiguracji określono wartości wyższych harmonicznych prądu i napięcia oraz współczynniki odkształcenia napięcia i prądu w liniach 15 kV Wszystkie obliczenia zostały przeprowadzone z wykorzystaniem programu MicroCap-8. (**Eliminacja wyższych harmonicznych napięcia w systemach elektroenergetycznych zasilanych przez układ prostownikowy**)*

Keywords: Higher harmonics of current and voltage, total harmonics distortion, filter of k^{th} harmonics
Słowa kluczowe: Wyższe harmoniczne prądu i napięcia, współczynnik odkształcenia napięcia i prądu, filtry wyższych harmonicznych

Introduction

Different compensating structures are used to reduce the effect of the nonlinear load [1,2,5]. One of such solution, leading to the reduction of the voltage distortion, is the application of the filters of higher harmonics. The branches of the filter are of capacitive characters for the frequencies below the resonance frequency, hence they may be used to compensate the reactive power for the fundamental harmonic. In practice such filters may be treated as the filtering-compensating devices (FCD). The main subject of this work is determination of the frequency characteristics of the absolute value of the impedance supplying system at different variants of installation of the filter of k^{th} harmonic. These characteristics are important in practice, since they inform us at what frequencies the reduction of the voltage is expected as a result of installation of such filter. High reduction of voltage may cause the increase of THD at the main supply point. This negative effect can be observed in the supply system, when the nonlinear load generating higher harmonics, is attached to the system. This situation is illustrated in Fig.1, when the nonlinear load will be attached at node 2.

System description

Figure 1 presents the general scheme of supplying the nonlinear load $u = f(i)$.

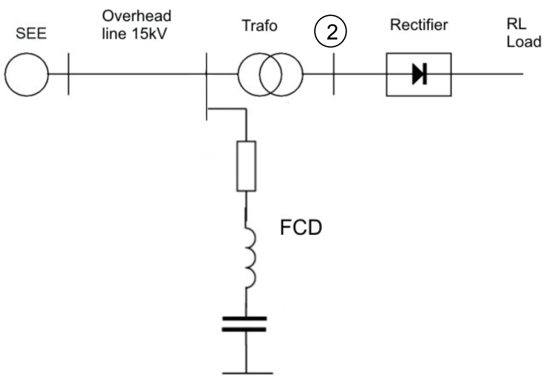

Fig.1. The general structure of the simulated system

The model presented in Fig. 1 is composed of the following elements:, transformer110/15kV, the main supplying point (PCC) 15kV of short-circuit power S_{zw}= 200 MVA, 4 km overhead supply line of 15 kV , of 120 mm2 cross-section and filter 5^{th} or 11^{th} harmonic and transformer 15/3 kV, 6- or 12- pulse rectifier (the nonlinear load $u = f(i)$) and the load of inductive character [3,4].

The parameters (R_S, L_S) of the model representing the supplying systems on the level 15 kV have been determined using following formulas (for $f = 50Hz$)

$$X_S = \frac{1{,}1 * U^2}{S_{ZW}} \quad R_S \approx 0{,}1 X_S \quad L_S = \frac{X}{\omega}$$

The unity parameters of the overhead transmission line 15 kV of the cross section S=120mm^2: R_1=0.245 Ω/km, L_1=1.3e^{-3} H/km, C_1= C_2=0.00489e^{-6} F/km

The supplying 15 kV line can be modeled by the 2-port of π structure and parameters depending on the elementary resistance, conductance and capacitance as well as the length of it [1,2].

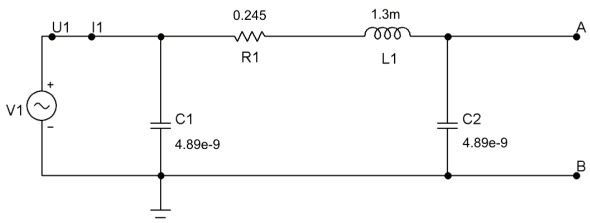

Fig.2. Model of the 1km supplying line

Comparing the analyzed characteristics of the simulated system we may conclude, that the best variant is placement of the filter of k^{th} harmonic at the end of supplying line (node 2 of Fig.1).

The discussed rectifier circuit, as the nonlinear load, follows the characteristic distortion on the supply side of the system. The main distortion in the power supply followed by the traction substation is the deformation of the power supply voltage. It follows from the 6-pulse converter generating k-th harmonics of [3,4] k = 2n±1 where n =3,6,9,.......

and 12-pulse converter

k = 4n±1 where n =3,6,9,.......

The additional distortion is the flicker of the voltage followed by the abrupt changes of the load.

The most basic measure of distortion is total harmonic distortion (THD) of the current (THDI) and voltage (THDV).[1,5]

$$THDI = \sqrt{\sum_{k=2}^{n}\left(\frac{I_k}{I_1}\right)^2}\cdot 100\%$$

$$THDV = \sqrt{\sum_{k=2}^{n}\left(\frac{U_k}{U_1}\right)^2}\cdot 100\%$$

where I_k, U_k - the r_{ms} value of k th harmonics of the current and voltage, I_1, U_1 - the r_{ms} value of the first (fundamental) harmonics of the current and voltage, n – maximum number of harmonic taken into account in calculations.

The subject of this work is concerned with the modeling of the real system, enabling the determination of the succeeding harmonics of the voltage and current, followed by the application of the traction converters, as well as their propagation to the supply sources side.

The influence of filtering-compensating device – FCD (the passive filter) on the voltage waveform is analyzed using the equivalent impedance of the nonlinear device terminals (terminals at node 2 in Fig.1), investigated as a function of frequency. In such way we may investigate the changes of impedance in the whole frequency range. Remember, that connecting even single filter causes the change of the frequency characteristics of the whole circuit.

To get the parameters concerning the deformation of the voltage and current in the system we have to know the transient values of the corresponding variables. Fig.7 and Fig.12 illustrate these transients used in further analysis.

One of the most important element of the system is transformer. It transforms the input voltage into the output voltage of the required level. At the same time the input and output currents are also accordingly transformed. In sequence these currents determine the distortion of the voltages on both sides of the transformer. For 6-pulse rectifier the Y/d11 transformer was modeled as as the three identical (ideal) 1-phase transformers.[4]

Ithe case of 12-pulse rectifier we have applied Y/d11/y0, as shown in Fig.10. Assuming the voltage ratio of the winding transformer Y/d11,υ = 0.15 as well as the of the winding transformer Y/y0, $\upsilon1$= 0.0876 as well as the magnitude of supply voltage 12600V we have got the transient voltages of the primary and secondary side. [3] .

12-pulse converter is serial connection of two 3-phase rectifier with power supplies shifted of 30 degrees.

The load of the simulated system is formed by the traction engines, converting the electrical energy into mechanical. We have applied the RL model of such engine, of the parameters adjusted adequately.

3. The system supplying the rectifiers at presence of the passive filter – the numerical results

We consider have the rectifying devices working in 6- and 12- pulse modes (Fig. 4 and Fig.10). They are working in the circuit of the parameters adjusted to the short-circuit power (S_{zw}= 200MVA).

The rectifiers, as the nonlinear devices cause the deformations of the currents flowing in the circuit. analysis The analysis of this process will done throng the time series analysis of currents. The impedance frequency characteristics of the whole system will be observed in the circuit structure presented in Fig.3.

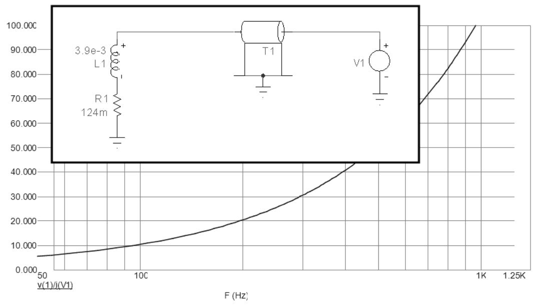

Fig.3. The change of the absolute value of the impedance Z_{we}= f(ω) of the supply system without FCD. T1 – overhead 15kV line of the length 4 km supplying the nonlinear load

In harmonic analysis we have to determine the values of impedances corresponding to specific frequencies characteristic for the applied type of rectifier system. Table1 presents the values of impedances of the supplying system for the specific kth harmonics

Table I. The values of impedances of the supplying system for the specific kth harmonics

		Harmonic order							
		5	7	11	13	17	19	23	25
Z	Ω	13.7	19.2	30.2	35.6	46.8	52.2	69.7	69.1

The effective method of limitation of the harmonic signals of the current is the application of the FCD included parallel in all phases of the supplying system. The choice of parameters of FCD depends on the value of assumed damping coefficient observe, that the impedance of the branch of FCD for the resonant frequency is resistive character. Figure 4 presents circuit model of the network with 6-pulse rectifier and with filter of 5th harmonic.

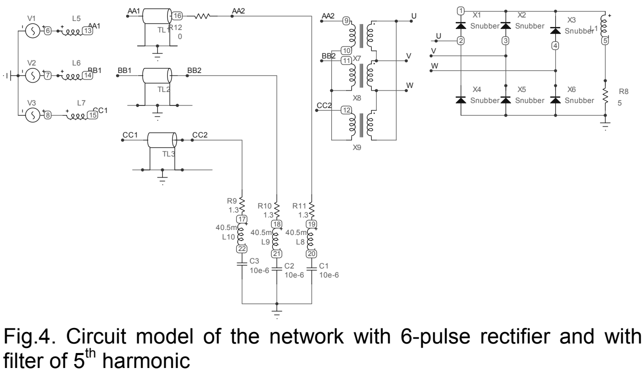

Fig.4. Circuit model of the network with 6-pulse rectifier and with filter of 5th harmonic

Let us assume the resistance of the filter for 5th harmonic equal R_f=0.5×Z=6,8Ω , the quality factor D=50, the reactance Xc =6.8×50=340Ω . At such assumption we get C=1.87μF. Assuming in practice C=2μF, from the relation X_L = X_C we get L=0.2H.The frequency characteristic of one phase of the supplying system in the presence of such filter is presented in Fig. 5.

Figures 3 and 5 present the change of the absolute value of the impedance Z_{we} = f(ω) of the power system seen from the nonlinear device terminals for the following cases: power system without FCD (Fig.3), power system with filter of 5th harmonic (R_f=0.5×Z, and D=50) attached at the end of supply line (Fig.5). Figure 6 presents spectrum of 15 kV voltage with 6-pulse rectifier.

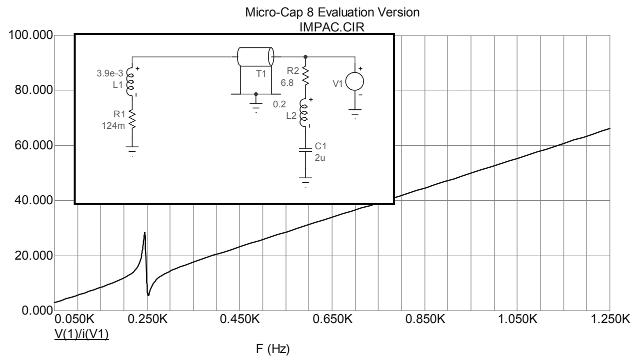

Fig.5. The change of the absolute value of the impedance Z_{we}= f(ω) of the supply system with filter of 5th harmonic attached at the end of supply line (R_f = 0,5×Z, and D=50)

Comparing the analyzed characteristics of the simulated system we may conclude, that the best variant is placement of the filter of kth harmonic at the end of supplying line (node 2 of Fig.1).

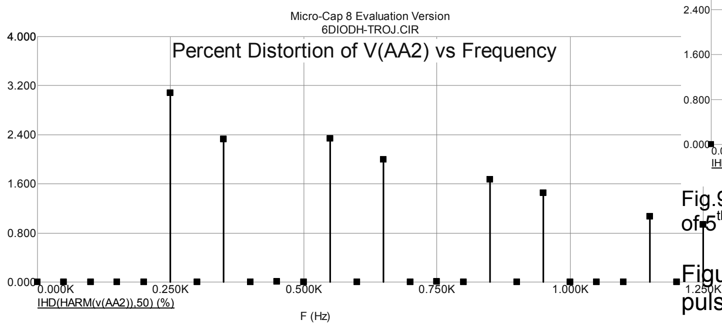

Fig.6.Spectrum of 15 kV voltage with 6-pulse rectifier

Comparison of the values of higher harmonics of Fig .5 and Fig. 6 shows insignificant reduction of the deformation of the voltage at the point annexed of the filter of 5th harmonic. Better effect of reduction of this deformation is expected, when we assume the resistance of the 5th harmonic filter equal R_f = 0.1× Z = 1.3 Ω at the same quality factor D=50. In such case X_C = 1.3×50 =65 Ω and C=9.7μF.

Assuming C=10μF from the reactance X_L = X_C we got L=40.5 mH. The frequency characteristic of one phase of the supplying system in the presence of such filter is presented in Fig.8

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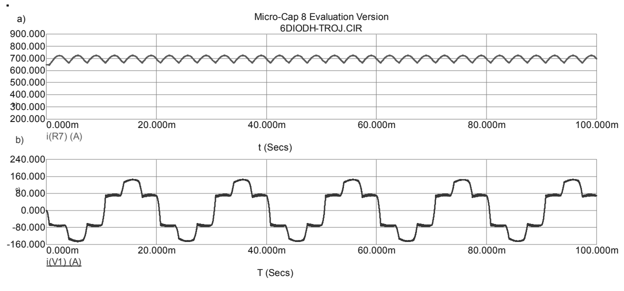

Fig.7.Transient signals of :a) rectified DC current, b)AC current at 15 kV side of the transformer without FCD

Figure 9 presents spectrum of 15 kV voltage with 6-pulse rectifier and with filter of 5th harmonic (R_f = 0.1×Z, and D=50).

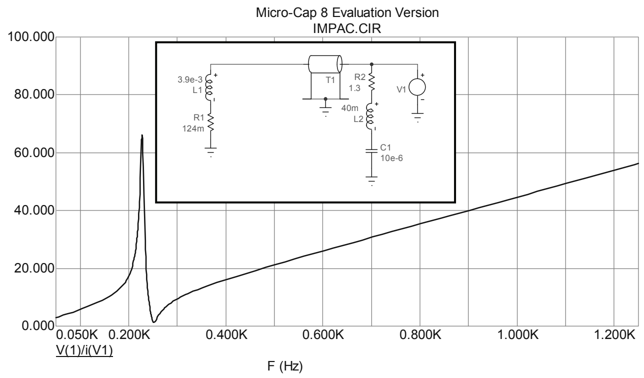

Fig.8. The change of the absolute value of the impedance Zwe= f(ω) of the supply system with filter of 5th harmonic attached at the end of supply line (R_f = 0.1×Z, and D=50)

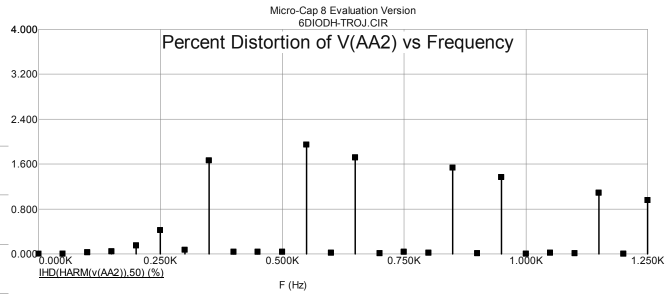

Fig.9.Spectrum of 15 kV voltage with 6-pulse rectifier and with filter of 5th harmonic (R_f = 0.1×Z, and D=50)

Figure 10 presents circuit model of the network with 12-pulse rectifier and with filter of 11th harmonic

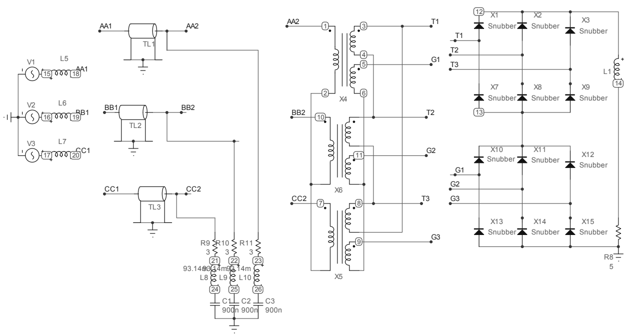

Fig.10. Circuit model of the network with 12-pulse rectifier and with filter of 11th harmonic

In the case of 12-pulse rectifier we should design the filter tuned to 11th harmonic, which dominates in such system. According to Table 1 the impedance of the supplying system for 11th harmonic (550 Hz) is equal Z_{11}=30.2 Ω. To get the significant reduction, of this harmonic we should assume R_f=0.1×Z=3 Ω. Our empirical knowledge suggests, that we should put the quality factor of the tilter equal D_k=k×10, where k is the number of considered harmonic (in our case k=11). Hence we get D=110, from which we get X_C=330 Ω and C=877μF. Putting C=900nF we get X_C=321.69 Ω and C=93.14mH.

Figure 11 presented the change of the absolute value of the impedance Z_{we}= f(ω) of the supply system with filter of 11th harmonic attached at the end of supplying line (R_f = 0,1×Z, and D=110).

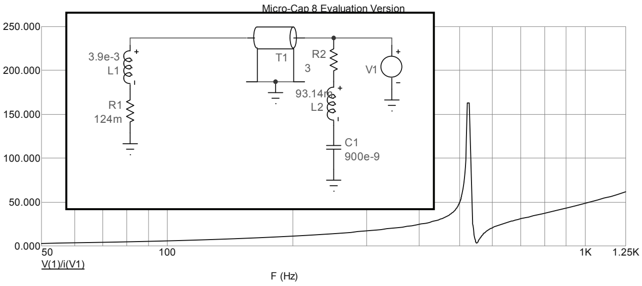

Fig.11. The change of the absolute value of the impedance Z_{we}= f(ω) of the supply system with filter of 11th harmonic attached at the end of supplying line (R_f = 0.1×Z, and D=110)

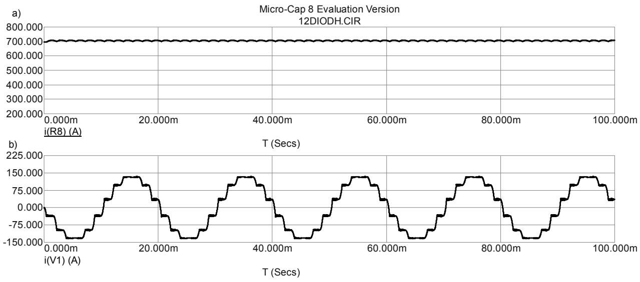

Fig.12.Transient signals :a) the rectified DC current, b) AC current at 15 kV side without FCD

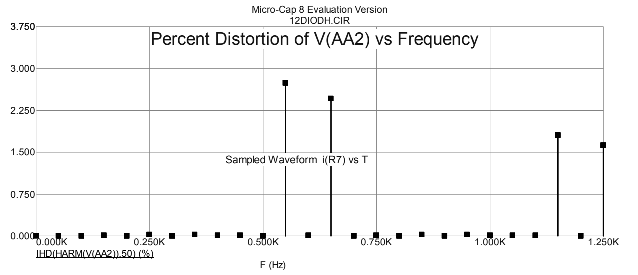

Fig.13.Spectrum of 15 kV voltage at 12-pulse rectifier

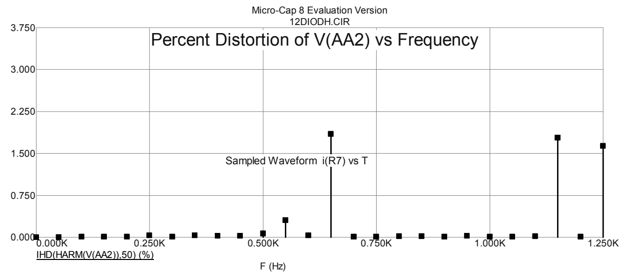

Fig.14.Spectrum of 15 kV voltage with 12-pulse rectifier and with filter of 11th harmonic

Table II. The values of kth harmonics of the rectified current

The values of kth harmonics of the rectified current		Harmonic order			
		6	12	18	24
6-pulse	I_k [A]	27.27	4.27	1.43	1.0
12-pulse	I_k [A]	-	4.1	-	0.582

The results have proved the filters of 5th (Fig.9) and 11th (Fig.14) harmonics are very efficient in improvement of THD in 15 kV power system.

On the basis of the experimental results we have compared the sensitivity of the current & voltage distortion parameters

$$U_{k\%} = \frac{U_k}{U_1} \cdot 100\% \qquad I_{k\%} = \frac{I_k}{I_1} \cdot 100\%$$

to the type of the applied converter, shown in table II and III.

The results suggest that application of 12-pulse converter leads to the limitation of the current distortion and as a result of it, also the voltage distortion.

Table III. The percentages of current I_k% and voltage U_k% harmonics at supplying system

U_k%, I_k% harm. at supplying system		5	7	11	13	17	19	$THD_{\%}$
6-pulse	$I_{k\%}$	20.9	11.28	7.22	5.22	3.36	2.5	25.8
	$U_{k\%}$	3.09	2.33	2.34	1.99	1.68	1.45	5.6
12-pulse	$I_{k\%}$	-	-	8.36	6.33	-	-	11.03
	$U_{k\%}$	-	-	2.74	2.45	-	-	4.41

Conclusions

The paper presents the simulation results of the power system supplied by the middle voltage overhead line with the filtering-compensating device (FCD).The magnitude characteristics of the system impedance presented as the function of frequency was considered. The FCD is placed at the end of the supplying line. The parameters of FCD device are adjusted to compensate the 5th harmonic of 6-pulse rectifier and 11th harmonic of 12-pulse rectifier. The numerical data used in experiments have been acquired from the real (physical) power system. In the paper we have included the exemplary results of the numerical calculations.

The results of the experiments have shown that the adjustment of parameters of the higher harmonics filter, based on the magnitude frequency characteristics of the impedance of the supplying system, is a very good method of elimination of higher harmonics of current and voltage in the system.

Presented results have proved that the filters of 5th & 11th harmonics are very efficient in improvement of THD in supplying system. The filtering-compensating devices are used to eliminate the appropriate harmonic components of the voltage. In practice we use either single or double filters. Their application improves the value of THD. At the same time it is advised to determine the change of the modules of impedance frequency characteristics before and after adding the FCD. The computer program, presented in the paper, implements this task.

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