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MODELING OF THE DETUNED FILTERS FOR HARMONIC REDUCTION

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Abstract: *The increasing use of modern power electronics such as converters, variable speed drives, uninterruptible power supplies and power semiconductors increasingly loads the power line with non-sinusoidal currents and voltages. If standard reactive power compensation capacitors are used they can form a resonant circuit in conjunction with the inductance of the feeding transformer. Experience shows that the self-resonant frequency of such a circuit is in the region of 5th and 7th harmonics. These resonance phenomena can be avoided by connecting filter reactors in series with capacitors, apropos by using detuned filters with resonant frequency below the 5th and the 7th harmonics. This paper describes simulation of using detuned filters which can be robust tool for dimensioning devices for reactive power compensation. Simulation results are compared with measured for one particular case ("Toplana", Subotica).*

Key words: ***Modeling / Compensation / Filters.***

1. INTRODUCTION

There are significant voltage and current distortions in industrial plants which use standard frequency converters for speed control of large power induction motors. Because of switching behavior of its input diode rectifier, a power converter consumes non-sinusoidal current which leads to distortion of distribution voltage. These distortions could be source of disturbances and damages in terms of safe functioning of the devices. In order to lay out measures for their limitation it is necessary to identify magnitude of the distortions for particular case. High-frequency harmonics also affects the precision of control and measuring equipment and could lead to interference in its functioning. Moreover, harmonics are undesirable from the viewpoint of the power supplier, because they spread in the distribution system and can lead to the electrical interference with other consumers, which certainly would require measures for their restriction [1].

Classical devices for reactive power compensation can not be used in such industrial plants due to the possible resonance in the distribution system. They do not have a satisfactory effect on the compensation of reactive power, resulting in significant, unnecessary costs for the consumed reactive energy from the distribution [2].

Refined waveforms of voltage and current of all unwanted harmonic components can be obtained by setting appropriate filters. The aim of the filters is to provide low impedances for the current harmonics and thus prevent their spreading in the distribution system. Usually, single or double filters are applied tuned to the dominant harmonic frequency of the 5th and the 7th harmonic [3, 4]. Although passive filters are simple, reliable and low cost, they have significant disadvantages. To be effective, they have to be very precisely designed and performed in order to absorb particular desirable harmonic. If not, they may cause additional resonance. For example: applied for power frequency converters harmonic mitigation, they can cause overcompensation, which must be canceled by adding parallel reactors, which entails additional costs. Besides, filters can cause at least one resonant or anti-resonant frequency, which must not match with any of the dominant higher harmonics frequencies in order to avoid their reinforcements. Moreover, they are not sufficiently flexible to be able to perform dynamical compensation of different harmonic components.

Therefore, plant for power factor correction must be carefully planned, so to make a compromise between complexity and the allowable level of distortion. Such a plant essentially represents a series of parallel connected capacitor batteries, controlled by a special automatic device. It is desirable that they work without losses and to respond to changes in requirements for reactive power without delays. Possible resonance could be avoided by adding filter reactors in series with capacitor batteries [2]. Series connection of filter reactor and capacitor represents resonant circuit, where the disadvantage of filters regarding to capacitive component on fundamental frequency introduce the requirement for its cancellation by connecting additional parallel reactor. In order to avoid that it is convenient to choose the elements of the series connection of reactors and capacitors to have so-called detuned resonant frequency, which is below of 5th harmonic.

Complete analysis of the system comprised of distribution grid loaded with frequency converters with installed compensating devices could be made using the software package MATLAB/Simulink and its modules, intended for simulation of dynamic systems. Analysis of solution and correct choice of individual elements of the compensating device for one particular case (plant "Toplana", Subotica) is done in this paper by comparing the results of measurements and simulation.

2. DETUNED FILTER APPLICATION

The impact of a harmonic current on the power system can be estimated by calculating the resulting harmonic voltage at a point in the supply system shared with other consumers. The interest is to control the quality of the power delivered to consumers at the point of common coupling (PCC). The basic equivalent circuit for this calculation is shown in Fig. 1.

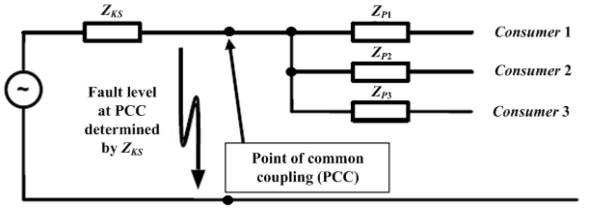

Fig. 1. *A simplified equivalent scheme of power supply.*

For the study of harmonics, the principle of superposition is used which means that the grid source is turned off (bypassed) and the consumer being studied is considered as a source of harmonic current, as shown in Fig. 2.

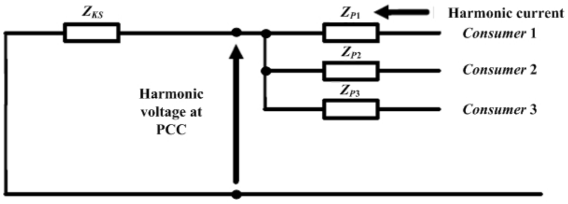

Fig. 2. *Scheme arranged for harmonic analysis.*

Each harmonic is analyzed in turn. The voltage at PCC for each harmonic is simply the product of the current and short circuit impedance of the supply system for that harmonic frequency:

$$U_h = Z_h \cdot I_h \tag{1}$$

The short circuit impedance at fundamental frequency 50 *Hz* (or other grid frequencies) can be found from declared fault power level of the supply S_{KS}, which should be available from the distribution company. S_{KS} is usually expressed in *MVA,* so the impedance in *Ω* at the grid frequency can be calculated as follows:

$$Z_{KS} = \frac{{U_L}^2}{S_{KS}[MVA] \cdot 10^6} \tag{2}$$

where are:

U_L = line voltage,

Z_{KS} = fault impedance of one line.

Short circuit impedance is usually predominantly inductive, so that for harmonic of order *h* the impedance is $h \cdot Z_{KS}$.

From Fig. 2 it is clear that the harmonic voltage within the premises of consumer will be higher than that at the PCC, because of the voltage drop in Z_P. Meeting satisfactory distortion at the PCC is no guarantee of tolerable harmonic levels within the system of the consumer generating the harmonics. The limits applied at the PCC by regulations and standards contain considerable safety margin, so it is unlikely that the consumer will experience difficulty in this respect, but there is always possibility of harmonic disturbance especially if Z_{KS} is small (stiff supply) and Z_P large (long transmission line or small power transformer).

In order to analyze a practical system, the known harmonic data for all the power converters and other non-linear loads must be combined to predict a total current. Each harmonic from each unit is a vector quantity which can only be added to the others trough vector addition. It can cause a problem because usually the phase angle is unknown and it can vary with operating condition.

For uncontrolled diode rectifiers, the phase angles of the dominant harmonics will be similar, so the amplitudes can be added directly. Standard permits the application of a coincidence factor of 0.9 to reflect the fact that perfect addition is not possible [1]. However, a simulation provides possibility to model real situations.

Behavior analysis of the system with compensation batteries, or with detuned filters obtained by adding filter reactors in series with them, can be made according to the scheme shown in Fig. 3.

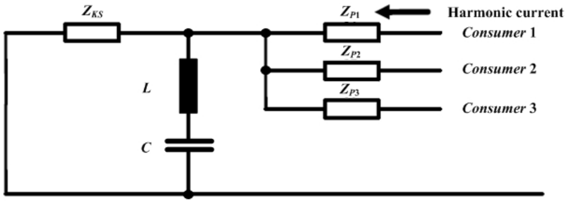

Fig. 3. *Equivalent scheme for the analysis of a series connection of filter reactor and capacitor.*

It is convenient to choose the elements of the filter series connection to have so-called detuned resonant frequency, in our case of 189 Hz. This is accomplished by adding reactors with short-circuit voltage of 7% (at the fundamental frequency), according to the Eq. 3:

$$\begin{gathered} 0.07 \cdot \frac{1}{2 \cdot \pi \cdot f \cdot C} = (2 \cdot \pi \cdot f \cdot L) \Rightarrow \\ (2 \cdot \pi \cdot f_{rp}) = \frac{1}{L \cdot C} \Rightarrow \\ f_{rp} = \frac{f}{\sqrt{0{,}07}} = 189(Hz) \end{gathered} \tag{3}$$

The behavior of the reactor and capacitor series connection as a function of frequency is illustrated in Table 1. It can be said that for the fundamental frequency of 50 *Hz* it acts as a capacitor bank for power factor correction and that for the higher frequencies above the 5th harmonic, it acts as an inductance and does not contribute to the resonance appearance. This favorably effects on the reducing distortion and on loading capacitor bank with higher current harmonics.

Table 1. Behavior of the filter reactor and capacitor series connection, with short circuit voltage of filter reactor equal to 7%.

Frequency [Hz]	f < 189	f = 189	f > 189
Impedance of detuned resonant circuit	Capacitive	Zero	Inductive
Function	Generating reactive power, PFC at 50 Hz		Reducing higher current harmonics

3. MEASURING RESULTS

Voltage and current waveforms for two phases were measured and registered in the real system (plant "Toplana", Subotica), and also their effective value and frequency, the frequency spectrum of recorded waveforms, harmonics voltage and current factors, and individual harmonic distortion (HD) and total harmonic distortion (THD). Besides that, the trends and changes of voltage and current effective values and their total distortion factor THD were recorded, although only for relatively short periods of time according to the character of nearly constant load. At the end, a power factor and a phase position of the first harmonic were measured for several different loads.

Typical measurement results are given in the Figs. 4 to 7. The first two figures (Figs. 4 and 5) show the grid voltages and currents, when it was loaded with two largest power frequency converters in the plant, while the next two ones (Figs. 6 and 7) show the same, but when the capacitors bank (without series reactors) were involved. Plant on which measurements were performed contains two transformers connected in parallel so that the displayed power is half of the actual load.

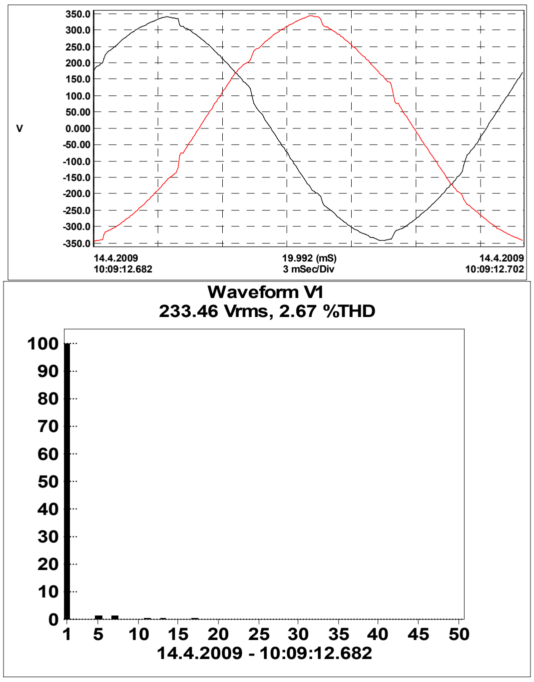

Fig. 4. *Phase voltage waveforms and their harmonic content – without capacitor bank.*

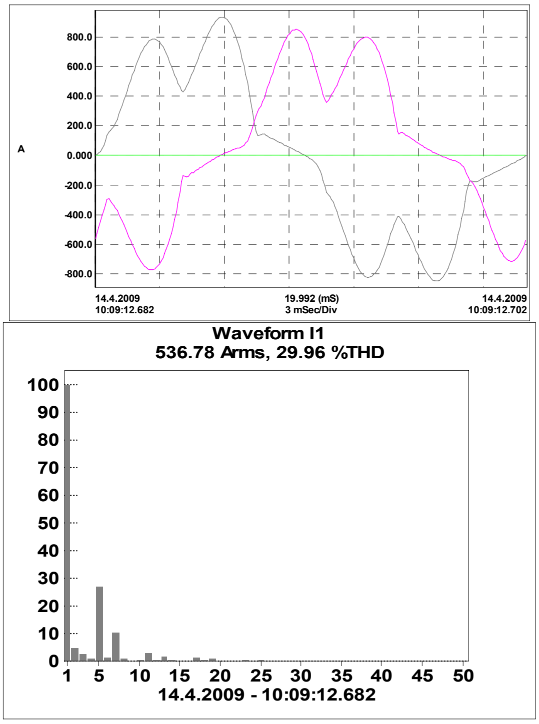

Fig. 5. *Phase current waveforms and their harmonic content – without capacitor bank.*

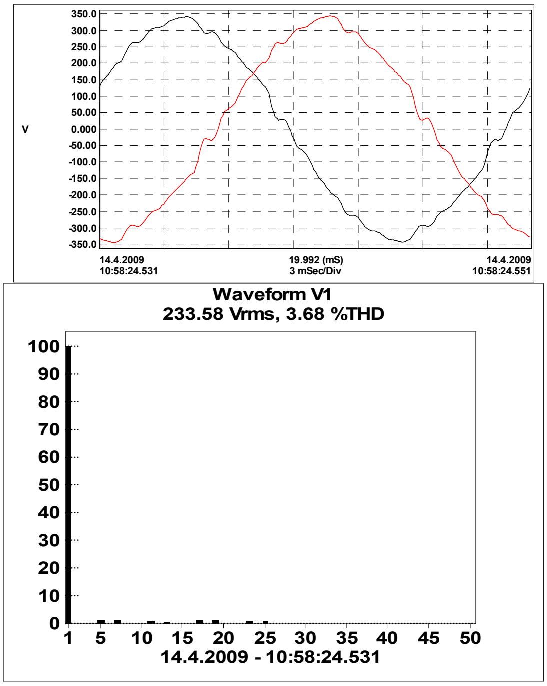

Fig. 6. *Phase voltage waveforms and their harmonic content – with capacitor bank.*

From Figs. 4 to 7 it is obvious that the voltages and currents have significant the 5th, 7th, 11th, 13th, 17th, 19th, 23rd and 25th harmonics. In this case there was a clear result differences between the individual phases of the transformer. Due to the different distribution of the load per transformer's phases, the 2nd and 3rd harmonics are present, strongly expressed in current in regard to voltage. Distribution and distortion of individual harmonics are fully consistent with the expected load, such as power frequency converters. It could be clearly observed that the presence of capacitors for power factor correction caused a complex situation where the resonance brought to the increased amplitude of higher frequency harmonics above the 7th.

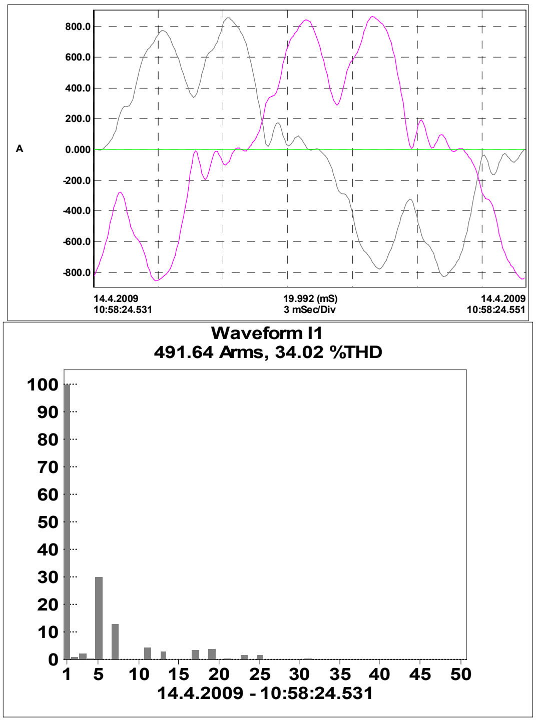

Fig. 7. *Phase current waveforms and their harmonic content – with capacitor bank.*

4. SIMULATION RESULTS

From measurement results it was clear that the capacitor bank where erroneously chosen and that it is contributing to the even worse voltage and current waveforms. In order to correct previous mistake and to achieve real power factor correction, series of simulations of the system were performed.

Grid simulation model loaded with base linear consumers and frequency converter with compensating detuned filters is presented in Fig. 8. Individual elements which are important for the simulation and measurement could be easily noted from Fig. 8. The parameters of the elements were chosen according to the values listed in the manufacturer's catalogues.

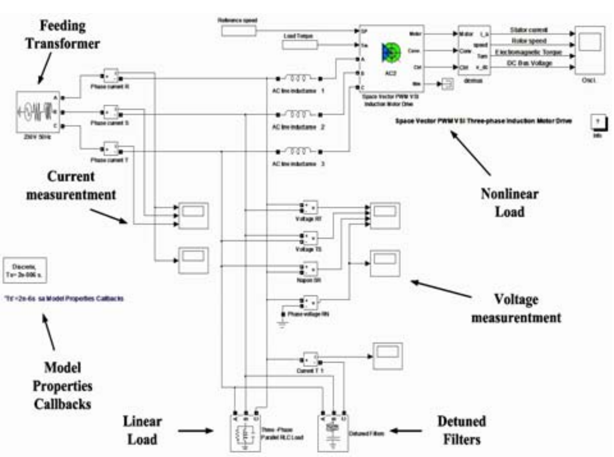

Fig. 8. *Grid simulation model with frequency converter and compensating detuned filters.*

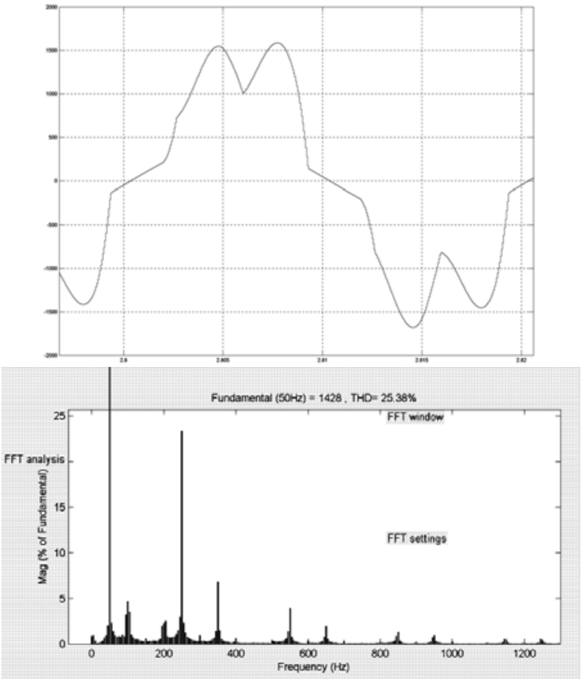

Fig. 9. *Simulated phase current waveform and its harmonic content – without compensating device.*

The model of the frequency converter, the induction motor and vector control is a standard part of MATLAB/Simulink toolboxes [5, 6, 7], and for this analysis their description is not necessary, since in principle it is important to know only its non-linear behavior in the system. By changing element's values in the system three different cases were simulated: without compensating capacitor batteries, with pure capacitor batteries and with series connection of capacitor batteries and filter reactors. This provided the possibility to compare measuring results with equivalent simulation results.

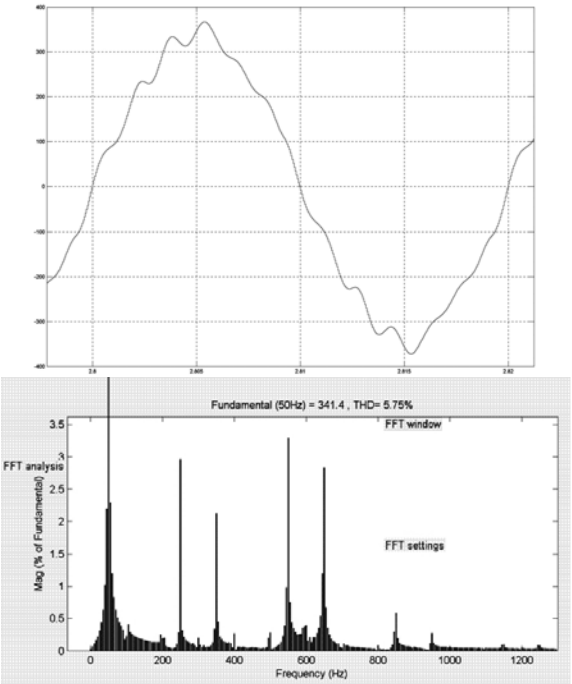

Fig. 10. *Simulated phase voltage waveform and its harmonic content – with pure capacitor batteries.*

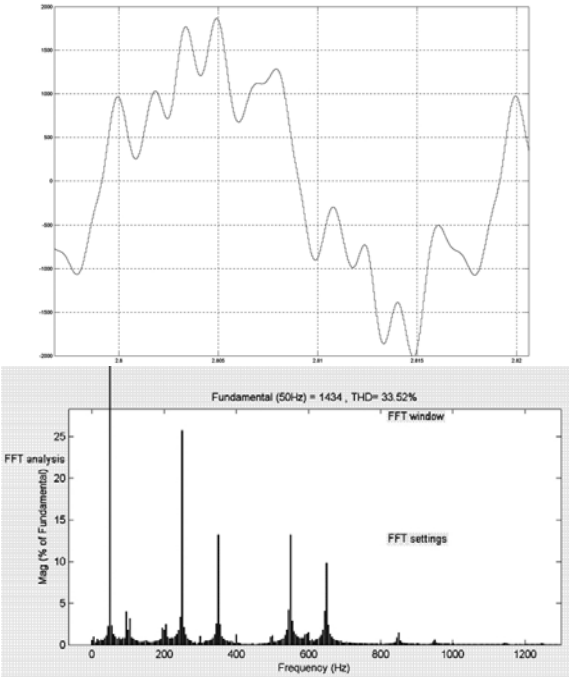

Fig. 11. *Simulated phase current waveform and its harmonic content – with pure capacitor batteries.*

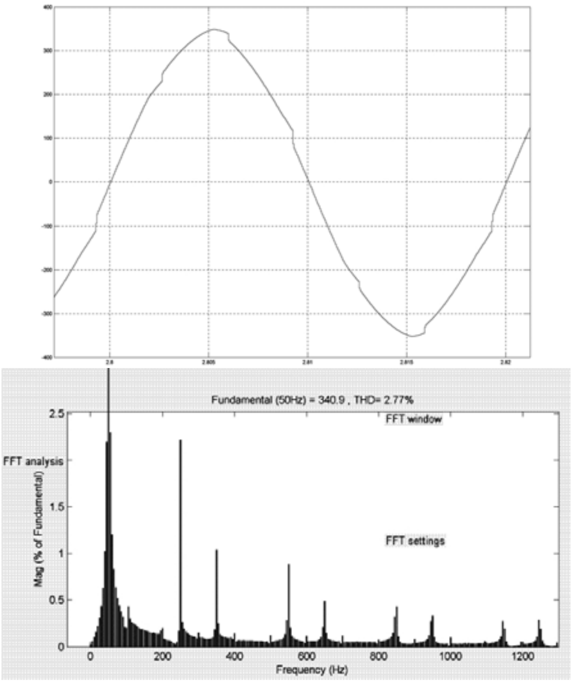

Fig. 12. *Simulated phase voltage waveform and its harmonic content – with detuned filters.*

In Figs. 9 to 13 the results of simulation are shown, i.e. voltage and current waveforms and its harmonic content for indicated three different cases.

Comparing the obtained values with the measured, it could be observed that the simulated oscillations are more significant, but at the same frequencies as measured. This difference may be explained by the inability to evaluate ohmic resistance elements in the model, which contribute to the attenuation.

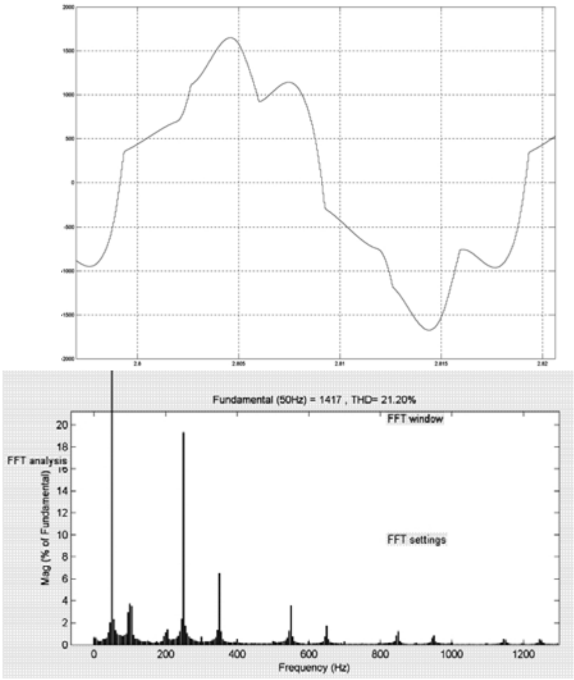

Fig. 13. *Simulated phase current waveform and its harmonic content – with detuned filters.*

5. CONCLUSION

Comparing the simulated values of individual HD and total harmonic distortion THD of the phase voltages and currents, general conclusion could be made that the recommended measures for adding series filter reactors lead to significant reduction in the value of distortion, especially for the voltages. So generally, the application of detuned filters does not remove harmonics completely, but with significantly less required investment they contribute to the distortion reduce and allow their application for reactive power compensation.

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