HARMONICS IN MEDIUM VOLTAGE DISTRIBUTION NETWORK OF NIS

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INTRODUCTION

Power quality becomes especially up to date with energy market deregulation and competition between power distribution companies. In this environment, electrical energy is treated as ware with the quality. The problem of the quality of delivered energy, i.e. power quality, is connected with the power system stability, disturbances and mutual influences system-consumer. This has become especially important with the appearance of so called “sensitive devices” as are computers, processor equipment in the industry, complex devices that are controlled by microprocessors, etc.

Power quality violation manifest through deterioration of basic voltage parameters and its waveform distortion. Therefore, power quality factors can be devided into two groups: those regarding basic voltage parameters, and those that relate waveform distortion, Katic (1). The first group of power quality factors defines regular operation of the power system and it involves rms voltage variation, frequency variation and unbalance. The second one comprehends: transients (impulses and oscilations), sags, swells, undervoltages, overvoltages interraptions, DC offset, harmonics, interharmonics, notches, voltage fluctuations and noise.

Distribution systems are designed for sinusoidal waveforms of voltages and currents. Nonsinusoidal currents can appear due to nonsinusoidal generator voltage, nonlinear device operation in the network and nonlinear load devices. Overall usage of nonlinear devices Tolbert, Hollis and Hale (2) and Korunovic and Stojanovic (3) such are TV sets, fluorescent and mercury lamps, computers, etc., as well as variable speed drives and uninterraptible power supplies can violate power quality and cause serios problems such as increase of power and energy losses in lines and transformers, capacitor failures, inadequate electronic equipment operation and inadvertent circuit breaker tripping. Current waveform and harmonic spectrum for the most frequently used low-voltage nonlinear devices are presented in (2) and (3).

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This paper is continuation of previous authors' research where it has been noted that the presence of higher order harmonics in the currents of many low-voltage devices is significant. Also, it has been found that the waveforms of the supply voltages of these devices measured at many different locations have distortion. The measurements in transformer substations (TS) 10/0.4kV that supply representative of university buildings, commercial load and residential load have been shown that the presence of current and voltage harmonics is significant even for the transformer that supplies residential load. It initiated the authors to perform the measurements in medium voltage network to see weither the presence of harmonics in these network is beyond international standard limits or not. Thus, this work presents the measurement results of total (*THDI* and *THDU*) and individual (HDI_h and HDU_h) current and voltage harmonic distortions obtained on 10kV and 35kV voltage level of distribution network of Nis. All measurements are performed by power analyzer C. A 8332.

MEASUREMENT RESULTS

The measurements are performed in TS "Medijana" 35/10kV that supplies mostly residential part of the town, several suburban setllements and near by villages. These results are for two 10kV feeders supplying urban and rural residential load and they give the answer to the question weither the amound of harmonic currents depends on the type of settlement or not. Also, obtained values of harmonic currents and voltages are compared with previously published results measured on 0.4kV level of TS 10/0.4kV that is supplied by one of considered feeders.

The results of simultaneous measurements on 35kV voltage level of the transformer 110/35kV in TS "Nis 13" and at 10kV side of the transformer 35/10kV in TS "Stevan Sindjelic" fed from TS "Nis 13" are presented, too. These results consider harmonic currents and voltages on 35kV and 10kV voltage level of the part of medium voltage distribution network of Nis that also supplies predominantly residential load. These measurements quantify the difference in the harmonic amount in different periods of a day in a week.

Urban and rural residential load

As mentioned before, two 10kV feeders, "Medijana 2" and "Francuska 2" are chosen for the comparison of higher order harmonic presence in two kinds of residential load. The first one supplies urban area of the town mostly with electrical heating, and the second one supplies rural residential load. The measurements are performed during December 2004 and January 2005.

Load curves for a "typical" winter working day and corresponding power factor values for both feeders are presented in Fig. 1. These load curves are recorded on Wednesday 22nd and Thursday 30th December when maximum daily temperatures amounted 1 and 2°C, respectively.

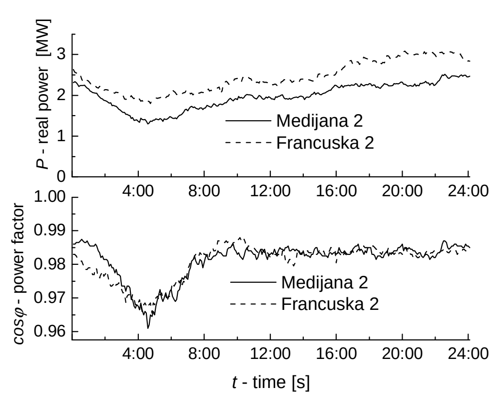

Fig 1. Load curves and power factors
for urban ("Medijana 2") and rural ("Francuska 2") residential load

Fig. 1 shows that the load diagrams are very similar. In the evening the load is practically constant and maximum appears around 8 and 10:30 PM for rural and urban load, respectively. Minimum appears around 4:30 AM for both types of residential load, and the ratio of maximum and minimum power is

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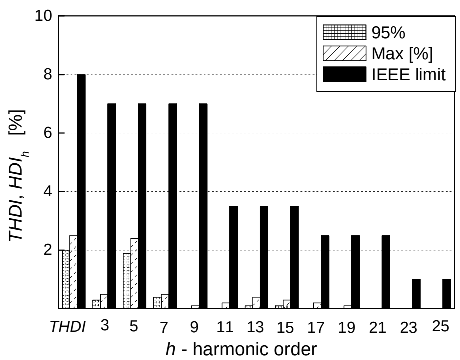
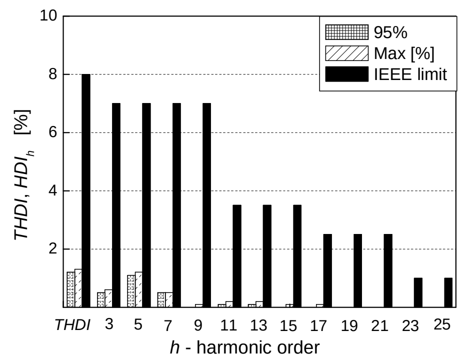
approximately 2 for rural and 1.7 for urban residential load. Furthermore, power factor during a day changes in narrow ranges from 0.961 during the night to 0.988 in the evening and it is of similar shape for rural and urban residential load. Although Fig. 1 demonstrates the activities of the people are similar in urban and rural settlements, the harmonic analysis shows that there is the difference in harmonic currents of two considered feeders.

For feeders ”Medijana 2“ and ”Francuska 2“ maximum and 95% probability of *THDI* and odd harmonic currents for one winter week and corresponding limits that IEEE Standard 519 specifies are presented in Fig 2. All 95% values of considered variables have been fairly below the limits. The feeder with rural residential load has approximately two times lower total and individual harmonic distortions. For example *THDI* of feeder with the urban load amouns 2% and for the feeder with rural load 1.2%. These notifies that there is the difference between two kinds of residential load regarding harmonics. This is probably because of smaller number of computers and sparse lighting of rural settlements. Namely, computers and mercury lamps are one of the greatest harmonic sources in distribution networks (2).



a)



b)

Fig. 2. *THDI* and the spectrum of a) “Medijana 2” and b) “Francuska 2” feeder current

THDU and individual voltage harmonic distortions recorded during a week of the winter are presented in Fig. 3 along with different international standard limits - IEEE 519, IEC 6100-2-4 and CIGRE lower limits. It indicates that 95% probability values of all variables are below these limits.

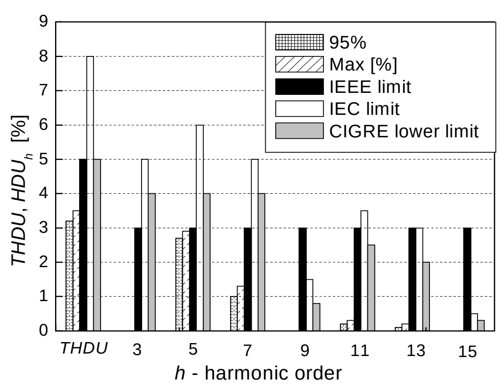


Fig. 3. *THDU* and the spectrum on 10kV voltage level

The measuremens of harmonics have been performed in summer, too. These measurements showed harmonic current indicators are approximately two times larger in summer than in the winter. They have also confirmed that the presence of harmonics is approximately two times larger for urban residential load than for rural residential load. For feeder ”Medijana 2“ 95% probability value of *THDI* amounted 4.1%, HDI_3=0.8%, HDI_5=4%, HDI_7=0.8%, HDI_9=0.1%, ect. and for feeder ”Francuska 2“ *THDI*=2.2%, HDI_3=0.6%, HDI_5=2.1%, HDI_7=0.3%, HDI_9=0%. All these values are remarkablly below IEEE 519 standard limits although these are approximately two times larger in the summer than in the winter. It can be explaned by larger participation of resistive load in the total feeder load during the winter. Although the harmonic currents were larger in summer, 95% probability of *THDU* in the summer week was 3.3% and that is close to the value of 3.2% measured in winter. It indicates that the network is strong enough to keep the voltage distortion under allowed limits in both seasons.

Also, a general conclusions for, winter and summer seasons, can be made that the presence of higher order harmonics in the voltage is minimum after midnight (4-5 AM) when power system load is minimum, and total voltage distortion is largest approximately at 9 PM when the load is maximum.

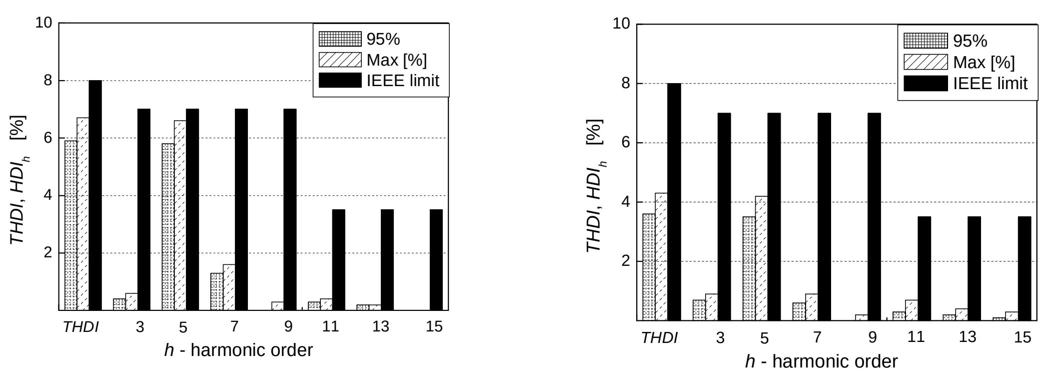
The measured variables presented in this paper are compared with those presented in (3) that relate to the measurements on low voltage of TS 10/0.4 kV "Medijana 2" in the summer. This transformer substation is the first one of five transformer substations 10/0.4kV feed through feeder "Medijana 2". 95% probability values of *THDI* amounted 7.4%, HDI_3=7%, HDI_5=2.8%, HDI_7=1.8%, HDI_9=0.9%, *THDU*=3.5%, HDU_3=0.4%, HDU_5=3.3%, HDU_7=1.3%, HDI_9=0.1, ect. Since the presence of higher order harmonics is significantly lower at 10kV voltage level it indicates that a distribution transformer 10/0.4kV with delta- grounded star connection is a good farmonic filter. There are not the third and the ninth harmonic voltages on 10kV voltage level.

Simultaneous measurements at 35kV and 10kV level

As the presence of harmonics in a network supplying residential load is larger during the summer the results of measurements on 35 and 10kV voltage level in other parts of the town in summer season will be presented in next paragraphs.

The measurements were performed on 35kV voltage level of transformer 110/35kV in TS "Nis 13". This transformer feeds three transformer substations 35/10kV: TS "Stevan Sindjelic", TS "Medijana" mentioned in previous subsection, and TS "Ratko Pavlovic". The first one supplies urban residential load, the second the mixture of urban and rural load, while the third one besides the urban residential load (68.9% of total installed power) supplies industrial (12.4%), commercial (10.5%) load, hospitals (5.3%) and schools (2.9%). At the same time the measurements were performed in TS "Stevan Sindjelic" at low voltage side of one of two transformers 35/10kV that operate in parallel.

Fig. 4 presents 95% probability values of *THDI* and individual odd harmonic distortions on 35 and 10kV voltage level for one working summer day. Since the results given in next paragraphs approve the presence of harmonics is larger in a working day in comparison with Saturdays and Sundays, typical working summer season day with maximum daily temperature of 23°C is used for comparison with IEEE standard limits. It is the most critical day regarding harmonics, and it can be the indicator that further harmonic research should be accomplished.



a) b)

Fig. 4. *THDI* and the spectrum at a) 35kV voltage and b) 10kV voltage

Fig. 4 and Fig. 5 show that:

- harmonic currents on 35 and 10kV voltage are bellow IEEE standard limits during the summer working day;
- harmonic voltages are bellow IEC limits and CIGRE lower limits;

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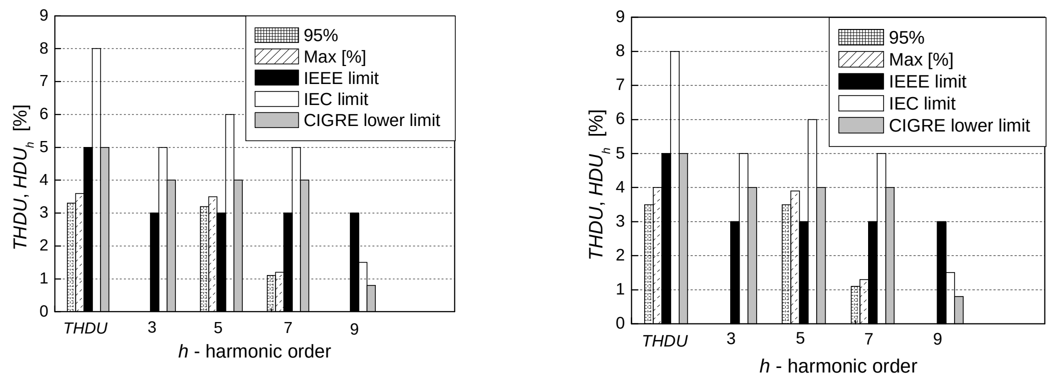
- HDU_5 has higher value than IEEE limit;
- *THDI* and HDI_h are larger on 35kV voltage level in comparison with those of 10kV voltage level, that indicates the industrial and commercial load are significant harmonic sources;
- *THDU* and HDU_h are lower for 35kV voltage level indicating 35kV network is stronger and keeps the voltage distortion to be lower;
- there are not third and ninth harmonic voltages on 35 and 10kV voltage levels.

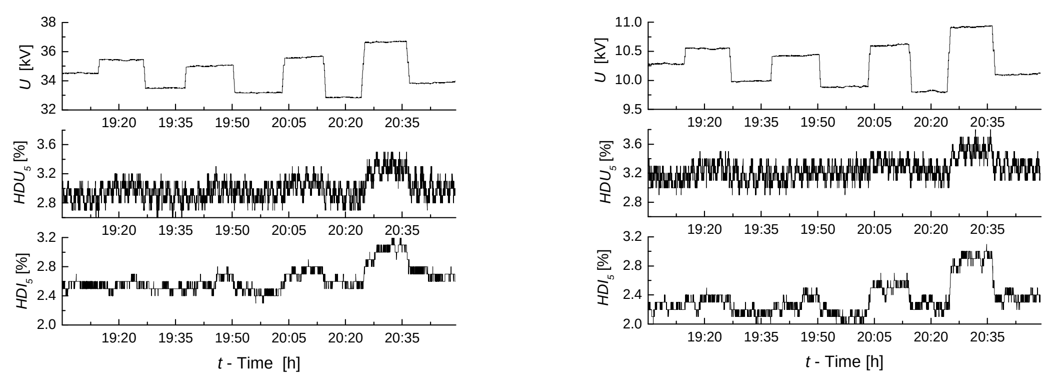


a) b)

Fig. 5. *THDU* and the spectrum of a) 35kV voltage b) 10kV voltage

The results of harmonic analysis during the experiments of voltage change at 35kV side of the transformer 35/10kV by on-load tap changer in relatively wide range from 0.95 to 1.1p.u. are presented, too. Simultaneous measurements on 10kV and 35kV voltage were performed in the morning approximately from 9 to 11 AM, in the afternoon from 4 to 6 PM and at night when the load is maximum, from 7 to 9 PM. These experiments started on Friday 30th September and finished on Sunday 2nd October in 2005.

For illustration, voltage rms value, and individual voltage and current harmonic distortions of the dominant fifth harmonic on 35 and 10kV voltage for one of the tests that consists of several voltage changes (for Saturday night) are presented in Fig. 6. This figure shows that the presence of the fifth harmonic of voltage and current increase with voltage increase for both voltage levels, and vice versa. It also matters other voltage and current harmonics, but these are not presented here. There are remarkable increments in harmonics for the voltages above 1.05 p.u. and it is the consequence of distribution transformer saturation.



a) b)

Fig. 6. The values of HDU_5 and HDI_5 at a) 35kV and b) 10kV voltage level during the voltage changes

From Fig. 6 it can be also noticed that the presence of the fifth harmonic is larger for 10kV voltage, but its proportional change is nearly the same for both voltage levels. It is not the case for the fifth harmonic current that has larger range of variation for 10kV voltage in comparison with that measured at 35kV voltage level. Furthermore, HDI_5 at 10kV level starts from lower value of 2.3% because TS “Stevan Sindjelic” supplies residential urban load, while larger harmonic presence on 35kV voltage can be explained by commercial and industrial load components participating in total load of 110/35kV transformer.

The detail analysis of different higher order harmonic presence during rms voltage change will not be presented here due to space limitation and it will be the subject of further authors’ research. In this paper the results of the measurements during the voltage changes, which also can be the part of normal power system operation, are used for the comparison of harmonic amount at 35 and 10kV voltage levels in different days of the week and different day intervals.

The presence of harmonics in currents and voltages is specified by 95% probability values of total and individual harmonic distortions during the tests and they are presented in Table 1. From the tests that are similar for all periods of examined days and cause average voltage to be somewhat higher than that of normal operating conditions (for a part of a percentile), several conclusions can be made:

- *THDI* and individual current harmonic distortions vary in relatively wide ranges, for example $THDI \in [1.8;4.2]$,
- *THDI* and individual current harmonic distortions do not exceed IEEE standard limits regardless the voltage changes,
- *THDU*, HDU_5 and HDU_7 vary in relatively narrow ranges ($THDU \in [3;3.8]$);
- there are not third and ninth voltage harmonics and HDU_3 and HDU_9 are omitted from the table;
- *THDU*, HDU_5 and HDU_7 values are bellow IEC limits and CIGRE lower limits no matter the voltage change;
- the fifth harmonic is dominant higher order current harmonic, the presence of the seventh one is significant while ninth and fifteenth are negligible;
- *THDI*, HDI_5 and HDI_7 have lower values at night than in other day intervals due to increase of resistive load component in total load;
- in all periods of Friday and Saturday and Sunday nights *THDI* is larger on 35kV voltage level than on 10kV level, but on Saturday and Sunday mornings and afternoons it is opposite. It is most probably owing to industrial and commercial load components of TS “Ratko Pavlovic”;
- *THDU* on 35kV level is lower than *THDU* on 10kV voltage level regardless day and a day period indicating the 35kV network is strong enough to keep the voltage to be close to sinusoidal waveform whatever the harmonic currents amount;
- there is somewhat larger amount of fifth voltage harmonic as in previous research on 0.4kV voltage level of TS 10/0.4kV supplying residential load;

Table 1 - *THDI*, HDI_h, *THDU* AND HDU_h FOR DIFFERENT DAYS, DAY PERIODS AND VOLTAGE LEVELS WITH CORRESPONDING IEEE, IEC LIMITS AND CIGRE LOWER LIMITS

Day	Period	Voltage	*THDI*	HDI_3	HDI_5	HDI_7	HDI_9	HDI_{11}	HDI_{13}	HDI_{15}	*THDU*	HDU_5	HDU_7
Fri	Morning	35kV	4.1	0.3	4.0	1.1	0	0.3	0.2	0	3.2	3.1	1.1
		10kV	2.7	0.3	2.6	0.5	0.1	0.3	0.2	0	3.4	3.3	1.1
	Afternoon	35kV	4.2	0.4	4.1	1	0	0.3	0.2	0	3.4	3.3	1.1
		10kV	3.2	0.6	3.1	0.6	0.1	0.3	0.2	0	3.6	3.5	1.1
	Night	35kV	3.3	0.4	3.2	0.5	0	0.3	0.2	0	3.6	3.5	0.9
		10kV	2.3	0.5	2.2	0.4	0	0.3	0	0	3.8	3.7	1
Sat	Morning	35kV	3.4	0.4	3.3	0.9	0	0.2	0	0	3	2.9	1
		10kV	3.7	0.6	3.6	0.7	0	0.2	0.2	0.2	3.3	3.2	1.2
	Afternoon	35kV	3.5	0.3	3.4	0.7	0	0.3	0.2	0	3.4	3.3	1
		10kV	3.7	0.6	3.6	0.5	0	0.3	0.2	0.1	3.7	3.6	1.1
	Night	35kV	3	0.3	2.9	0.6	0	0.2	0	0	3.3	3.2	1
		10kV	2.9	0.5	2.8	0.4	0	0.3	0	0	3.6	3.5	1
Sun	Morning	35kV	3.5	0.3	3.4	0.7	0	0	0	0	3.4	3.3	0.9
		10kV	4.1	0.4	3.7	0.8	0	0.1	0.2	0.1	3.8	3.7	1.0
	Afternoon	35kV	2.7	0.4	2.6	0.4	0	0.2	0	0	3.3	3.2	1.1
		10kV	2.8	0.5	2.7	0.5	0	0.2	0.2	0	3.6	3.5	1.2
	Night	35kV	2.1	0.3	2.0	0.4	0	0.2	0	0	3.2	3.1	1.0
		10kV	1.8	0.3	1.7	0.3	0	0.2	0	0	3.6	3.5	1.1
IEEE limit			8	7	7	7	7	3.5	3.5	3.5	5	3	3
IEC limit											8	6	5
CIGRE lower limit											5	4	4

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CONCLUSION

In this paper the results of harmonic analysis on 10 and 35kV voltage level in three transformer substations in different parts of town Nis are presented. The results of measurements on 10kV feeders supplying urban and rural load show that higher order harmonic currents are two times larger for rural residential load. Also, in summer season total and individual harmonic distortions are approximately two times larger than those for winter for both types of residential load, but they are bellow IEEE 519 limits. *THDU* and HDU_h 95% probability values are bellow IEEE, IEC limits and CIGRE lower limits.

The simultaneous measurements on 35kV and 10kV voltage of two transformers show that *THDI* and HDI_h have lower values than IEEE standard limits, and *THDU* and HDU_h are bellow IEC limits and CIGRE lower limits. During a working day the amounts of harmonic currents are larger in comparison with Saturday and Sunday when resistive load participation in total load increases. The rms voltage variations indicate the change of harmonic voltages and currents. It is especially significant for the voltages above 1.05p.u. due to saturation of distribution transformers. Although during the measurements the voltage changed by on-load tap changer in the wide range, from 0.95 to 1.1p.u. 95% probability values of *THDI* and HDI_h did not exceed IEEE limits, and *THDU* and HDU_h were bellow IEC limits and CIGRE lower limits.

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