ISSN 1330-3651
UDC/UDK 621.316.015.1:658.56(497.5-11)

VOLTAGE VARIATION PERFORMANCE INDICES IN DISTRIBUTION NETWORK

Zvonimir Klaić, Srete Nikolovski, Zorislav Kraus

Original scientific paper

This paper analyzes voltage sags distribution for distribution feeder in eastern Croatia. It presents the result of online power quality indices monitoring at 110/35 kV transformer station. Measurements were performed at the secondary sides of two transformers, by the power quality network analyzers. Results are aggregated and statistically arranged: voltage events were classified according to the EN 50160 and IEEE 1159:1995, and RMS variation performance indices were calculated. The research was performed during the Leonardo Power Quality Initiative project, since the Faculty of Electrical Engineering in Osijek was the LPQI's affiliate partner.

Key words: *power quality, voltage sag, distribution feeder, RMS variation indices, distribution of measured voltage sags*

Pokazatelji učestalosti promjena efektivne vrijednosti napona u distribucijskoj mreži

Izvorni znanstveni članak

U ovom radu analizira se razdioba naponskih propada na distribucijskom izvodu u istočnom dijelu Hrvatske. Prikazan je rezultat nadzora (monitoringa) pokazatelja kvalitete električne energije na transformatorskoj stanici 110/35 kV. Mjerenje je izvedeno pomoću mrežnih analizatora kvalitete električne energije i to na sekundarnim stranama dvaju transformatora. Rezultati su objedinjeni i statistički obrađeni: naponski događaji klasificirani su u skladu s normama EN 50160 i IEEE 1159:1995, a izračunati su i pokazatelji učestalosti promjena efektivne vrijednosti napona. Istraživanje je izvedeno u sklopu projekta Leonardo Power Quality Initiative, u kojem je Elektrotehnički fakultet Osijek bio pridruženi partner.

Ključne riječi: *kvaliteta električne energije, naponski propad, distribucijski izvod, pokazatelji promjena efektivne vrijednosti napona, razdioba mjerenih naponskih propada*

1 Introduction

Electrical appliances become more complex due to complicated functions and mutual interactions. There are many advantages of automated manufactory systems and variable speed drives in industry, as well as information systems and fluorescent lights at the public and domestic consumers. Therefore, development of these systems and equipment is very fast and their usage is growing. Most of nowadays electrical equipment is more sensitive to deviations from sinusoidal supply voltage. At the same time, the same or other equipment causes modifications to the characteristics of the supply voltage [1, 2].

Costs of power quality disturbances (interruptions, voltage sags, harmonics, surges etc.) are very significant and have the highest impact on industry. In order to minimize those costs, it is necessary to analyze the electrical system and then try to determine possible future problems. Only after that, it is possible to improve the system in the right way.

HEP d.d. – (Croatian electricity company) Corporative development and strategy division and the Faculty of Electrical Engineering in Osijek were partners in the EU project Leonardo Power Quality Initiative (LPQI). Activities carried out within that project include measuring, analyzing and statistical data processing of power quality indices. This paper presents the result of online power quality indices monitoring at HEP DSO in the transformer station TS 110/35 kV at the secondary side on one of the two transformers which mainly supply the urban cable network in the city of Osijek. Power quality indices were measured with a permanently built-in three-phase power quality network analyzer Qualitrol QWave Power CO. Data were collected offsite with a modem via analog telephone line, and stored in MS SQL database. Voltage events were classified according to the EN 50160 and IEEE 1159:1995, and RMS variation performance indices were calculated.

2 Voltage sags

Voltage sags are short duration reductions in rms voltage and can be characterized by residual voltage (or depth) and duration. They are caused by short circuits, overloads or by starting of large motors. The interest in voltage sags is mainly due to the problems they cause on several types of equipment: adjustable-speed drivers, process-control equipment, computers etc. [3].

According to the European norm EN 50160 [4], voltage sag is a sudden drop in the voltage supply to a value between 90 % and 1 % of the agreed voltage U_C, shortly followed by the reestablished original voltage level. As agreed, the duration of voltage sag is between 10 milliseconds and 1 minute. IEEE Standard 1159:1995 – Recommended Practice for Monitoring Electric Power Quality [5] defines a voltage sag as reduction in the rms voltage between 0,1 and 0,9 p.u. of the nominal voltage, for a duration of 0,5 cycles to 1 min.

Voltage sags are the most frequent cause of power quality problems. They introduce considerable economic losses and have high impact on industry and other consumers. The most sensitive applications are continuous production lines, (paper mill, cement production etc.) lighting and safety systems and computer equipment. Although voltage sag could not cause such damage in industry as an interruption could, the total damage due to voltage sags is larger, because in a long period (a year or longer) there are more sags than interruptions [3, 7].

When assessing the total annual dip related cost, one has to find out how many dips are expected. Thus, from an economic point of view the dip frequency, i.e. the annual number of dips, is very important. One approach is to use stochastic mathematical methods for assessing more precise figures. Stochastic prediction methods use modeling techniques to determine results. They are as accurate as the model and the data used [7].

Some rough estimation can be acquired from measurement over a shorter period, but the best way to assess voltage sag performance of the bus is the monitoring of voltages at power system buses.

3 RMS Variation Performance Indices

RMS variation indices are tools for the assessment of service quality for a specified circuit area, [8]. The indices may be applied to systems of varying size: from a single feeder to entire power system.

3.1 $SARFI_X$

The abbreviation SARFI stands for System Average RMS-variation Frequency Index and it should be seen as the voltage dip equivalent of SAIFI as defined for interruptions [6]. $SARFI_X$ is a power quality index that represents the average number of specified RMS variation measurement events that occurred over the assessment period, where the specified disturbances are those with a magnitude less than *x* for sags or a magnitude greater than *x* for swells. It can be defined as a single monitor location, a single customer service, a feeder, a substation, and groups of substations or for an entire power delivery system.

$$SARFI_X = \frac{N_E}{D} 30 \text{ days}. \tag{1}$$

Where N_E is the number of events and *D* is the number of days measured at a single site.

3.2 $SIARFI_X$

System Instantaneous Average RMS (Variation) Frequency Index represents the average number of specified instantaneous RMS variation measurement events that occurred over the assessment period. The specified disturbances are those with a magnitude less than *x* for sags or a magnitude greater than *x* for swells and duration in the range of 10 – 500 ms [8].

$$SIARFI_X = \frac{N_{IE}}{D} 30 \text{ days}, \tag{2}$$

where N_{IE} is the number of specified instantaneous RMS events and *D* is the time period of measurement in days at a certain single site.

3.3 $SMARFI_X$

System Momentary Average RMS (Variation) Frequency Index. In the same way that $SIARFI_X$ is defined for instantaneous variations, $SMARFI_X$ is defined for variations having durations in the range of 500 ms to 3 seconds for sags and swells and in the range of 10 ms to 3 seconds for interruptions.

$$SMARFI_X = \frac{N_{ME}}{D} 30 \text{ days}, \tag{3}$$

where N_{ME} is the number of specified momentary RMS events and *D* is the time period of measurement (number of days) at a certain single site.

3.4 $STARFI_X$

System Temporary Average RMS (Variation) Frequency Index is defined for temporary variations which have durations in the range of 3 – 60 seconds.

$$STARFI_X = \frac{N_{TE}}{D} 30 \text{ days}, \tag{4}$$

where N_{TE} is the number of specified temporary RMS events and *D* is the time period of measurement (number of days) at a single site.

3.5 $SARFI_{CURVE}$

SARFI – curve corresponds to a number of voltage sags (or swells) outside of equipment compatibility curve over assessment period. There are two basic equipment compatibility curves:

- ITIC curve
- SEMI curve.

ITIC curve is a replacement for CBEMA curve. The new ITIC curve is proposed by Information Technology Industry Council to be more suitable for reflecting real world performance of electronic equipment. SEMI curve (Semiconductor Equipment and Materials International Group) describes voltage sag problems for semiconductor manufacturing equipment.

4 Voltage Events Analysis

The research project of voltage supply quality monitoring included the MV distribution feeder in eastern Croatia. The measurement was performed on the secondary side of the 110/35 kV transformer. Although power quality network analyzer QWave Power CO measures according to the EN 50160 norm, the measured data are agregated and statisticaly arranged according to IEEE Standard 1159:1995 – Recommended Practice for Monitoring Electric Power Quality. A measurement was conducted during the period of 762 days.

Tab. 1 represents summed voltage events for MV distribution feeder measurement.

Fig. 1 (3D view) which derives from Tab. 1, shows that most voltage sags are found in upper rows (in the 70 to 90 % U_C) and in the duration ranges between 20 ms and 500 ms. Those voltage sags are typical in the range of fault-clearing time and reflect on System Instantaneous Average RMS-variation Frequency Index (SIARFI).

Fig. 2 shows Information Technology Industry Council (ITIC) curve. This voltage tolerance curve gives minimum equipment immunity. Events above the upper curve are presumed to cause the disoperation and also the damage of information technology equipment (e.g., computers, computer network components, and communications networks) and events below the lower curve could cause

Table 1 Summed voltage events measured on the MV distribution feeder

Phase L1, L2, L3	0 – 20 ms	20 – 100 ms	100 – 500 ms	0,5 – 1 s	1 – 3 s	3 – 20 s	20 – 60 s	60 – 180 s
Surge >110 %	5	2	2	1	-	2	1	-
Dip < 90 %	-	-	-	-	-	-	-	-
85…< 90 %	6	137	23	5	-	-	-	-
70…< 85 %	1	220	57	-	-	-	-	-
40…< 70 %	-	53	22	1	-	-	-	-
10…< 40 %	-	1	8	33	-	-	-	-
Interruption	-	-	1	8	-	-	1	2

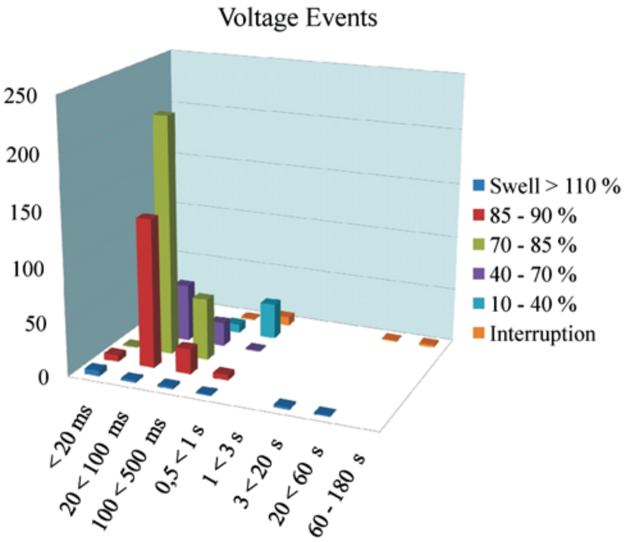

Figure 1 Voltage events measured on the MV distribution feeder

only the disoperation. According to [6], the practical use of an ITIC curve makes sense only when the number of events exceeding the curve is limited. This is the responsibility of both network operators and the customer.

As it can be seen in Tab. 1, during the measurement period 592 voltage events occurred: 567 voltage sags, 13 swells and 12 short interruptions. Fig. 2 reveals that there were 8 voltage events (swells) that violated upper ITIC curve and 156 events (138 sags and 18 interruptions) that violated lower ITIC curve.

Classification of RMS voltage variations by the magnitude and duration of disturbances according to IEEE Standard 1159-1995, [5], is shown in Tab. 2. Events are divided into three classes according to duration: instantaneous, momentary and temporary events. Most of them (528 sags and 9 swells) are instantaneous, while momentary (59 sags, 1 swell and 9 interruptions) and temporary events (3 swells and 1 interruption) were comparably rare. The events mentioned above are all short duration variations, but several long duration variations were also recorded (8 sustained interruptions).

Tab. 3 shows $SARFI_X$, $SIARFI_X$, $SMARFI_X$ and $STARFI_X$ indices which have been calculated by means of events arranged according to IEEE 1159:1995, in Tab. 2. Events were recorded during the time period of 762 days. $SARFI_X$ corresponds to the counting or rate of voltage sags, swell and/or interruptions bellow a voltage threshold. For instance, $SARFI_{90}$ takes into account all voltage sags and interruptions that are below 90 % of a system nominal voltage, while $SARFI_{85}$ has its threshold at 85 % and takes into account all sags and interruptions below that limit. Accordingly, when talking about swells, $SARFI_X$ takes into account all swells that are above threshold X (e.g. $SARFI_{110}$ takes into account all swells with RMS value greater than 110 % of a system nominal voltage). In the same manner other site indices are calculated. $SARFI_X$, $SIARFI_X$, $SMARFI_X$ and $STARFI_X$ in Tab. 3 were calculated for voltage thresholds (X) of 140, 120, 110, 90, 85, 70, 40 and 10, similar to UNIPEDE table.

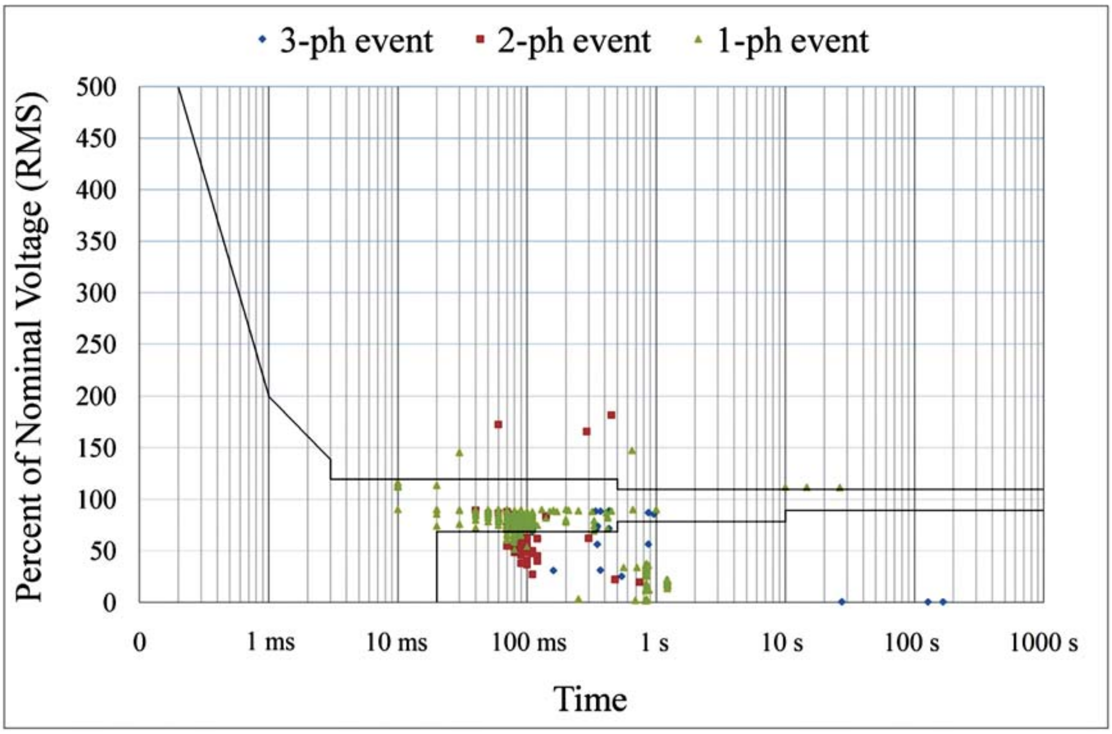

Figure 2 Information Technology Industry Council (ITIC) curve of measured voltage events on the MV distribution feeder

Table 2 Measured voltage events classified according to IEEE 1159-1995

Category	Duration	Voltage Magnitude	Number of Events
Short Duration Variations			
Instantaneous			
Sag	10 ms to 500 ms	10 to 90 %	528
Swell	10 ms to 500 ms	110 to 180 %	9
Momentary			
Interruption	10 ms to 3 s	< 10 %	9
Sag	500 ms to 3 s	10 to 90 %	59
Swell	500 ms to 3 s	110 to 180 %	1
Temporary			
Interruption	3 s to 1 min	< 10 %	1
Sag	3 s to 1 min	10 to 90 %	0
Swell	3 s to 1 min	110 to 180 %	3
Long Duration Variations			
Sustained Interruption	> 1 min	0 %	8
Undervoltage	> 1 min	80 to 90 %	0
Overvoltage	> 1 min	110 to 120 %	0

As there were altogether 596 voltage sags and interruptions measured at this location, the number of voltage sags and interruptions that are included in $SARFI_{90}$ is 596. So, $SARFI_{90}$ consists of all voltage sags with the minimum values of voltage below 90 percent of nominal voltage and time duration between 10 ms and 60 seconds. These events that were recorded during the measurement period of 762 days can also be expressed as 23,50 events per 30 days. Expressing indices in this manner enables easy comparison of different measurement locations in terms of power quality. SARFI indices with other voltage threshold are: $SARFI_{85}$ = 16,69, $SARFI_{70}$ = 5,79, $SARFI_{40}$ = 2,80 and $SARFI_{10}$ = 0,35. $SARFI_{140}$ and $SARFI_{120}$, have the same value of 0,20 because they are both the result of five voltage events with a magnitude around 173 percent of nominal voltage. These surges are consequences of single-phase faults in isolated systems, when the voltage in non-faulted phases increases [3].

Table 3 RMS Variation site indices derived from measured voltage events

x	$SARFI_X$	$SIARFI_X$	$SMARF_X$	$STARFI_X$
ITIC	5,91	-	-	-
140	0,20	0,16	0,04	0,00
120	0,20	0,16	0,04	0,00
110	0,51	0,35	0,04	0,12
90	23,50	20,79	2,68	0,04
85	16,69	14,25	2,48	0,04
70	5,79	3,31	2,48	0,04
40	2,80	0,35	2,44	0,04
10	0,35	Undef.	0,35	0,04

$SARFI_{110}$ was 0,51. $SIARFI_X$, $SMARFI_X$ and $STARFI_X$ site indices were calculated, as well as the $SARFI_{ITIC}$. $SARFI_{ITIC}$ considers voltage sags and interruptions that are below the lower ITIC curve. This curve does not limit the duration of an RMS variation event to 60 seconds; therefore, therefore, the $SARFI_{ITIC}$ is valid for events with durations greater than 10 ms. During the measurement period there were 150 recorded events placed under the lower ITIC curve resulting with $SARFI_{ITIC}$ of 5,91.

Fig. 3 graphically shows the number of voltage sags (expressed as a number of sags per 30 days) classified according to severity of sag.

It clearly reveals that the vast majority of voltage sags have the remaining voltage of sag over 70 % of nominal voltage (over 0,7 p.u.).

As the voltage threshold decreases, so the number of sags decreases more rapidly: there are only 16,69 sags below 85 % and only 5,79 below 70 % nominal voltage, of the total 23,50 sags per month.

Regarding duration of events, the majority of the sags are instantaneous: of overall 23,50 sags, only 2,68 are momentary and 0,04 are temporary sags.

These kinds of voltage events, according to ITIC, should not cause disoperation of sensitive electronic equipment and thus expensive industry intermissions.

5 Conclusion

The Faculty of Electrical Engineering in Osijek performed the long term power quality measurement (monitoring) within Leonardo Power Quality Initiative (LPQI), since HEP d.d. – (Croatian electricity company) Corporative development and strategy division and the Faculty of Electrical Engineering in Osijek were affiliate partners in the project LPQI.

The measurement was performed during the period of 762 days on the secondary side of the MV transformer station 110/35 kV in Osijek, which is one of the three most important transformer stations of the local distribution power network. The fact that MV transformer also supplies a very long overhead line, explains the causes of a notable number of measured events.

All measured voltage events were classified according to the recommendation of EN 50160 and IEEE 1159:1995 standards, and RMS variation performance indices were calculated. *SARFI* indices were recomputed to be

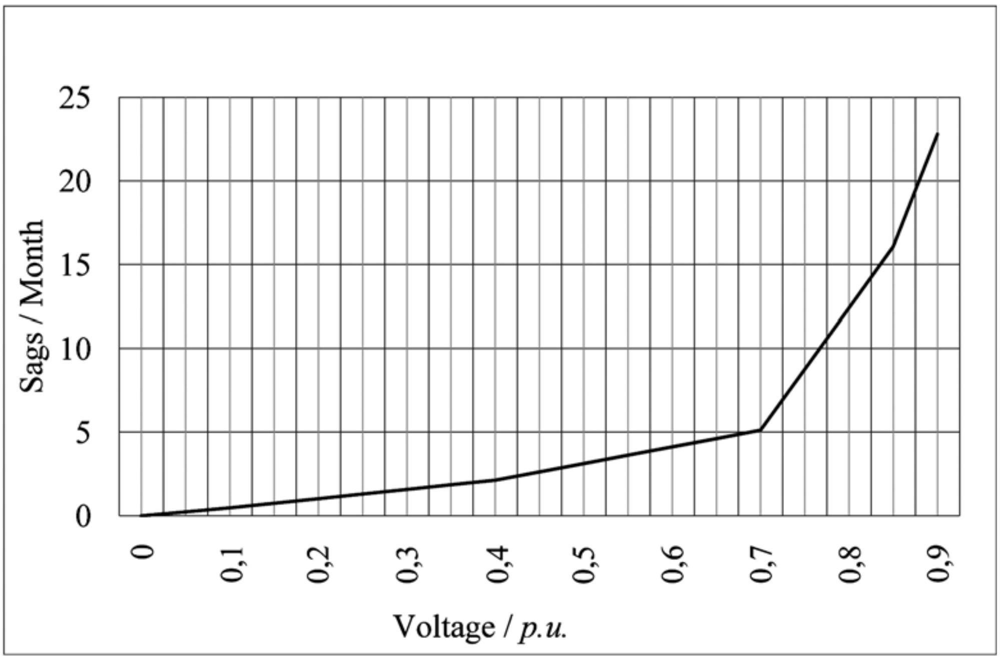

Figure 3 Distribution of measured voltage sags on the MV distribution feeder

represented as the number of events per 30 days. *SARFI* indices are very suitable due to their possibility of comparing different sites, or an even entire power systems.

Most of the measured voltage sags have the remaining voltage above 70 % of nominal voltage, and regarding the duration of events, the majority of the sags are instantaneous. So, after the analysis of the recorded voltage events, one can conclude that most of them should not cause disoperation of sensitive electronic equipment, which is the major issue for industrial consumers.

6 References

[1] Ferracci, Ph. POWER QUALITY, Cashier Technique Schneider Electric no. 199, October 2001.

[2] Power Quality in European Electricity Supply Networks – 1st edition, Eurelectric, Belgium, February 2002.

[3] Bollen, M. H. J. Understanding Power Quality Problems: Voltage Sags and Interruptions. // IEEE Press, New York, 1999.

[4] HRN EN 50160:2008, Naponske karakteristike električne energije iz javnog distribucijskog sustava, izvornik: Voltage characteristics of electricity supplied by public distribution networks (EN 50160:2007).

[5] IEEE std 1159:1995 – IEEE Recommended Practice for Monitoring Electric Power Quality, IEEE Standards Board, 1995.

[6] Bollen, M. H. J.; Yu-Hua Gu, I. Signal Processing of Power Quality Disturbances. // IEEE Press, Piscataway, NJ, 2006.

[7] Djokić, S. Ž.; Milanović, J. V.; Chapman, D. J.; McGranaghan M. F. Shortfalls of Existing Methods for Classification and Presentation of Voltage Reduction Events. // IEEE Transactions on Power Delivery, 20, 2(2005).

[8] Brooks, D. L.; Dugan, R. C.; Waclawiak, M.; Sundaram, A. Indices for Assessing Utility Distribution System RMS Variation Performance. // IEEE Trans. on Power Delivery, 13, 1(1998), pp. 254-259.

[9] Park, C-H.; Jang, G. Stochastic Estimation of Voltage Sags in a Large Meshed Network. // Transactions on Power Delivery, 22, 3(2007).

[10] Šljivac, D.; Klaić, Z.; Šimić, Z. Pokazatelji kvalitete i pouzdanosti napajanja električnom energijom. // Elektroenergetika - časopis za proizvodnju, prijenos, distribuciju i korištenje električne energije, 5, (2008).

[11] Stojkov, M.; Komen, V.; Šljivac, D. Improved Procedures of Distribution Power Network Failure Data Collection for Supply Availability Index Evaluation. // Strojarstvo: časopis za teoriju i praksu u strojarstvu, 51, 2(2009), 127-138 (članak, izvorni znanstveni), Zagreb.

[12] Šljivac, D.; Šimić, Z.; Stojkov, M. Survey on Customer Power Supply Interruption Costs and Calculation of Expected Customer Damages. // Tehnički vjesnik - Technical gazette, 16, 4(2009), 47-53.

[13] Stojkov, M.; Trupinić, K.; Nikolovski, S. Procedure for determination of harmonic distortion along the distribution network. // Tehnički vjesnik - Technical gazette, 16, 4(2009), 19-26.

[14] Klaic, Z.; Nikolovski, S.; Baus, Z., Statistical Analysis of Voltage Sags in Distribution Network According to EN 50160 Standard – Case Study. // 19th International Conference and Exhibition on Electricity Distribution (CIRED), Vienna, 2007.

[15] Nikolovski, S.; Klaić, Z.; Kraus, Z.; Novinc, Ž.; Baus, Z. Power Quality Indices of Distribution Feeder in Eastern Croatia under Electricity Market Conditions, EEM 2008, 5th International Conference on European Electricity Market, Lisboa, 2008.

Authors' addresses

Zvonimir Klaić, dr. sc.
Elektrotehnički fakultet Osijek
Kneza Trpimira 2b
31000 Osijek, Croatia
Tel. 031 224 722
Fax. 031 224 605, Mob. 091 2246 051
e-mail: zvonimir.klaic@etfos.hr

Srete Nikolovski, prof. dr. sc.
Elektrotehnički fakultet Osijek
Kneza Trpimira 2b
31000 Osijek, Croatia
Tel. 031 224 600, Fax. 031 224 605
e-mail: srete.nikolovski@etfos.hr

Zorislav Kraus, dipl. ing. el.
Elektrotehnički fakultet Osijek
Kneza Trpimira 2b
31000 Osijek, Croatia
Tel. 031 224 600, Fax. 031 224 605
e-mail: zorislav.kraus@etfos.hr