VOLTAGE QUALITY ANALYSIS IN A NETWORK POINT OF INTEREST

LEŞE D.*, MAIER V.**, PAVEL S.G.**, BELEIU H.G.**
* S.C. "Electrica" S.A., Baia Mare,
** Technical University of Cluj-Napoca, Memorandumului no. 28, Cluj-Napoca.
lese@mmelectrica.ro, virgil.maier@enm.utcluj.ro, sorin.pavel@enm.utcluj.ro, horia.beleiu@enm.utcluj.ro

Abstract – Harmonics development of the wave corresponding to the rms working voltage and the emphasis of those with periodicity in the interval (5min÷24h) are not satisfying neither the end-user nor the supplier. An expressive analysis must start from highlighting possible levels of the voltage wave and their interpretation as structural implication of the supplying system for the considered electrical distribution network (EDN) point. The paper is firstly presenting the specific indicators of voltage slow variations and experimental bases for voltage quality measurements. The voltage wave decomposition method, in actions and harmonics is developed and applied in the next step. The step type actions are the results of switching the power transformers and auto-transformers plots, the changing electrical networks configurations, switching the capacitor banks steps or of some power consumption recorded jumps The importance of monitoring the dispatcher or end-user measures taken in order to maintain the working voltage in the admissible range of values is also revealed.

Keywords: harmonics, power quality, low voltage variations, voltage monitoring.

1. INTRODUCTION

In power quality (PQ) field, a stage where the theoretical development has to be confronted with the practical reality, has been reached, from the needs of which are both partakers the suppliers and the end-users. There are quite developed standards which have to be known and applied for their provisions to deal with specific application and even in order to their future improvement.

On the other side, the measurement technique has been developed so much that also the common electronic counters are capable to offer a large number of data, many of them being part of the PQ indicators category.

The electrical power system (EPS) interest for the PQ disturbances is illustrated in [1], which started on both, the beneficiary and the performer, a series of preparatory activities, mostly related. Therefore, in case of organizational preparing, has been succeeded to establish the form of the monitoring performed activities, during the measurements period, on the system elements such as transformers and auto-transformers, electrical lines, capacitor banks and generally any configuration change in that system part which are analyzed.

Regarding the contract performer (U.T.C.-N.), the finalization of some research papers [2], [12], [13] and the analysis concept development of the slow voltage variations (SVV), through the voltage wave decomposition into actions and harmonics, have favored the approach in a more favorable theoretical context of the SVV analysis issue.

2. SLOW VOLTAGE VARIATIONS

2.1. SVV Causes

Knowing the causes leading to SVV appearance is important because one of the SVV analysis goals is represented by emphasizing those causes which have led to voltage deviations outside the admissible limits. In a synthetic speech, the significant voltage decreases are produced by the fact that "the impedance between the supplying and the consumption point is too large" or because "the system is too weak for that load" [4].

The SVV causes are found in most part to the end-user but there are also some contributions of the transmission and distribution system, which is mentioned in the following.

Of the SVV causes, which are in the end-users responsibility, are mentioned the following:

- the load variations through both power components, active P and reactive Q, as evidenced by load curves $P(t)$ and $Q(t)$;
- repeated starting of some motors with significant powers for the considered consumption point;
- setting voltage on the transformers and auto-transformers plots from the end-user electric station (if any) and on the transformers from the power substation as well;
- reactive power compensation, in steps or continuously, the last solution can have the fast compensation aspect, with applicability to the arc furnace of other similar receivers;
- supplying scheme modification through the connector

point switching, looping or un-looping, coupling or uncoupling in parallel some electrical lines.

Relating to transmission and distribution system, this influences the voltages regime through continuously adaptation on the consumption requirements and through the specific intervention methods for maintaining the voltage into established bands. Thereby, the SVV causes, which can be assigned to the transmission and distribution system, are the following:

- setting the transformers or auto-transformers plots switches positions from the electric stations;
- longitudinal reactance compensation of the transmission and distribution system;
- in steps or continuously compensation of the transited reactive power;
- network configuration modification through changing the supplying points (injection), looping or un-looping, coupling or uncoupling in parallel of some electric lines.

2.2. SVV Analysis

Further on, is considered the fact that the consecutive rms voltage values, from one phase or line, form a function called **wave voltage** in report with time variable. Appling the concept of voltage waves decomposition in actions and harmonics [2] facilitates emphasizing the causal links in SVV analysis through separation the consequences of some binary actions (exist/doesn't exist, 0/1) from the ones which lead to the continuous variations of rms voltage values.

Through **actions** are defined those interventions, expressed as a step or binary function, by which the supplier maintains the rms voltage between admissible limits, as follows:

- setting the power transformer or auto-transformer plots;
- configuration changes of power transmission or distribution lines;
- connecting or disconnecting some capacitor banks steps;
- coupling or un-coupling of end-users.

Graphically, functions corresponding to actions are represented as unitary step signals, for which a general form was considered and the corresponding Fourier development was determined.

Having an infinite number of harmonics, such a development reveals the sinusoidal functions ensemble, on which the unitary step function equates them in concrete conditions of duration and periodicity.

Practically, the step functions are emphasized under some **levels** shape of the voltage wave for a day, applying the rms values mediation on different intervals of time.

The second step in the slow voltage variations analysis is represented by the Discrete Fourier analysis for voltage wave during a day after the compensation of the already highlighted levels.

Finally, the voltage variations that are not justified either by actions or by load variations can be attributed to voltage variations upstream the supplying point, which suggests extending the measurements and the PQ parameters monitoring, especially the voltages, in this point also.

2.3. SVV Indicators

The periodic rms voltage variations can be slow variations, consisting in deviations up to ± 20% of its rated value and periodicity in the interval (5 min ÷ 24 h) and fast variations, called fluctuations, with deviations up to ± 10% in the range (40 ms ... 5 min).

To appreciate the slow voltage variations, generally called **voltage irregularity**, indicators are used to express the voltage deviation from its nominal value, U_n, specific to each power system segment.

The real voltage, in considered point and moment is called **working voltage**, U_s, and since the use of relative quantities is expressive and convenient, the size named relative working voltage u_s or **voltage level** is introduced by the relation:

$$u_s = \frac{U_s}{U_n}, \quad (1)$$

which can be used as above or in percentage expression.

For the average value of the voltage is correct to use the mean square from the point of view of both the recommendation concerning the statistical averages calculation and especially because it corresponds to the criterion of electrical power equivalence. Therefore, if we consider that the fundamental periods T_k can be distinct, then the correct mediation relationship is square-weighted type:

$$\overline{U_s} = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_T}(U_{sk}^2 \cdot T_k)}\ , \quad (2)$$

and if differences between periods T_k are neglected and we consider $T_1 = T_2 = ... = T_{NT}$, then the average working voltage is calculated with square mean:

$$\overline{U_s} = \sqrt{\frac{1}{N_T}\sum_{k=1}^{N_T}U_{sk}^2}\ . \quad (3)$$

The SVV PQ indicators are summarized in Table 1, in report with rms voltage, as an absolute size, and in report with the rms values, the working voltage in percentage $u_{\%}$ and the voltage level u_s (rel. 1) as well. The absolute sizes expressed in percentage are mostly preferred in practice, reason why they were primarily included in table.

Voltage deviation limit values are indicated at the delimitation points (DP). So, in normal working conditions, the average rms of the delivered voltage, for 10 min intervals on a period representing 95% during any period of weeks, have to show percentage deviations which must fall within the ranges [10]:

$\Delta u_{\% adm} = \pm 10\%$ of the rated voltage U_n, for LV installations;

$\Delta u_{\% adm} = \pm 5\%$ of the contracted voltage U_c, for MV and HV installations.

Table 1. Calculus relations of slow variations specific indicators, in relation to the absolute and relative voltage

Size	Working Voltage U_s, V	Working Voltage percentage, $u_{\%} = 100 \cdot U_s / U_n$, %	Voltage Level $u_s = U_s / U_n$
Voltage Mean	$\overline{U_s} = \sqrt{\frac{1}{N_T}\sum_{k=1}^{N_T} U_{sk}^2}$	$\overline{u_{\%}} = \sqrt{\frac{1}{N_T}\sum_{k=1}^{N_T} u_{\%k}^2}$	$\overline{u_s} = \sqrt{\frac{1}{N_T}\sum_{k=1}^{N_T} u_{sk}^2}$
Voltage Deviation	$\Delta U = U_s - U_n$, V	$\Delta u_{\%} = u_{\%} - 100$, %	$\Delta u_s = u_s - 1$
Voltage Mean Deviation	$\overline{\Delta U} = \frac{1}{T_0}\sum_{k=1}^{N_T} \Delta U_k \cdot T_k$, V	$\overline{\Delta u_{\%}} = \frac{1}{T_0}\sum_{k=1}^{N_T} \Delta u_{\%k} \cdot T_k$, %	$\overline{\Delta u_s} = \frac{1}{T_0}\sum_{k=1}^{N_T} \Delta u_{sk} \cdot T_k$
Square Mean Deviation	$\sigma_U = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_T} (U_{sk} - \overline{U_s})^2 \cdot T_k}$	$\sigma_U = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_T} (u_{\%k} - \overline{u_{\%}})^2 \cdot T_k}$	$\sigma_U = \sqrt{\frac{1}{T_0}\sum_{k=1}^{N_T} (u_{sk} - \overline{u_s})^2 \cdot T_k}$
Voltage Variation Coefficient	$C_U = \frac{\sigma_U}{U_s}$	$C_{u\%} = \frac{\sigma_{u\%}}{u_{\%}}$	$C_{us} = \frac{\sigma_{us}}{u_s}$

3. APPLICATION

3.1. Experimental data

The SVV was the main goal of the voltage wave quality analysis [1], but this opportunity was used for harmonics investigation as well. The measurement point of interest was established to the general low voltage (LV) column, point where the research beneficiary has mounted a measurement and monitoring equipment (Fluke 434), giving data about network voltages and power consumption characteristics. Through the offered facilities, the mentioned equipment, meets the conditions of a three-phase power-meter being next identified with the element PM1.

Due to difficulty of the LV column access the monitoring equipment PM2 was connected in the measurement point represented by the LV bars of the general panel. These included the following devices, shown in Figure 1:

- 400 A amps clamps and afferent conductors W2, for current transducers connections;
- conductors set W1 with isolated crocodiles for voltage transducers connections;
- voltage and currents transducers block EB, with its own power source;
- data acquisition board N1;
- computing system EC with virtual instruments (VI) software, in LabVIEW.

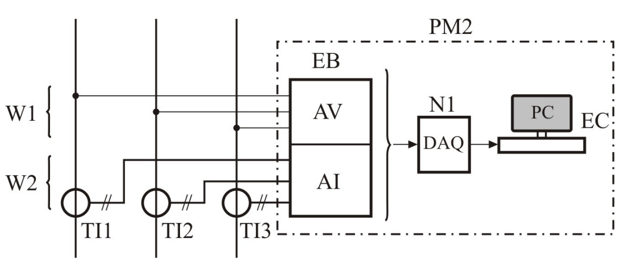

Fig. 1 - Network connection of the monitoring equipment, PM2

The observation period was established to T0=24 h justified through the daily mostly cyclical consumption and considered as enough for this stage of research. The measurements were performed between 21.12.2011, 10,00 am and 22.12.2011, 10,00 am.

Because of the large number of values that would be retained and processed, the monitoring equipment PM2 was set to hold in the file the average rms voltage for each second. The voltage variations chart during a day is represented in Fig. 2 as follows:

- the rms voltage variations UTVS (on one phase) considered as an average on the very short time interval, TVS = 3 s are rendered with dark line (black);
- by light line it was drawn the moving average mean UTSH, calculated for 10 min intervals (TSH) to better overtake the voltage variation general trend.

Because of the voltage variations symmetry on the network three phases it was analyzed and will be presented the results on one phase only. So, in Figure 2 is shown the voltage variations graph during one day (24 h), with highlighting the moving average UTSH on short time intervals (10 min), in the measurement point PT 290 DIETER (Baia Mare).

Through the territorial dispatcher (TD) kindness it could prepare a graphic of the realized actions into the local EPS, with consequences over the voltage level in the considered measurement point. The retained actions and graphically rendered in Figure 3 are referring about switching plots of the transformer no.2 Săsar, through the electrical power is transmitted from the supplying point PA7 and the main electrical line toward to the measurement point, and to switching the 6,3 kV medium voltage (MV) capacitor bank no.1, as well.

On the figure is observed the used Np plot position, during the monitoring period, was in the range Np∈{1, 2, 3, 4}, with an extended standing on second position, Np=2. Also it can be observed (Fig.3, b) that the capacitor bank was uncoupling in the time interval t∈[21.12.12, 21h 30´÷22.12.12, 7h 11´] and being coupled in the other time interval.

In the down side of figure (Fig. 3, *c*) is indicated the calendar date of measurements and actions progress, being considered the fact that these were performed on two consecutive days.

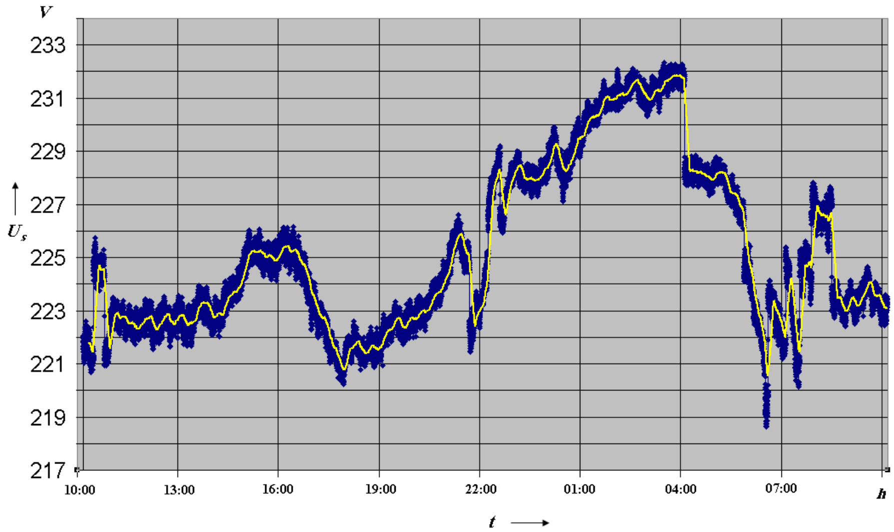

Fig. 2 - Voltage variations graph over 24 *h* period, highlighting the moving average on short time intervals U_{TSH}=10 min, in measurement point PT 290 DIETER.

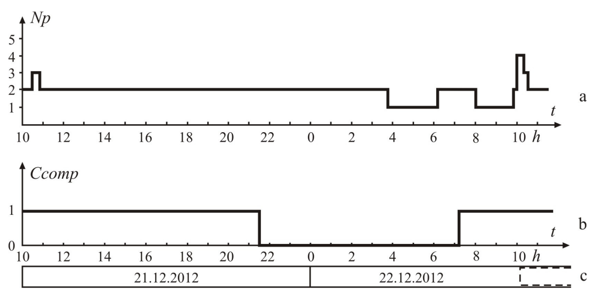

Fig. 3 - The actions chart taken by the TD for maintain the voltage within admissible limits: *a* –plots positions to the transformer no.2 Săsar; *b* – coupling the MV capacitor bank; *c* – calendar date.

3.2. Voltage variations range

The rms working voltage Us considered by representative values for the 1 s interval which led to the average values determination (UTVS) on the 3 s interval were in the following range during the observation period:

$$U_s \in [218{,}6;\ 232{,}3]\,V \qquad (4)$$

In this way, the voltage deviation was situated between,

$$\Delta u_{\%} \in [-4{,}95; +1{,}01]\%\ , \qquad (5)$$

so in the admitted range. [10].

3.3. General statistical characterization of voltage variations

The mean working voltage UTD for the entire observation period of one day is determined by applying the relation (3) , that is a statistical mean calculation:

$$U_{TD} = \sqrt{\frac{1}{M}\sum_{j=1}^{M} U_s^2} = 225{,}27\ V\ , \qquad (6)$$

where M=86,4·103 values on one day. In accordance with this basis, the percentage mean voltage level is:

$$\bar{u}_{s\%} = \frac{U_{TD}}{U_n}\cdot 100 = 97{,}95\ \%\ . \qquad (7)$$

The mean voltage deviation is calculated for the real case, without any significant frequency variations (f≈const.) during measurements:

$$\overline{\Delta u}_{\%} = \frac{1}{M}\sum_{k=1}^{M} \Delta u_{\%k} = -2{,}06\ \%\ . \qquad (8)$$

The voltage mean square deviation is determined through adapting the general relation, from Table1, to the considered case:

$$\sigma_U = \sqrt{\frac{1}{M}\sum_{k=1}^{M}\left(U_{sk} - U_{TD}\right)^2} = 9{,}92\ V\ . \qquad (9)$$

Finally, the voltage variation coefficient is determined with the relation (Table 1):

$$C_{vU} = \frac{\sigma_U}{U_{TD}} = \frac{9{,}92}{225{,}27} = 0{,}044\ . \qquad (10)$$

So, as overall assessment, we can say that the average voltage is lower with about 2,06% than the rated value, but the deviations are in the range of allowed values. Also, there have not been revealed voltage dips, short duration over-voltage or voltage impulses during measurements. The voltage variation coefficient, expressed in percentage, is below 5%, without being standardized, which can be acceptably considered.

3.4. Highlighting levels in the voltage chart

To make more visible the possible levels from the voltage variations chart the moving average was firstly represented of a range exceeding 10′, adopting a half-hour (30′) interval. The obtained graph, similar to one from Fig. 2, but with slower variations, has facilitated to emphasize the following four levels presented in Fig. 4:

- the first level with mean voltage Umed1=222,8 V, recorded between 1010-1430, and having the working voltage $U_s \in [220{,}7;\ 225{,}7]\,V$;
- the second level with mean voltage Umed2=224,9 V, recorded between 1430-1700, and having the working

voltage $U_s \in [223{,}3;\ 226{,}2]\,V$;

- the third level with mean voltage Umed3=222,8 V, recorded between 1700-2140, and having the working voltage $U_s \in [220{,}2;\ 226{,}6]\,V$;
- the 4th level with mean voltage Umed4=229,2 V, recorded between 2140-410, and having the working voltage $U_s \in [221{,}5;\ 232{,}3]\,V$;
- the 5th level with mean voltage Umed5=227,8 V, recorded between 410-600, and having the working voltage $U_s \in [224{,}5;\ 228{,}8]\,V$;
- the last level with mean voltage Umed6=223,8 V, recorded between 600-1010, and having the working voltage $U_s \in [218{,}6;\ 227{,}8]\,V$.

Even without detailing every single level, can be noticed some particularities on the complete representation of the voltage wave (Fig. 2). So, relating to the first level, can be observed that at the beginning, around 1100 am, there is clearly manifested the up-step plot position switching of the supplying transformer and after about 20 min its revenue, action highlighted by the TD diagram as well.(Fig. 3), the average voltage jump at the increasing plot position is around 3 V. Otherwise, the rms voltage presents oscillation around the average value (of 222,8 V), with slow periodicities, of 30÷45 min and amplitudes of 0,3÷0,4 V.

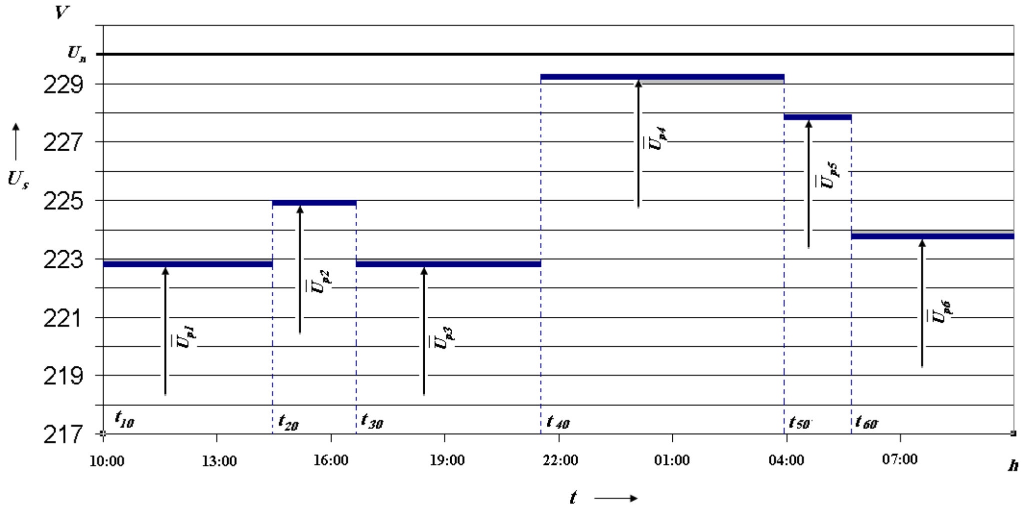

Fig. 4 - Proposed levels for voltage variations graph, on the one day observation period, and the characteristic intervals.

Remaining to more general appreciations about the next levels can be made the following observations:

- the second and the 5th levels are just “calm” like the first one after that double plot commutation was passed;
- the 3rd and the 4th levels reveal the continuous load decreasing on them periods.
- the last level, more “disrupted”, presents the cumulative aspect of the load increasing with those relative frequent plots switching, through which the voltage maintaining system occurs automatically. The amounted effect of the load variation and of the plots and capacitor bank switching, lead to an inedited shape (“saw-tooth”), of the voltage wave, during on this last level period.

3.5. SVV Harmonics

The voltage variations periodicity, framed within the slow variations family is settled in the range $T_{UL} \in [5\,\text{min};\ 24h]$, so, if T_1=24 *h* is considered as the fundamental period, 288 harmonics should be identified.

It is known that in the Discrete Fourier analysis [8] the continuous component is determined with the following relation:

$$U_0 = \frac{1}{2p} \cdot \sum_{k=0}^{2p-1} U_k\ . \qquad (11)$$

where (2*p*) represents the total number of samples (values) and the considered period is equal with the observation time;

U_k – a sample size, equal in this case with the rms voltage or with one of the moving mean values, on very short (TVS=3 *s*) or short interval (TS=10 min).

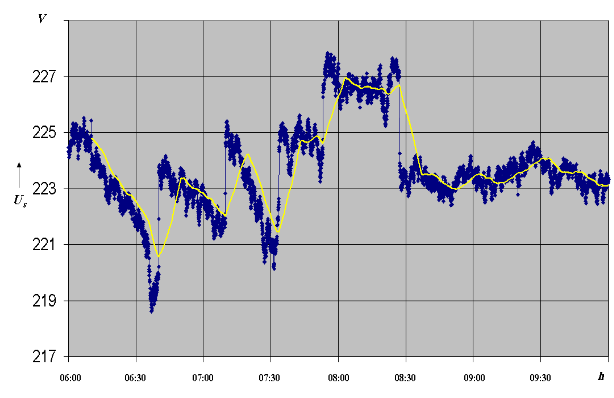

Fig. 5 - Graficul variațiilor de tensiune pe ultimul palier (06:00-10:10) cu evidențierea mediei mobile pe o perioadă de aprox. 10 min.

Running the harmonic analysis program *VI* REGIDE for the last level emphasized in the voltage variation wave, given more detailed in Figure 5, led to the results shown in Table 2.

ERR=0,05 was introduced in the program as a relative error so that all harmonics with amplitudes in the error range are neglected. For the analyzed observation period (of 250 min) the 5 min limit periodicity corresponds to the 50th order harmonic. Therefore, all identified harmonics with a higher order than 50 are in the voltage fluctuations range and are not included in the table.

Among these, the following eight harmonics have the most important weights:

$k_{imp} \in \{1, 2, 4, 8, 10, 11, 13, 15\}$,

highlighting the network manifestation of some consumption characteristics with following periodicities:

$T_k \in \{17, 19, 23, 25, 31, 63, 125, 250\}\text{min}$.

Is can be noted that the most important slow voltage variation is quite the fundamental with 250 min periodicity while among slow variations with lower periodicity, the 34th order harmonic has a significant weight with a 7,4 min periodicity.

The SVV harmonics amplitudes, from the last level, are found in the following range:

$U_k \in [0{,}3 \div 1{,}33]\ V$.

Table 2. Voltage varations harmonics coresponding to the 6th level

k	*U$_k$*, V	*k*	*U$_k$*, V	*k*	*U$_k$*, V	*k*	*U$_k$*, V
0	0,108	9	0,323	19	0,123	33	0,159
1	**1,325**	**10**	**0,520**	20	0,247	34	0,229
2	**1,310**	**11**	**0,523**	23	0,157	36	0,130
3	0,613	12	0,197	24	0,290	37	0,096
4	**0,893**	**13**	**0,346**	25	0,237	38	0,098
5	0,271	14	0,194	26	0,164	40	0,168
6	0,276	**15**	**0,301**	27	0,235	41	0,158
7	0,234	17	0,280	29	0,119	42	0,114
8	**0,428**	18	0,274	31	0,120	50	0,134

A very important observation emerges from slow voltage variations analysis that is the highlighted harmonic amplitudes do not monotonically decrease with their order which is visible from the third to 4th harmonic transition, from 7th to 8th etc.

The analysis of end-users processes would be able to reveal actions with the emphasized periodicities which were significantly manifested in SVV.

5. CONCLUSION

Applying the relative recent proposed methodology of decomposition the voltage wave in actions and harmonics, through the SVV identification, new aspects were emphasized in this application, such as “saw-tooth” variation profile. These aspects result through the effects of some continuous processes overlap, such as load variation, with some step type ones, where the actions like transformers plots and capacitor banks steps switching, are framed.

Comparing the decomposed voltage wave in levels, based on moving average, with the afferent actions diagram on the distribution system elements, a good correlation between them was observed. In consequence, when an actions diagram is disposed, it must be placed on the levels defining base from the voltage wave.

In the measurement point of interest, the voltage average is lower with about 2,1% than the rated value, but the deviations are within admissible limits. The average deviation reduction toward zero may be a voltage control objective for this consumption point.

The emphasized levels in the analyzed voltage wave on one day have mostly a good justification through the variation form and through the power consumption evolution as well. It can be affirmed that the realized analysis in this application claims the decomposition methodology of the voltage wave in actions and harmonics, for emphasizing the SVV.

The experimental methodology, interlock to SVV analysis, must be developed through monitoring some points upstream the point of interest and also through the participation of all factors which occur through actions in transmission and distribution system.

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