CHARACTERISTICS OF VOLTAGE MAINTAINING METHODS FOR ELECTRICAL NETWORKS

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REZUMAT. Dintre metodele analizate în lucrare fac parte utilizarea de tensiuni suplimentare prin reglajul prizelor la transformatoare şi autotransformatoare, modificarea parametrilor reţelelor şi controlul circulaţiei de putere reactivă. În bună parte, aceste metode sunt disponibile atât la nivelul furnizorilor, cât şi al consumatorilor, chiar dacă cu ponderi relativ diferite.

Cuvinte cheie: regim deformant, calitatea energiei electrice, variaţii lente de tensiune, monitorizarea undei de tensiune.

ABSTRACT. Among the analyzed methods there are the additional voltages uses by setting the transformers and autotransformers traps, the network parameters changing by parallel coupling/decoupling and the reactive power flow control. These methods are available on both the suppliers and the end-users, even if they have different weights.

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

1. INTRODUCTION

Recent studies performed by the authors led to the idea of the voltage wave decomposition first in actions and then in harmonics. As actions, are considered all technical interventions in the power system to maintain the rms working voltage in the prescribed standards.

The actions are “nothing-all” or “0-1” type in binary, which may be characterized as durations and action mode through unitary step functions. The appreciation of the gap produced by actions requires previous quantitative assessments of the voltage variations monitoring and analyzing process to allow identifications of cause-effect type.

The main goals of this paper are represented by reviewing the methods of the working voltage maintenance in transmission and distribution electrical networks, their analytical bases and especially the positive or negative jumps evaluations which these measures produce on the voltage average values.

The voltage variations identification, especially the slow voltage variations with periodicity in the range (5 min÷24 h) represents an increased interest in supplier and end-user relationship.

Because the most Power Quality (PQ) aspects utilized the rms sizes, real frequency estimation, through the most exactly fundamental period determination is the first step in any approach relating to PQ. [4], [5]

2. METHODOLOGICAL BASIS

2.1. Voltage maintenance measures

The working voltage in any point electrical power system (EPS) has to be situated around the corresponded rated values, in a range defined by admissible deviations for the specific voltage level, according to the relationship:

$$U_s \in \left[(1-\Delta u_{\%admi}/100)\cdot U_n ; (1+\Delta u_{\%adms}/100)\cdot U_n\right] \quad (1)$$

where $\Delta u_{\%admi}$ and $\Delta u_{\%adms}$ represent the admissible percentage deviations as inferior and respectively superior limits for the voltage level characterized by rated line voltage, U_n, through norms and standards; in some cases the percentage inferior and superior limits may have different absolute values [6].

The available **methods** to the electrical power system level for maintaining the working voltage between limits given by relation (1) are the follows:

- setting the synchronous generators voltage (SG) in electrical utility;
- setting the voltage in transmission and distribution electrical lines which is reflected in the use of additional voltages, changing the network parameters and reactive power flow control.

The voltage drops on the transmission and distribution systems elements, being dependent on the variable and vehiculated load are established and followed *the voltage bands* by the dispatchers on each characteristic period for every utility and power station distribution bar.

The available measures to the Territorial Dispatchers (TD) level are:

- setting the auto-transformers or power transformers plots switches positions;
- coupling in parallel of some electric lines (EL) or uncoupling some EL functioning in parallel;
- looping or un-looping some distribution schemes of main line type (ML);
- power factor control by optimization of reactive power consumption;
- controlling, scheduling and limiting the energy consumption to end-users.

The end-users, in accordance with the consumption size and the internal power system equipment may contribute to the maintenance of the correspondent voltage value in the separation point and in the internal supplying system through the following measures:

- setting the power transformers plots switches positions from the own electric station (ESt), if any and from the power substation (PS) as well;
- coupling in parallel of some EL or uncoupling some radial EL functioning in parallel;
- looping or un-looping some distribution schemes of main line type (ML);
- individual, of group or centralized compensation of the reactive power;
- energy consumption management and implementing all technical and organizational measures to flatting the energy consumption and limiting current shocks or major variations.

2.2. General electric scheme

If to collect data referring the voltages of one or all phases was considered sufficient by now [1], [4], the experience of performing some analyzes on voltage variations in real conditions and having as purpose their interpretation, led to the expanding of the problematic area upstream of the measuring point, and on some characteristic variables of the consumption as well, such as: active, reactive and apparent powers, currents in different representative points of the network where the measuring point belongs.

The general distribution scheme of a supplying path from the electrical power system (EPS) to the measuring point of interest is shown in figure 1, indicating some intervention ways to adjust the voltage and the measuring points required for a full analysis of voltage variations in the point of interest. The minimum equipment which may perform even a protective role, besides the switching one is indicated in the figure, separators being not specified.

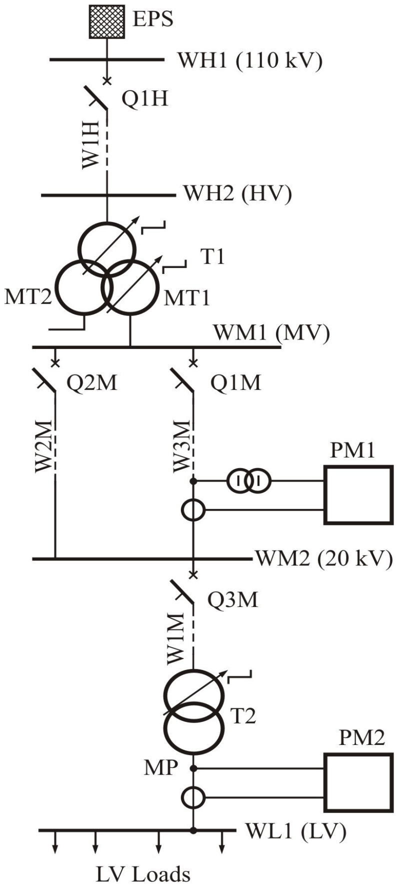

Fig. 1. Distribution scheme for measuring point of interest.

The electric high voltage (HV) line W1H is protected at its departure by the circuit breaker Q1H and is supplying an electric station provided with T1, a three windings transformer. The arrows and the step sign attached to HV and MT1 windings indicates that these windings are step-like adjustable, as follows: the high voltage winding is “on load” adjustable with a plot switcher, and the MT1 winding is adjustable only is absence of load. From the power station MV bars the energy may be transported by one of the MV lines W2M, W3M or through both, in parallel.

The additional point of measure is provided on the side from the MV bars WM2 when only the W3M line is used. Here, a three phase power meter device PM1 is connected being capable to collect voltage and electrical load data. Further on, the low voltage EL W1M is presented, being initially protected by the circuit breaker Q3M and feeding the power substation provided with step-down transformer T2. This one has the possibility of adjusting the plots, in the absence of load, on the MV winding.

The measuring point of interest is MP, where the monitoring equipment PM2 is connected in order to collect the low voltage system from the power substations bars WL1 and the line currents system that feeds them. If in the monitoring equipment case, voltages can be transmitted directly to the voltage transducers, measuring voltage transformers are required for the device PM1 (figure 1).

2.3. Slow voltage variation analysis

Relating to the slow voltage variations, outlined as a priority aim, the new concept of voltage wave decomposition was defined, indicating the rms values of voltage variations during the observation period, into actions and harmonics. The actions are those interventions, expressed as a step function or binary, through which the TD, the supplier or the end-user contributes to the maintaining of the rms voltage within limits (see section 2.1).

Graphically, such functions are represented as unitary step signal [8], for which a general form has been considered and the corresponding Fourier development, consisting of an infinite amount of harmonics has been also determined.

The harmonic decomposition of the of unitary step function argue, as a first step in the slow voltage variations analysis, the emphasizing of the "nothing-all" or "0-1" actions, these ones corresponding to the continuous components.

It is known that the dc component in the Fourier analysis is determined by the relationship [4]:

$$U_0 = \frac{1}{2p} \cdot \sum_{k=0}^{2p-1} U_k \ , \qquad (23)$$

where (2p) is the total number of samples (values) for the considered period equal to the observation time in this case;

U_k - a sample size, equal in this case with the voltage rms value or with one of the medium voltage (MV) values, on very short (3s) or short time (10 min) interval.

The variable assigned to each ordinate level of the voltage wave variation gain a real meaning, namely the arithmetic mean of individual values of the respective level. With this remark is also justified the harmonic analysis application on the time intervals set during the levels definition.

Figure 2 shows the set of four fictive levels pointed out on a variation of the working voltage wave.

Each level *"i"* is characterized by the mean square $\overline{U_{pi}}$, $i \in \{1, 2, 3, 4\}$, which may be situated above or below the rated value U_n as well as the corresponding beginning moments t_{i0}, considering that the last moments of a level coincides with the start of the next level.

The interpretation of differences between levels or steps might be done in better conditions, if an interventions list would exist at the territorial dispatcher level, under which the monitored point of consumption is also located.

As some actions, such adjusting switches plots, take place without the intervention of the human operator, identifying them is relatively difficult.

Further on, we can proceed to the Discrete Fourier Analysis of the slow voltage variations performed either on the each time interval corresponding to the emphasized levels or on the entire observation period. It is recommended to remove the levels values form the voltage variations graph and to consolidate the voltage mean values up to 1 min; this last recommendation is related to emphasize the harmonics with the periodicity of at least 5 min (for voltage mean values at each minute it can be identified harmonics with periodicity longer than 4 min).

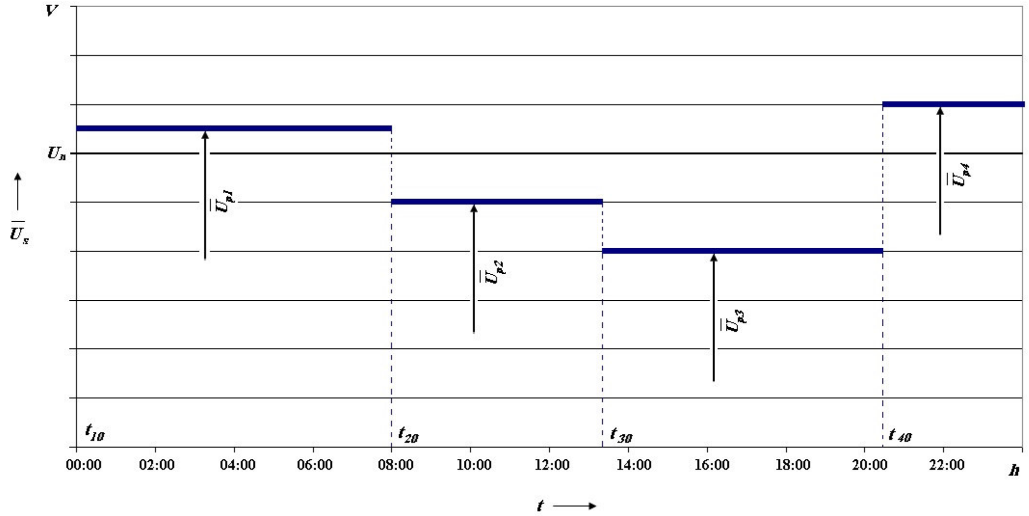

Fig. 2. The highlighted levels in the voltage variations graph, on the observation period, for a day and their time intervals.

Some of the periodically variations emphasized through Discrete Fourier Analysis can be related with load variations on the each distribution scheme segment (figure 1). Finally, the voltage variations that are not justified either by actions or by load variations can be attributed to voltage variations in the network supplying point, represented through high voltage (HV) bars WH1, in the general scheme (figure 1).

The analysis of processes which take place at the end-users supplied from the distribution point represented by the measurement point MP (figure 1) would be revealing the existence in technological processes of those periodicities, which have manifested with striking in the slow voltage variations.

3. CHARACTERISTIC OF VOLTAGE MAINTAINING METHODS

3.1. Additional voltages through direct setting

Direct setting is performed with power transformer and auto-transformers of witch working windings are constructed provided with taps, setting plots and switching plots.

At the low power transformers from the transformers power range designed for equipping supplying points, the setting is executed in the load current absence, so with removing the transformers under the voltage. The high power transformers are provided with a larger number of plots and can be under load adjustable, because of their important role in transmission and distribution networks.

In most cases, the setting plots are symmetrical disposed in relation to a **centre tap**, which correspond to the rated voltage of the adjusted winding. The rated voltage corresponding to the midpoint tap is higher with 10% than the rated voltage of the transformer secondary network, at the voltage step up transformers, and it is equal with the primary voltage at the step-down transformer.

Usually, the winding that contains the setting plots has the higher voltage, so the transformer primary for the step-down transformers voltage. This solution is motivated by the fact that the HV winding is more accessible being disposed to the coiling exterior and especially by the simplifying plots switching construction, which are sized for lower working currents.

The plots switching has to ensure the transition from an working tap to another without current interruption and without coils direct short-circuit between two consecutive plots.

The setting plots number in the same way is noted with ***p***, so the transformer is provided with $(2p+1)$ plots. The plots order number N_p can take one of the integer numbers from the range:

$$N_p \in [-p,+p],\ N_p \in Z \tag{3}$$

The setting step, noted with a, designates the additional voltage ΔU introduced only in absence of load, in positive or negative way, at the one unit modification of the working number plot, in respectively way, being percentage expressed beside the median plot voltage U_0 through the relationship:

$$a = \frac{\Delta U}{U_0} \cdot 100,\ \%\ . \tag{4}$$

With these notes, for a step-down transformer with two windings the secondary voltage to lower loads can be determined in relation with switching plot position with the relationship:

$$U_2 = U_{n2} \frac{U_1 / U_{n1}}{1 - N_p \cdot a / 100}\ , \tag{5}$$

the „minus" sign being justified of the above convention related with the setting step, as an effect for the secondary voltage (for the $+p$ plot is corresponding the higher secondary voltage and for the $-p$ plot the lower secondary voltage). From the relation (5) it can be observed that the secondary voltage U_2 at one time depends on the primary voltage U_1 and also on the plot order number N_p.

Finally, the difference between two consecutively positions of the switching plots, with taps for setting and for output circuit, can be determined (is considered that is passing from the plot N_p to N_{p+1}) which is a function of the switching plots order number N_p, according the relationship:

$$\Delta U_2(N_p) = \frac{(100/a) \cdot (U_1 / U_{n1}) \cdot U_{n2}}{(100/a - N_p) \cdot [100/a - (N_p + 1)]}\ , V\ . \tag{6}$$

The situation is similarly to the auto-transformers with the difference that there is only one winding with taps for setting and for output circuit. There are also auto-transformers with the nominal report 1:1 with setting limits up to ±20%, design for networks voltage setting with the same value.

The three windings transformers including one of HV and the other two of MV having different values are provided with taps on two of the windings related to the next voltage general notation:

$$(U_{n1} \pm p_1 \cdot a_{1\%}) / (U_{n2} \pm p_2 \cdot a_{2\%}) / U_{n3} \tag{7}$$

where p_1 represents the setting plots number in the same way for the HV winding;

$a_{1\%}$ - the setting step for the HV winding, in %;

p_2 *and* $a_{2\%}$ - similar quantities but for the MV winding with higher rated value $U_{n2} > U_{n3}$.

On the three windings transformers only the HV winding is adjustable on load, while the MV one are adjustable only in absence of load. For such a transformer type it can be defined a transformation report $\boldsymbol{K_{MT1}}$, no-load work, between the HV and the fixed MV windings (e.g. with the 6kV rated voltage) with the relation:

$$K_{MT1} = \frac{U_{n1}}{U_{n3}} \cdot \left(1 - \frac{N_{p1} \cdot a_1}{100}\right), \qquad (8)$$

(where was introduced the sign convention defined on expression (5)), and also a transformation report $\boldsymbol{K_{MT2}}$, on no-load work, between the HV and the adjustable MV windings (e.g. with the 35kV rated voltage)

$$K_{MT2} = \frac{U_{n1}}{U_{n2}} \cdot \left(\frac{1 - N_{p1} \cdot a_1 / 100}{1 + N_{p2} \cdot a_2 / 100}\right), \qquad (9)$$

where the plots current numbers N_{p1} and N_{p2} are taken according to the relationship (3) reported to the plots number in one way p_1, respectively p_2. In the expression (9) the sign convention different between secondary and primary is clearly observed, but so that for the positive plots and with a superior order number, primary and also secondary, to result secondary voltage increasing.

Regarding to the secondary voltages value for the fixed MV winding, it can be determined with the relationship (5) and for the adjustable MV one – with the expression:

$$U_2 = U_{n2} \frac{(U_1 / U_{n1}) \cdot (1 + N_{p2} \cdot a_2 / 100)}{1 - N_{p1} \cdot a_1 / 100}, \qquad (10)$$

where the variables quantities U_1, N_{p1} şi N_{p2} are noted.

The secondary voltage jump determination is the same as at the two windings transformers, with the expression (6), for the fixed secondary winding case and for the adjustable secondary winding it will be considering the primary plots setting case and also the secondary ones. Thereby, if we admit that the setting is made to the primary winding only, from the plots N_{p1} to (N_{p1}+1), the voltage jump is given by the expression:

$$\Delta U_2(N_{p1}) = \frac{(U_1/U_{n1}) \cdot (1 + N_{p2} \cdot a_2/100) \cdot (a_1/100) \cdot U_{n2}}{(1 - N_{p1} \cdot a_1/100) \cdot [1 - (N_{p1}+1) \cdot a_1/100]}, V, \qquad (11)$$

and if we talk about the secondary winding switching from the plots N_{p2} to (N_{p2}+1) the voltage jump is given by:

$$\Delta U_2(N_{p2}) = \frac{(U_1 / U_{n1}) \cdot (a_2 / 100) \cdot U_{n2}}{1 - N_{p1} \cdot a_1 / 100}, V. \qquad (12)$$

The voltage setting characteristics of the power transformers made by “Electroputere Craiova” are indicated in table 1, in function of the transformer type and destination, that is for the power substation (PS) or for the electric station (STe). The setting step numbers on one way and also the percentage setting step are indicated. Related data to the setting possibilities are useful for emphasizing the levels, in real voltages curves.

As was firstly mentioned, the voltages calculated with the relations (5) and (10) are applicable to unloaded running and lower loads. For transformers and auto-transformers working it must be taken into account the voltage drops and their own equivalent impedance which for the two windings transformers are determined with the relationship:

$$\Delta U_T = \left(\frac{\Delta P_{sc}^{kW} \cdot \cos\varphi_s}{S_{Tn}^{MW}} + 10 \cdot u_{sc\%} \cdot \sin\varphi_s\right) \cdot k_T \cdot U_{Tn}, V, \qquad (13)$$

where S_{Tn} represents the transformer rated voltage, in MVA;

ΔP_{sc} – transformer rated losses in short-circuit, in kW;

$u_{sc\%}$ – transformer short-circuit relative voltage, in %;

$\cos\varphi_s$ – load power factor;

$k_T=S_T/S_{Tn}$ – transformer load factor;

U_{Tn} – transformer line rated voltage, on the side where the voltage variations are determined, in V, which case the voltage losses on the transformer are also resulting in V.

Related to voltage jumps, determined with the expressions (6), (11) and (12), these are only slightly affected by voltage losses on load, considering the fact that the electrical loads in the two successively moments are the same or relative closely.

Finally, is required to emphasize that the voltage setting through the introduction of additional voltages is efficient only if at the end-users or in the network are available sufficient reserves of adjustable reactive power for its increasing compensation to the voltage increasing.

3.2. Network parameters changing

The parameters changing of an electrical network for voltage adjustment can be realized through modification the parallel function circuit number and also through the line inductive reactance compensation.

a. Modification the parallel circuit number

An electric line can have one or two circuit and in an electrical station a consumption point can be supplied from one or more lines. Coupling in parallel of some electrical line circuit and also coupling some electrical lines or supplying paths, in parallel working in terms of electrical, lead to decreasing network impedance, the voltage drop being reduced. In this way, the voltage in the considered consumption point returns to values from the admissible range.

In Figure 3 is represented the supplying scheme on an bars system WJ, through two circuit or parallel lines, LE1 and LE2 and also through two parallel power transformers T1 and T2; on the figure are indicated only the primary devices necessary strictly for the parallel coupling or uncoupling commutations, represented through the automatic circuit breakers Q1÷Q4.

Table 1

Characteristics of power transformers voltage setting, made by "Electroputere" Craiova

Transformer type		Rated power range, MVA	Setting type	Setting possibilities, ±*p*x*a*%
With two windings	For PS	0,04÷0,25 0,1÷2,5	No-load run, on HV	±1x5% ±1x5%; ±2x2,5%
	For STe	2,5÷10 12÷63	Normal run, on HV	±4x2,5%; ±9x1,78%; ±13x0,768% ±6x1,5%; ±8x1,25%; ±9x1,78%
With three windings		10÷400	Normal run, on HV	±6x1,5%; ±8x1,25%; ±9x1,78%
			No-load run, on MV	±2x2,5%

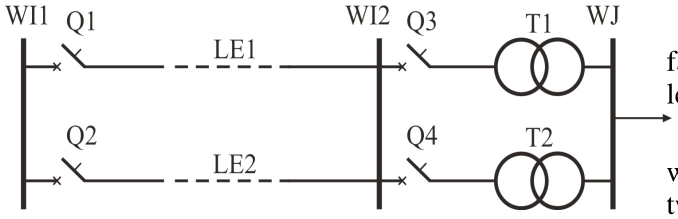

Fig. 1 Supplying network for an end-user with two parallel circuit

When the electrical load consumption connected to the bars WJ is increasing, parallel coupling the lines LE1 and LE2 and also the transformers T1 and T2 represents applicable alternatives for the territorial dispatcher. But if the load is decreasing and it returns to a functioning regime with lower load, the voltage on the WJ bars can increase above the admissible value. Through uncoupling a line circuit or a transformer from the power substation or station can be act to decrease the voltage on these bars.

If we consider only the parallel circuit section the voltage losses on this section can be determined with the general expression:

$$\Delta U_{Lk} = \frac{R_{Lk} P + X_{Lk} Q}{U_{av}}, \text{ V}, \tag{14}$$

where R_{Lk} and X_{Lk} represent the electrical parameters resistance, respectively reactance, corresponding to the line numbers and transformers coupled in parallel $k \in \{1, 2\}$;

P, Q – active and reactive power transmitted on the considered section;

U_{av} – line voltage at downstream end of the considered section;

If the electrical parameters of the parallel coupled circuit are relative closely then between the voltage losses on one of this section, corresponding to situations when the functionality is with one and two parallel coupled circuit ΔU_{L1} and ΔU_{L2} there is the relationship:

$$\Delta U_{L2} \cong \frac{\Delta U_{L1}}{2}, \text{ V}, \tag{15}$$

fact that is found in differences between consecutively levels voltage.

$$\Delta U_{pk} = U_{p(k+1)} - U_{pk}, V, \tag{16}$$

where U_{pk} şi $U_{p(k+1)}$ are the voltage corresponding of two consecutively levels (Figure 2)

b Line reactance compensation

If we talk about the inductive line reactance compensation, that is also named longitudinal or series compensation. The series capacitor banks installation on a line has the resultant, longitudinal reactance reduction, as an effect, and then the corresponding voltage drop decreasing.

Because the total compensation leads to short-circuit currents inadmissible increasing, providing a capacity that leads to a voltage drop ΔU_C on the capacitive reactance is recommended according to the expression:

$$\Delta U_C = X_C \cdot I \in [0{,}05 \div 0{,}2] \cdot U_n, \tag{17}$$

from which results the corresponding capacitance size for the longitudinal compensation:

$$C \in [5 \div 20] \cdot \frac{I}{\omega U_n}. \tag{18}$$

In defining the capacitor type, is going to take into account the working voltage and also the not exceeding its rated reactive power. Considering known the provided capacitor type for the line inductive reactance compensation results a voltage losses decrease, when we introduce this in series with the line impedance, with next value:

$$\Delta U_{CL} = \frac{(X_L - 1/\omega C) Q}{U_{\ln}}, V, \tag{19}$$

which also has to found in the voltage differences between levels (Figure 2).

A similar problem, but with reverse action, is represented by the reactance coils direct connected in derivation to the HV and very high voltage (VHV) lines or to the auto-transformers tertiary winding, and consume reactive power produced by line capacity, in low load or no load regimes, so reducing the possible over-voltages. Besides the fact that they contribute to the voltage maintaining, between admissible limits, have also the role to limit the short-circuit currents.

The reactance coils influence evaluation on the voltage values is made also with the relationship (19). Because the reactance coil characterization is made by relative reactance $x_{B\%}$, which is a dimensionless size, required firstly its reactance determination X_B with relationship:

$$X_B = \frac{U_{\ln}}{\sqrt{3}\,I_{Bn}} \cdot \frac{x_{B\%}}{100}, \Omega, \qquad (20)$$

where I_{Bn} is the coil rated current and U_n – (line) rated voltage.

3.3. Reactive power flow control

Except the reactive power control, realized to the power generation level there are intervention possibilities, in this sense, also at the STe, PS and end-users level. Between the reactive power compensation methods, is relevant for the studies relating to slow voltage variations, only the centralized compensation. The individual and group compensation, are switched together with receivers and equipments, that are connected to, so they are not distinctly highlighted in the voltage chart.

The centralized capacitors banks are made with one fixed step and (3÷5) adjustable steps, of equal or different values, automatic switched in relation with reactive power consumption. For highlight that the constructive fixed quantity for a capacitor is electrical capacity and the rated reactive power Q_{cn} is given at the rated voltage U_n; for each voltage U, different other than the rated one, the reactive power given by capacitor is:

$$Q_c = \left(\frac{U}{U_n}\right)^2 \cdot Q_{cn}\text{, var}. \qquad (21)$$

As we can see, the reactive power provided by capacitor bank is direct proportional with square of the network voltage, at the capacitor installation point, which is a disadvantage where there exists a reactive power deficit; because the lower voltage leads to increasing the reactive power deficit and to additional voltage decreasing. In case of the reactive power excess and working with higher voltage the power provided by capacitor is increasing leading to an additional voltage increasing.

Regarding to the voltage losses decreasing, on a section "*k*", having parameters R_{Lk} and X_{Lk}, when the consumed reactive power decreases from Q to (Q-Q_c) through connecting a capacitor step with power Q_c, this can be estimated with follow relationship:

$$\Delta U_{Lk} = \frac{X_{Lk}(Q - Q_C)}{U_l}, \text{V}, \qquad (22)$$

where all quantities have the meaning above defined. If the capacitor bank switched step has a significant power Q_c, is possible to determine, according with expression (22), a voltage resizable jump in the measuring point of interest.

Through associating the capacitors banks with the adjustable reactance coils, series or parallel connected, compensation static sources is accomplished, that can working in capacitive and inductive regime also, but because there is a continuously adjustment they don't lead to emphasize any jumps in the voltage graphic.

4. CONCLUSIONS

✓ The slow voltage variations analysis, with decomposition of the voltage time variation chart, as rms value, in actions and harmonics, permit the results interpretation only if the action type interventions are already evaluated and recorded into an dispatcher actions list, if is possible.

✓ Knowing the part of the electrical power system, from which the measuring point of interest belongs, represents a measurements previous condition. The paper emphasizes the aspects type which must be considered to reveal the distribution scheme to the measuring point of interest. The methods and relations which determine the step type variations from the real voltage chart are also indicated. Even in absence of a dispatcher actions list the highlighted level succession through moving average method can be interpreted, based on voltage jumps quantitative evaluation, in load presence or absence.

✓ The slow voltage variations can have three causes: the load variations, the step type actions, undertaken on distribution scheme and the variations from the EPS itself, from which the considered distribution scheme is being part. The recommendation to perform system measurements, into a point being upstream the measuring point of interest, is likely to allow emphasizing those voltage variations causes which are related to the system.

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