14^{th} International Research/Expert Conference
”Trends in the Development of Machinery and Associated Technology”
TMT 2010, Mediterranean Cruise, 11-18 September 2010

POWER QUALITY INDICES FOR UNBALANCE CHARACTERIZATION IN NON-SINUSOIDAL CONDITION

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ABSTRACT

The unbalanced non-sinusoidal operation represents a common steady state of the modern distribution power grids. The unbalance is produced by supplying of unbalanced loads or by different unbalanced faults. According to the existing norms, this operating state is evaluated using the well-known negative and zero unbalance factors that practically keep out the harmonic pollution that coexists with the unbalance. The paper proposes a new way of determining the negative and zero unbalance factors, which takes into consideration the non-sinusoidal operating state, too. At the end of the paper, some study cases are analyzed in order to underline the difference between the existing way to evaluate the unbalance in harmonic polluted systems and the proposed one.

Keywords: unbalance, harmonic distortion, symmetrical components, power quality, distribution grid

1. INTRODUCTION

An electric grid represents an assembly of circuit elements that are connected through electric relationships and whose electromagnetic behavior is completely determined by the currents intensities and voltages at the terminals.

Usually the power system works as a balanced 3-phase system. However, numerous LV or MV distribution grids supply many unbalanced 3-phase or single-phase loads, i.e. high power thermoelectric installations (induction ovens, welding transformers, etc.), ventilation and air conditioning installations, fluorescent lighting circuits with electronic or conventional ballasts, PC for data processing and paper consumable, etc. If the load is unbalanced, the currents system is also unbalanced and it causes different voltage drops on the supply grid electric lines. Consequently the voltage system at the load terminals is also unbalanced.

Taking into consideration the above mentioned aspects, it results that the normal operating state of the distribution grids is unbalanced and it depends on the grids structure and running operating states. Usually the balanced state is considered the real operating state of the power systems, thus there can be made many simplifications in the representation and study of the considered system.

The rapid development of the industrial and transport processes and their modernization based on the power electronics have encouraged the infiltration and extension of non-linear equipments, which are real sources of distortion for the currents and voltages waveforms. In the power systems this fact causes the proper functioning perturbation of the transport, distribution and consumption installations that were designed for working under sinusoidal conditions.

The power system elements were designed and developed to work considering a steady state that is sinusoidal (fundamental frequency established individually by each country) and balanced. The non-linear elements on whose terminals is applied a sinusoidal voltage distorts the current waveform that determines non-sinusoidal voltage drops in other nodes of the distribution grid and consequently non-sinusoidal voltage at the terminals of different linear and non-linear circuit elements.

The non-sinusoidal unbalanced operating state negatively influences all grids elements, leading to new unwanted phenomena or to the increase of others, already known: overheating of electrical machines, supplementary power losses in electric lines and transformers, diminution of bank capacitors efficiency, etc. As a result, in order to mitigate these negative effects, the level of this operating state must be known and evaluated as accurate as possible. In order to evaluate this state, the existing standards propose two indices: the negative and the zero unbalance factors. Unfortunately, these factors determine the severity of the unbalance by neglecting the existing non-sinusoidal state (the factors are calculated only for the fundamental). Therefore, at the moment, the quantification of the unbalanced non-sinusoidal operating state does not correspond to the reality.

In the paper there is presented the impact of the two operating states (non-sinusoidal and unbalanced) on the proper working of the distribution grids. In order to appreciate their influences, the authors propose new indices for the negative and zero unbalance factors that takes in consideration the steady harmonic polluted functioning state.

2. STEADY UNBALANCED OPERATING STATE

A 3-phase system of phasors is considered symmetric if its most representative phasors (current or voltage) are characterized by the following two properties: (i) equal modulus and (ii) phase difference between two consecutive phasors is 2π/3. A 3-phase power system is supposed to be symmetric and balanced when its phases are equal, balanced loaded and the system supply voltage is symmetric.

For the analysis of unbalanced operating states there is often used the symmetrical components theory (Stokvis-Fortescue theorem). In the case of systems that have unbalanced loads, its application allows the particular analysis of each phase. The symmetrical components method consists in dividing of a three quantity system in two symmetrical systems that are said to be of positive and negative sequence respectively, and a system which phasors are in phase that is said to be of zero sequence.

The unbalanced operating state effects the electric equipments (rotative electric machines, transformers, capacitors banks, and static power converters), transport and distribution grids consumers and NPS grids. The main effect that emerges in the transport and distribution power grids due to the currents unbalance is the appearance of supplementary power losses. On the other hand, in the industrial distribution grids the currents unbalance most significant negative influence appears on the energy transfer efficiency.

In most countries, the unbalance of a voltage 3-phase system is estimated using several coefficients, which values are expressed in percentages. These coefficients are determined as the ratio between the negative or the zero sequence voltage components and the rating voltage on one hand, or the positive sequence component on the other hand. The coefficient that is most used for the unbalance appreciation is the negative unbalance factor that can be calculated using the following mathematical relationship:

$$k_{nU}^{-} = \frac{U_2}{U_1} \cdot 100\,[\%], \tag{1}$$

where: U_2 represents the rms value of the negative sequence component;
U_1 – the rms value of the positive sequence component.

Similarly, the zero unbalance factor has the following mathematical relationship:

$$k_{nU}^{0} = \frac{U^{0}}{U^{+}} \cdot 100\ [\%]. \tag{2}$$

3. THE STEADY UNBALANCED AND NON-SINUSINUSOIDAL OPERATING STATE

An unbalanced non-sinusoidal operating state is characterized by 3-phase systems of phasors (voltages and currents) that are unbalanced to which it is added the fact that the voltages or currents waveforms are non-sinusoidal (they contain harmonic components).

This state is the steady operating state of the modern power grids. For the characterization of the unbalanced state of the distribution grids functioning under non-sinusoidal conditions the authors have developed several new indices that were named global unbalance factors. Considering the fact that the indices proposed in the previous authors' papers were applicable only for cases in which the system had in its structure a Steinmetz circuit, for the general case, the proposed negative global unbalance factor has the following definition:

$$k_{Ug}^{-} = \frac{U^{-}}{U^{+}} = \sqrt{\frac{U_C^{-2} + U_D^{-2}}{U_A^{+2} + U_B^{+2}}} \cdot 100\,[\%], \tag{3}$$

while the zero global unbalance factor definition is:

$$k_{Ug}^{0} = \frac{U^{0}}{U^{+}} = \sqrt{\frac{U_E^{0\,2} + U_F^{0\,2}}{U_A^{+2} + U_B^{+2}}} \cdot 100\ [\%]. \tag{4}$$

In the above equations that express the new unbalance indices, the used quantities have the following mathematical relationships:

$$U_A^{+} = \sum_{k=1}^{n}\left[U_{1_k}\cdot\cos\left(n_k\cdot\varphi_{1_k}\right) + U_{2_k}\cdot\cos\left(n_k\cdot\varphi_{2_k} + \frac{2\cdot\pi}{3}\right) + U_{3_k}\cdot\cos\left(n_k\cdot\varphi_{3_k} + \frac{4\cdot\pi}{3}\right)\right];$$

$$U_B^{+} = \sum_{k=1}^{n}\left[U_{1_k}\cdot\sin\left(n_k\cdot\varphi_{1_k}\right) + U_{2_k}\cdot\sin\left(n_k\cdot\varphi_{2_k} + \frac{2\cdot\pi}{3}\right) + U_{3_k}\cdot\sin\left(n_k\cdot\varphi_{3_k} + \frac{4\cdot\pi}{3}\right)\right];$$

$$U_C^{-} = \sum_{k=1}^{n}\left[U_{1_k}\cdot\cos\left(n_k\cdot\varphi_{1_k}\right) + U_{2_k}\cdot\cos\left(n_k\cdot\varphi_{2_k} + \frac{4\cdot\pi}{3}\right) + U_{3_k}\cdot\cos\left(n_k\cdot\varphi_{3_k} + \frac{2\cdot\pi}{3}\right)\right];$$

$$U_D^{-} = \sum_{k=1}^{n}\left[U_{1_k}\cdot\sin\left(n_k\cdot\varphi_{1_k}\right) + U_{2_k}\cdot\sin\left(n_k\cdot\varphi_{2_k} + \frac{4\cdot\pi}{3}\right) + U_{3_k}\cdot\sin\left(n_k\cdot\varphi_{3_k} + \frac{2\cdot\pi}{3}\right)\right];$$

$$U_E^{-} = \sum_{k=1}^{n}\left[U_{1_k}\cdot\cos\left(n_k\cdot\varphi_{1_k}\right) + U_{2_k}\cdot\cos\left(n_k\cdot\varphi_{2_k}\right) + U_{3_k}\cdot\cos\left(n_k\cdot\varphi_{3_k}\right)\right];$$

$$U_F^{-} = \sum_{k=1}^{n}\left[U_{1_k}\cdot\sin\left(n_k\cdot\varphi_{1_k}\right) + U_{2_k}\cdot\sin\left(n_k\cdot\varphi_{2_k}\right) + U_{3_k}\cdot\sin\left(n_k\cdot\varphi_{3_k}\right)\right];$$

and n represents the number of considered harmonics;
n_k – k harmonic order;
$U_{1_k}, U_{2_k}, U_{3_k}$ – rms values of the phase-to-phase voltages that correspond to the k harmonic;
$\varphi_{1_k}, \varphi_{2_k}, \varphi_{3_k}$ – the phase-to-phase voltage phase angles.

Relationships (3) and (4) are available also for the currents system.

4. STUDY CASES

In order to analyze from an energetic point of view the proposed global factors, the following cases are well thought-out:

Case A. It is considered a balanced system of non-sinusoidal currents that is defined according to the data from table 1 and presented in figure 1.

Case B. An unbalanced system of non-sinusoidal currents is considered; the system is defined according to the data from table 1 and it is presented in figure 2.

In all these cases, the unbalance level was evaluated according to the existing norms (which take into consideration only the fundamental), and to the methodology proposed in the paper. The obtained results are comparatively presented in table 2.

By analyzing the obtained data, the following conclusions can be formulated:

- in the case of a balanced system of non-sinusoidal currents (case A), according to the existing standards, both the negative and zero unbalance factors are equal with zero. Unfortunately, even if the system of currents is balanced from an electric point of view, negative and zero sequence current components will flow in the power system, producing the corresponding well-known effects. The presence of these components (important from energetic point of view) is underlined by using the factors proposed in the paper;
- in the B case, the proposed unbalance factors provide bigger values then the standard ones, due to the fact that the new relationships take into consideration the non-sinusoidal operation of the distribution power grids, too (new negative and zero sequence current components due to the presence of harmonics);
- taking into consideration that the zero sequence components reflect the loading of neutral conductor, one can observe that in LV modern systems this loading is heavier in reality than it was supposed.

Table 1. The rms values and phase angles of harmonics for study cases A and B

Case		Harmonics			
		1	3	5	7
C	I^a	1	0,3	0,2	0,1
	φ^a	0	0	0	0
	I^b	1	0,3	0,2	0,1
	φ^b	0	0	0	0
	I^c	1	0,3	0,2	0,1
	φ^c	0	0	0	0
D	I^a	1	0,3	0,2	0,1
	φ^a	0	0	0	0
	I^b	1,1	0,35	0,22	0,09
	φ^b	$\pi/6$	$\pi/3$	$\pi/5$	$\pi/7$
	I^c	0,99	0,32	0,15	0,12
	φ^c	$\pi/8$	$\pi/4$	$\pi/6$	$\pi/9$

Table 2. The current sequence components and unbalance factors for the four study cases

Case	Sequence components					
	I^+	I^-	I^0	I_g^+	I_g^-	I_g^0
C	1	0	0	1.005	0.2	0.3
D	1.005	0.146	0.18	1.029	0.252	0.345
	Unbalance factors					
	k^-	k^0	k_g^-	k_g^0		
C	0	0	19.9	29.85		
D	14.57	17.97	24.528	33.50		

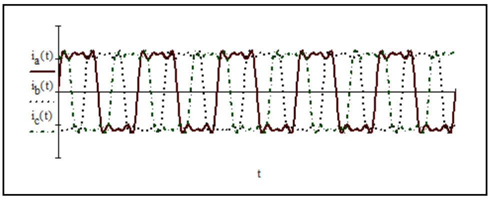

Figure 1. Balanced system of non-sinusoidal currents Characteristics of voltage dip

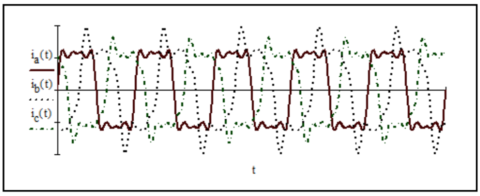

Figure 2. Unbalanced system of non-sinusoidal currents

5. CONCLUSIONS

The main conclusions of this paper relate to the existing power quality approach for the evaluation of unbalanced and non-sinusoidal operating state in power systems and the differences between the classic unbalance factors and the global unbalance factors (proposed in the paper).

Nowadays, the real operating state of the distribution power grids is unbalanced and harmonic distorted. In the existing power quality standards, these two aspects are described separately, by corresponding indicators. The unbalance is quantified using the negative and zero sequence factors that take into consideration only the fundamental waves. This kind of approach eliminates the existence of harmonics, so that the reality is not accurately evaluated. The authors propose two new unbalance factors that consider the influence of existing harmonics.

The numerical results obtained by analyzing four study cases underline the differences between the two approaches: the new factors provide the same values as the standard factors in the case of pure unbalance sinusoidal state; in the case of unbalance under non-sinusoidal conditions, the new numerical values are higher if compared to the classic factors. This is due to the fact that apart the fundamental component, the influence of the existing other harmonic components is also considered.

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