Voltage Unbalance Emission Assessment

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ABSTRACT: Aim of this paper is to draw the attention on the principle origin for unbalance, taking into account the part caused by negative sequence currents as well as the part arising from non ideal grid impedance with non negligible coupling impedance between the positive and negative sequence system. This system inherent part originates from non transposed lines or parallel three phase lines operating over long distances. In 61000-3-13 this is taken into account by a factor k_{uE}, which is explained in this paper.

1. Introduction

IEC technical report 61000-3-13 „Assessment of emission limits for the connection of unbalanced installations to MV, HV and EHV power systems" [1] from the IEC 61000-3 series provides guidance on principles which can be used as the basis for determining the requirements for the connection of unbalanced installations (i.e. three-phase installations causing voltage unbalance) to MV, HV and EHV public power systems. The scope is on the coordination of the negative-sequence type of voltage unbalance between different voltage levels in order to meet the compatibility levels at the point of evaluation.

While there exists a lot of literature for harmonics and flicker, unbalance plays only a marginal role in the area of power quality.

Assessment of emission level might be necessary for pre connection study (planning stage) and post connection study (proof of guaranteed/contractual values). Closely related to the assessment of disturbance emission of an installation are

- the pre-existing disturbance level, caused by the other installations but the considered ("background level")
- the total disturbance level after connection of the considered installation
- the individual emission level of the considered installation

2. General Comments on Emission

The emission level is defined as the disturbance the considered installation gives rise to at the point of evaluation after connection. Primarily it is expressed as index related to the **voltage** at the point of evaluation (POE). Those voltage indices usually result from disturbing (i.e. harmonic, fluctuating or unbalanced) currents of the installation multiplied with the corresponding impedance of the grid at the POE. The impedance can be the actual impedance or (contractual) reference impedance. The actual impedance – especially the harmonic impedance – is often not known.

Harmonic and unbalance are represented by (complex) phasors with magnitude and phase angle. Summation of single contributions is done vectorial, so the sum might be **larger** or **smaller** than the single contributions, depending on the individual phase angles. Unfortunately most of commercial available measurement instruments do not provide phase angle information for harmonics and unbalance.

On the contrary in the case of flicker, the quantities P_{st} and P_{lt} represent not phasors. Summation is done by using an empiric nonlinear summation law. The summation of the emission of different flicker sources usually results in an increased total disturbance level[1].

General information about emission assessment can be found in [2].

3. Unbalance

The impedance characteristics of a network at the POE can be characterized by the impedance matrix. Diagonal elements of the complex[2] impedance matrix $\underline{\mathbf{Z}}_{\mathbf{abc}}$ represent self-impedances while the off-diagonal elements represent mutual impedances. As well known, this impedance matrix can be transformed to symmetrical impedances $\underline{\mathbf{Z}}_{\mathbf{012}}$ with $\underline{\mathbf{S}}$ being the transformation matrix for symmetrical components and $\underline{\mathbf{T}}$ being its inverse.

$$\underline{Z}_{012} = \begin{pmatrix} \underline{Z}_{00} & \underline{Z}_{01} & \underline{Z}_{02} \\ \underline{Z}_{10} & \underline{Z}_{11} & \underline{Z}_{12} \\ \underline{Z}_{20} & \underline{Z}_{21} & \underline{Z}_{22} \end{pmatrix} = \underline{S} \cdot \begin{pmatrix} \underline{Z}_{aa} & \underline{Z}_{ab} & \underline{Z}_{ac} \\ \underline{Z}_{ba} & \underline{Z}_{bb} & \underline{Z}_{bc} \\ \underline{Z}_{ca} & \underline{Z}_{cb} & \underline{Z}_{cc} \end{pmatrix} \cdot \underline{T} \qquad (1)$$

Assuming ideal symmetric network impedance, the following applies:

[1] Connection of a dynamic compensator, induction motor or synchronous machine will reduce the total flicker level.

[2] Complex quantities are identified by underline in this text.

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$$\underline{Z}_{aa} = \underline{Z}_{bb} = \underline{Z}_{cc} \text{ and } \underline{Z}_{ab} = \underline{Z}_{bc} = \underline{Z}_{ca} . \tag{2}$$

In this case $\underline{\mathbf{Z}}_{012}$ becomes a diagonal matrix with all off diagonal elements being zero and therefore showing no coupling between the symmetrical components.

Taking into account asymmetric network impedances, e.g. due to untransposed lines, the above mentioned simplifications are no longer valid. Instead of the diagonal matrix one has to use the generic full matrix $\underline{\mathbf{Z}}_{012}$ according to (1). Nevertheless, the off diagonal elements are still small compared to the diagonal elements.

Generally, the voltage at the POE can be described as a function of the connected installation i with the help of the impedance matrix using symmetrical components as:

$$\begin{vmatrix} \underline{U}_0 \\ \underline{U}_1 \\ \underline{U}_2 \end{vmatrix} = \begin{vmatrix} \underline{U}_{0,oc} \\ \underline{U}_{1,oc} \\ \underline{U}_{2,oc} \end{vmatrix} - \begin{vmatrix} \underline{Z}_{00} & \underline{Z}_{01} & \underline{Z}_{02} \\ \underline{Z}_{10} & \underline{Z}_{11} & \underline{Z}_{12} \\ \underline{Z}_{20} & \underline{Z}_{21} & \underline{Z}_{22} \end{vmatrix} \cdot \begin{vmatrix} \underline{I}_{0,i} \\ \underline{I}_{1,i} \\ \underline{I}_{2,i} \end{vmatrix} \tag{3}$$

The vector $\underline{U}_{012,oc}$ stands for the open-circuit voltage, representing unbalance from already connected loads ("background unbalance"). In EHV and HV systems, the background unbalance is mostly almost zero. All quantities ($\underline{U}$, $\underline{I}$, $\underline{Z}$) are complex values with amplitude and phase angle. It is assumed, that the currents drawn by the installation are independent of the bus voltage, which is usually true in practice. The impedance matrix $\underline{\mathbf{Z}}_{012}$ represents the network impedance as seen from the point of evaluation.

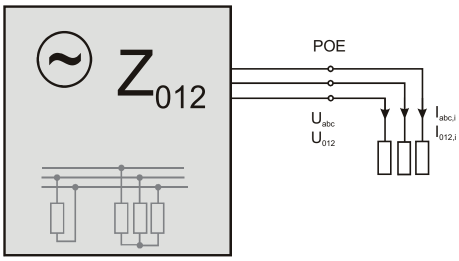


Fig. 1. Network with pre-existing unbalance (existing unbalanced loads) and unbalance level at the point of evaluation

According to standards, unbalance is expressed by the negative sequence voltage $\underline{U}_2$ respectively by the ratio of $\underline{U}_2$ and $\underline{U}_1$. Hence, the negative sequence voltage $\underline{U}_2$ at POE can be written as shown in (4), consisting – besides the pre-existing unbalance – of three parts:

$$\underline{U}_2 = \underline{U}_{2,oc} - (\underline{Z}_{21} \cdot \underline{I}_{1,i} + \underline{Z}_{22} \cdot \underline{I}_{2,i} + \underline{Z}_{20} \cdot \underline{I}_{0,i}) \tag{4}$$

1. The product of the coupling impedance $\underline{Z}_{21}$ respectively $\underline{Z}_{12}$ (between positive and negative sequence system) and the currents of the positive sequence system $\underline{I}_{1,i}$ can be of significance as the positive sequence current is usually large although the coupling impedance $\underline{Z}_{21}$ is relatively small.
2. The product of the negative impedance $\underline{Z}_{22}$ (often denoted simply as $\underline{Z}_2$) and the current $\underline{I}_{2,i}$ of the installation can be of significance.
3. The product of the coupling impedance $\underline{Z}_{20}$ (between zero sequence system and negative sequence system) and the zero-currents $\underline{I}_{0,i}$ can be neglected due to the fact that the coupling impedance $\underline{Z}_{20}$ and the zero sequence current $\underline{I}_{0,i}$ are usually very small.

Since the unbalance emission $\underline{U}_{2,i}$ of an installation i is defined as the part of $\underline{U}_2$ which is caused by this installation, it can be expressed as shown in (5).

$$\underline{U}_{2,i} = (\underline{Z}_{21} \cdot \underline{I}_{1,i} + \underline{Z}_{22} \cdot \underline{I}_{2,i}) = \underline{U}_{2,i-line} + \underline{U}_{2,i-load} \tag{5}$$

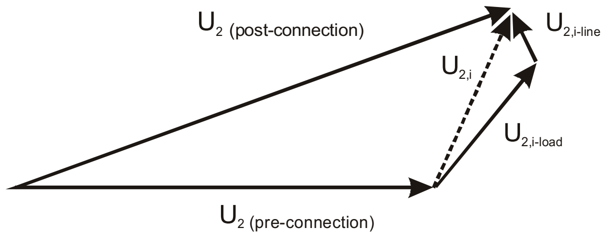


Fig. 2. Unbalance level and unbalance emission at the POE

It can be clearly seen that the first term ($U_{2,i\text{-line}}$) is related to **unbalanced impedance of lines**. The coupling impedance between positive and negative sequence systems $\underline{Z}_{21}$ can be of significance in the case of long untransposed lines. References [4] and [5] report cases where system inherent asymmetries have been seen to play a vital role in relation to unbalance. In special cases, line asymmetries were seen to be responsible for 65%–70% of total unbalance levels arising at bus bars [5]. The angle of the part of the voltage emission given by $\underline{Z}_{21}\underline{I}_{1,i}$ can be considered to be almost constant assuming that the angle of the positive sequence load current will vary only in a limited range (which is usually the case) and the coupling impedance is time invariant. Indicative values for Z_{21} are given in Fig. 3.

The second term of (4) is related to the **unbalanced current** of the installation ($U_{2,i\text{-load}}$). This may originate from unbalanced connection of the load or from unbalanced operation (e.g. electric arc furnace). In the case of an unbalanced load connection, the angle of the emission can be also considered to be nearly constant and depends on the mode of connection. Otherwise it will vary (stochastically) according to the variation of the angle of $\underline{I}_{2,i}$. The impedance $\underline{Z}_{22}$ (often simply denoted $\underline{Z}_2$) can be expressed by the conventional subtransient short circuit impedance with sufficient accuracy. Hence in the case of rotating machines, $\underline{Z}_2$ corresponds to the subtransient impedance (synchronous machine) respectively the starting impedance (induction machine).

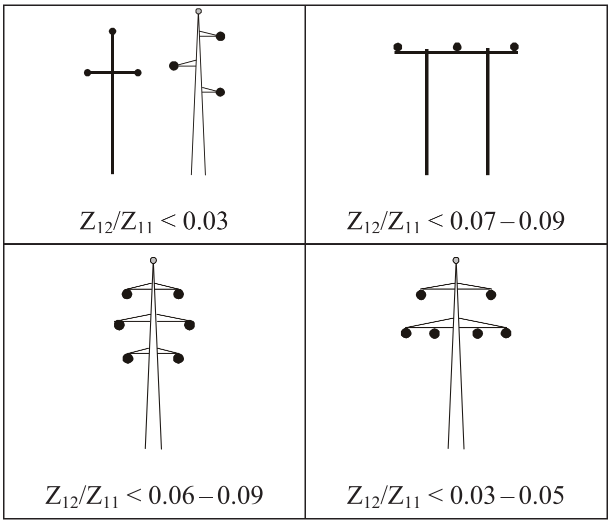


Fig. 3. Indicative values for the coupling impedance Z_{12} between negative sequence system and positive sequence system in the case of untransposed lines

Regarding the definition of unbalance emission, IEC TR 61000-3-13 [1] is not fully consistent. While the definition in chapter 6.2 addresses the difference between $\underline{U}_{2,\text{post-conn.}}$ and $\underline{U}_{2,\text{pre-conn.}}$ as emission of the installation, in Note 3 of the same chapter the system inherent part ($U_{2,\text{i-line}}$) is explicit declared as being not an emission of the installation.

For superposition of individual unbalance emission, a general summation law for the resulting voltage unbalance is given in [1]. A value of 1.4 is proposed for the coefficient α.

$$U_2 = \sqrt[\alpha]{\sum_i U_{2,i}^{\alpha}} \tag{6}$$

3. Emission Assessment

The following methods regarding the unbalance emission assessment are based on following assumptions:

- The connection of the installation does not influence the pre-existing background unbalance.
- The voltage unbalance in the POE will not influence the unbalanced current of the installation. This is actually not true in the case of presence of induction motors or synchronous machines.

The emission assessment consists of two principal stages:

In a **first step** one has to determine, whether the total voltage disturbance level U_2 in post-connection state is equal respectively decreased (a) or increased (b) compared to the pre-connection state (background disturbance). In the case of (a), the installation is not assigned an emission and no further investigations are necessary, although measured current might be unbalanced.

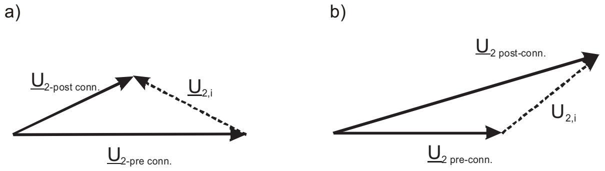


Fig. 4. Voltage unbalance level at the POE after connection of the load increased (a) or decreased (b)

In the case of (b), in a **second step** the emission of the considered installation must be determined and compared to the individual emission limit. As the vector $U_{2,i}$ includes the part $U_{2,\text{i-line}}$ which the system is responsible for, this vector not suitable but $U_{2,\text{i-load}}$ must be used. Determination of the emission is usually based on one or more of the following basic methods:

a. Single voltage measurement at POE with load connected

It is assumed, that the installation is the only or at least a dominant disturber and that the network is symmetrically so that $U_{2,\text{pre-conn.}}$ and $U_{2,\text{i-line}}$ can be neglected. The measured unbalance level $U_{2,\text{post-conn.}}$ at the POE is assumed to be approximately equal to the installation's emission $U_{2,\text{i-load}}$.

b. Voltage measurement at POE with and without connected installation

It is assumed, that the network is symmetrically so that $U_{2,\text{i-line}}$ can be neglected and that the background disturbance is does not change significantly with time. Measurement is done without and with connection of the investigated installation. If the phase angle is provided by the measurement instrument, the emission is calculated by vectorial difference of the unbalance level before and after connection.

$$\underline{U}_{2,\text{i-load}} \approx \underline{U}_{2,\text{post-conn.}} - \underline{U}_{2,\text{pre-conn.}} \tag{7}$$

Otherwise the emission can be calculated using the empirical summation law (6) with α being 1.4.

$$\left|\underline{U}_{2,\text{i-load}}\right| \approx \sqrt[\alpha]{\left|\underline{U}_{2,\text{post-conn.}}\right|^{\alpha} - \left|\underline{U}_{2,\text{pre-conn.}}\right|^{\alpha}} \tag{8}$$

c. Measurement of current

The voltage unbalance $U_{2,\text{i-load}}$ arising at the POE, which the installation i is responsible for, can be derived from current unbalance measurement with (9) based on (5).

$$\underline{U}_{2,\text{i-load}} = \underline{Z}_{22} \cdot \underline{I}_{2,i} \tag{9}$$

Keeping in mind, that the network's impedance for the positive sequence system equals approximately the impedance for the negative sequence system, can be rearranged as:

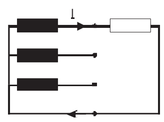
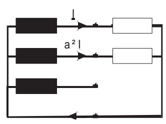
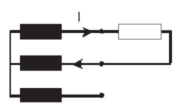
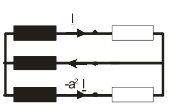
$$\frac{\underline{U}_{2,i-load}}{\underline{U}_1} = \underline{c}_{u,i-load} = \frac{S_i}{S_{scc}} \underline{c}_i \qquad (10)$$

with

- S_i agreed MVA of the installation
- S_{scc} short-circuit capacity (in MVA) at POE
- c_i negative sequence current emission (in terms of the current unbalance factor) of the installation

In Table 1 typical connections of unbalanced loads with their corresponding current unbalance factors are listed. Thus, if the connection of the installation results in an increase of the resultant unbalance level, the emission level calculated as per (10) can be used to compare against the emission limit. Under the assumption that the voltage unbalance at the POE will not influence the current unbalance, this method will give correct emission results even in the case of background unbalance and system inherent asymmetry due to untransposed lines. In principal the result can be evaluated using an arbitrary value for short circuit capacity, usually the contractual value shall be utilized.

Table 1. Current unbalance factor for different connections

connection		current	c_i
1-phase conection with neutral		$\underline{I}_{012} = \frac{I}{3}\begin{pmatrix}1\\1\\1\end{pmatrix}$	$c_i = 1$
2-phase connection with neutral		$\underline{I}_{012} = \frac{I}{3}\begin{pmatrix}a\\2\\-a^2\end{pmatrix}$	$c_i = 0.5$
1-phase conection without neutral		$\underline{I}_{012} = \frac{I}{3}\begin{pmatrix}0\\1-a\\1-a^2\end{pmatrix}$	$c_i = 1$
2-phase connection without neutral (V-circuit)		$\underline{I}_{012} = \frac{I}{3}\begin{pmatrix}0\\3-j\sqrt{3}\\j\sqrt{3}\end{pmatrix}$	$c_i = 0.5$

Nevertheless it must be stated that this assumption is not valid if the investigated installation includes a significant amount of induction motors or synchronous machines. Due to the small negative sequence impedance of these devices even small voltage unbalance might introduce considerable negative sequence currents. Assuming a synchronous machine with a subtransient impedance of 0.2 pu, a voltage unbalance of 1% would lead to an negative sequence current of 5% of the machine's rated current.

4. Meaning of k_{uE}

Technical report IEC/TR 61000-3-13 [1] addresses the issue of system inherent asymmetries by introducing a factor k_{uE} in the process of allocating the emission limits. The maximum allowable global contribution is derived from the unbalance planning level and includes system inherent asymmetries as well as contributions from unbalanced loads.

The emission limit for individual installations $E_{u,i}$ (respectively the maximum allowable unbalance emission $U_{2,i\text{-}load}$) is allocated according to the individual agreed power of the installation i. The factor k_{uE} represents the fraction of the global emission allowance that can be allocated to installations.

$$E_{u,i} = \left(\sqrt[\alpha]{k_{uE}} \cdot G\right) \cdot \sqrt[\alpha]{\frac{S_i}{S_t}} = U_{2,i-load} \qquad (11)$$

S_i corresponds to installation's agreed power and S_t represents the total supply capacity of the considered system. ($1–k_{ue}$) represents the fraction that accounts for system inherent voltage unbalance. Based on (11) and the summation formula (6), the allowable individual system inherent part of the unbalance emission can be expressed as follows.

$$U_{2,i-line} = \sqrt[\alpha]{1-k_{uE}} \cdot G \cdot \sqrt[\alpha]{\frac{S_i}{S_t}} \qquad (12)$$

Hence the ratio between $U_{2,i\text{-}line}$ and $U_{2,i\text{-}load}$ can be expressed using (5) on the one hand and (11) and (12) on the other hand. Having in mind that Z_{22} equals Z_{11}, k_{uE} can be expressed as a function of the ratio Z_{12}/Z_{11} and the current unbalance factor $c_i=I_{2,i}/I_{1,i}$.

$$\frac{U_{2,i-line}}{U_{2,i-load}} = \frac{Z_{12} \cdot I_{1,i}}{Z_{22} \cdot I_{2,i}} = \frac{\sqrt[\alpha]{k_{uE} \cdot \frac{S_i}{S_t}}}{\sqrt[\alpha]{(1-k_{uE}) \cdot \left(\frac{S_i}{S_t}\right)}} \qquad (13)$$

$$k_{uE} = \frac{c_i^\alpha}{c_i^\alpha + \left(\frac{Z_{12}}{Z_{11}}\right)^\alpha} \qquad (14)$$

Thus (14) can support grid operators to determine an appropriate value for k_{uE}, taking into account the typical current unbalance factor of connected and expected loads as well as the asymmetry of the grid, expressed as ratio Z_{12}/Z_{11}.

In the Table 2, k_{uE} for different grid conditions and a tolerable mean current unbalance factor for the total load of 10% is calculated and compared to the values given in the annex of 61000-3-13.

Table 2. Typical values for k_{uE}

Classification in 61000-3-13	Highly meshed system, generation near load centres, transmission lines fully transposed, otherwise very short (few km), distribution systems supplying high density load area with short lines or cables and meshed systems.	Mix of meshed system with some radial lines, local and remote generation, fully or partly transposed, distribution systems supplying a mix of high density and suburban area with relatively short lines	Long transmission lines generally transposed, generation mostly remote, generally radial subtransmission lines partly transposed or untransposed, distribution systems supplying a mix of medium and low density load area with relatively long lines
c_i	0.1	0.1	0.1
Z_{12}/Z_{11}	0.02	0,05	0.08
α	1.4	1.4	1.4
k_{uE} from (14)	0.90	0.73	0.58
$(1–k_{uE})$ from (14)	**0.10**	**0.27**	**0.42**
$(1–k_{uE})$ from 61000-3-13	**0.1-0.2**	**0.2-0.4**	**0.4-0.5**

5. Conclusion

Unbalance is a complex matter, especially due to the system inherent asymmetry. Even though the system inherent part arises because of connection of a (balanced) load, it should not be assigned as emission to this installation.

Several methods for the assessment of voltage unbalance emission of individual installations are presented in this paper whereas the method using measurement of current unbalance turns out to be the best one.

IEC TR 61000-3-13 proposes the use of a factor k_{uE} for allocation of an individual emission limit and taking into account the system's inherent asymmetry. In this paper a formula for estimation of a reasonable value for this factor is presented.

References

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