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:

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[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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$$\underline{Z}_{aa} = \underline{Z}_{bb} = \underline{Z}_{cc} \text{ and } \underline{Z}_{ab} = \underline{Z}_{bc} = \underline{Z}_{ca} . \qquad (2)$$

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:

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

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.

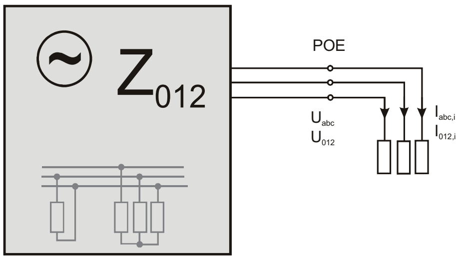

Fig. 1. Network with pre-existing unbalance (existing unbalanced loads) and unbalance level at the point of evaluation

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:

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

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).

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

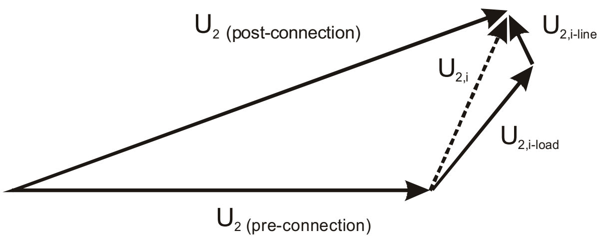

Fig. 2. Unbalance level and unbalance emission at the POE

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).