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Voltage unbalance management in power systems based on IEC 61000-3-13:2008: Implications on the use of 'kuE factor'

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Abstract

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Keywords

factor, management, unbalance, power, voltage, systems, iec, 61000, 3, 13, 2008, implications, kue

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Voltage unbalance management in power systems based on IEC 61000-3-13:2008: implications on the use of 'k_{uE} factor'

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***Abstract*—Voltage unbalance emission allocation principles prescribed in IEC61000-3-13:2008 Technical Report utilise a factor, k_{uE}, which allows separation of the total voltage unbalance that arises at a point of evaluation due to both the load under consideration and the supply network. As per the definition given, this factor (k_{uE}) accounts for the unbalance emission that arises due to the load whereas (1-k_{uE}) accounts for unbalance that arises due to the network. The technical report prescribes a range of values from which a suitable value can be chosen based on the system characteristics, however, no systematic methodologies exist to-date to determine the k_{uE} factor. Hence, the sensitivity of the k_{uE} factor to various system parameters cannot be examined. The work presented in this paper examines the sensitivity of this factor to system characteristics covering line asymmetry, load type and the level of load unbalance. While giving a systematic methodology for the evaluation of k_{uE} it is demonstrated that the use of a constant k_{uE} factor as given in IEC61000-3-13:2008 can lead to erroneous outcomes under certain conditions.**

***Index Terms*—power quality, voltage unbalance, current unbalance, voltage unbalance emission allocation, voltage unbalance emission assessment, system inherent asymmetry, load asymmetry, 'k_{uE} factor'**

I. Introduction

THE IEC technical report IEC/TR 61000-3-13:2008 [1] is the most comprehensive technical document available for managing negative sequence voltage unbalance (VU) in power systems. The main objective of this technical report is to provide guiding principles to system operators and owners to determine the connection requirements of three-phase unbalanced installations connected to public power systems such that adequate service quality is ensured to all customers. The philosophy of this report is similar to those of the counterpart IEC recommendations for harmonics (IEC/TR 61000-3-6) [2] and flicker (IEC/TR 61000-3-7) [3] allocation.

VU emission allocation methodology considering the fact that an unbalanced load and an upstream network can contribute to the total VU emission at the point of common coupling (PCC) is prescribed in [1]. But, the detailed work on compliance assessment of unbalanced installations at the post-connection stage is not yet developed other than the preliminary work covered in the CIGRE/CIRED C4.109 working group report on VU emission assessment techniques [4]. In this regard, [5] presents a new, deterministic approach to assess the individual VU emission contributions made by different sources of unbalance (i.e. load asymmetry, network asymmetry and upstream source unbalance) at the point of evaluation (POE) using pre-connection and post-connection voltage/current measurements at the POE together with known system characteristics for a radial power system. The proposed methodology is driven by the complex unbalance factors or unbalance emission vectors and it is generalised sufficiently to separate total VU emission at the POE into its constituent parts, irrespective of the balanced or unbalanced nature of the power system components.

Both the IEC VU emission allocation process and CIGRE/CIRED report [4] have relied on the 'k_{uE} factor' which makes a provision to account for the inherent system asymmetries of the power system to apportion the total VU emission level at the POE. However, there is no systematic approach to evaluate this 'k_{uE} factor' as defined in [1] other than a set of indicative values assigned to it depending on the network and load characteristics as described in Section II. The work presented in [4] (also in [6]) derives 'k_{uE} factor' as a function of current unbalance factor and the system impedances, but that approach does not reflect its dependency on the load type. Further, [7] provides some extended approaches to the concepts given in the IEC VU emission allocation procedure presented in [1], including new methodologies to evaluate global VU emission due to load and line asymmetries. Specifically, the line emission dependency on different load types and their evaluation methodologies related to VU allocation are discussed in [8] and [9].

The new, deterministic approach of VU emission assessment in radial power systems described in [5] can be utilised to further analyse the 'k_{uE} factor' approach used in emission allocation procedures as it decomposes individual emission levels given by the load asymmetry and line asymmetry independently. Therefore, the main objective of this paper is to investigate the validity of the present 'k_{uE} factor' approach, including implications on the emission allocation methodology based on the rigorous outcomes of [5].

The paper is organised as follows; a review of the 'k_{uE} factor' approach based on the IEC emission allocation method-

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ology is given in Section II. Key findings of the new deterministic approach on VU emission assessment are described in Section III. Section IV discusses the outcomes of new investigations on the '$\mathrm{k_{uE}}$ factor' including the implications on sharing unbalance between load and line contributions. Conclusions drawn by the study are presented in Section V.

II. Review of the '$\mathrm{k_{uE}}$ factor' approach based on the IEC VU emission allocation methodology

The IEC guidelines [1] for co-ordination of VU emission among different voltage levels of the power system prescribe allocation of individual emission limits to unbalanced installations through apportioning the global emission allowance (U_{global}). U_{global} can be derived using a general summation law, considering the total VU absorption capacity of the system and the upstream unbalance propagation incorporating transfer coefficients as shown in (1).

$$U_{\mathrm{global}} = \sqrt[\alpha]{(L)^{\alpha} - (TL^{\mathrm{us}})^{\alpha}} \tag{1}$$

where L and L^{us} are the planning levels (in terms of the VUF) of the system under assessment and the upstream (us) system respectively, α is the summation law exponent and T is the transfer factor from the upstream system to the downstream system under assessment.

The VU emission allowance, U_{global}, is then apportioned to various loads of the system in proportion to the ratio of apparent power to be supplied by a particular load to the total power to be supplied by the entire system. Further, unbalance emission is identified to be mainly due to the load asymmetry and line asymmetry, so that, for the x^{th} bus in the system, the VU emission ($U_{\mathrm{global}:x}$) can be calculated as follows:

$$(U_{\mathrm{global}:x})^{\alpha} = (U_{\mathrm{loads}:x})^{\alpha} + (U_{\mathrm{lines}:x})^{\alpha} \tag{2}$$

where, $U_{\mathrm{loads}:x}$, $U_{\mathrm{lines}:x}$ are the global emissions (in terms of the VUF) caused by unbalanced installations and asymmetrical lines respectively at busbar x.

According to the IEC emission allocation methodology, '$\mathrm{k_{uE}}$' is defined as the fraction of global emission allowance which accounts for load asymmetries. The emission allocation for the unbalanced installation can then be evaluated using the '$\mathrm{k_{uE}}$ factor' as described in the IEC/TR 61000-3-13:2008 [1], which is the fraction of global emission allowance that can be given to unbalanced installations. Conversely '$\mathrm{k'_{uE}}$'('1-$\mathrm{k_{uE}}$') represents the emission allocation corresponding to network asymmetries. Then the busbar allowance $U_{\mathrm{global}:x}$ is allocated to a customer installation i to be connected at busbar x as:

$$E_{i:x} = \sqrt[\alpha]{\mathrm{k}_{\mathrm{uE}:x}}\, U_{\mathrm{global}:x} \sqrt[\alpha]{\frac{S_{i:x}}{S_{\mathrm{total}:x}}} \tag{3}$$

where, $E_{i:x}$ is the emission limit of customer installation i to be connected at busbar x, $S_{i:x}$ is the agreed apparent power of customer installation i, $S_{\mathrm{total}:x}$ is the total power to be supplied by busbar x and $\mathrm{k}_{\mathrm{uE}:x}$ is the fraction of global emission allowance allocated to busbar x.

The Technical Report IEC/TR 61000-3-13:2008 recommends system operators to determine the $\mathrm{k_{uE}}$ factor for their specific networks considering the prevailing line construction practices and system characteristics and does not provide any systematic methodology to evaluate it other than the set of indicative values as in Table I.

TABLE I
INDICATIVE VALUES FOR $\mathrm{K_{uE}}$ (ADAPTED FROM [1])

System characteristics	**$\mathrm{k_{uE}}$ factor**
Highly meshed system with generation locally connected near load centres. Transmission lines fully transposed, otherwise lines are very short (few km). Distribution systems supplying high density load area with short lines or cables and meshed systems.	0.8-0.9
Mix of meshed system with some radial lines either fully or partly transposed. Mix of local and remote generation with some long lines. Distribution systems supplying a mix of high density and suburban area with relatively short lines (<10 km).	0.6-0.8
Long transmission lines generally transposed, generation mostly remote. Generally radial sub-transmission lines partly transposed or untransposed. Distribution systems supplying a mix of medium and low density load area with relatively long lines (>20 km). 3-phase motors account for only a small part of the peak load (e.g. 10%).	0.5-0.6

The work presented in [7] provides an extended definition to the '$\mathrm{k_{uE}}$ factor' based on the IEC explanation as shown in (4) and (5).

$$\mathrm{k}_{\mathrm{uE}:x} = \left(\left| \frac{U_{\mathrm{loads}:x}}{U_{\mathrm{global}:x}} \right| \right)^{\alpha} \tag{4}$$

$$\mathrm{k}'_{\mathrm{uE}:x} = \left(\left| \frac{U_{\mathrm{lines}:x}}{U_{\mathrm{global}:x}} \right| \right)^{\alpha} \tag{5}$$

In the general IEC methodologies, the absence of phasor information and the nature of random variations of all emission vectors are accompanied in the derivations by introducing the general summation law. Accordingly, the extended work in [7] defines $\mathrm{k_{uE}}$ and $\mathrm{k'_{uE}}$ in terms of magnitudes of emission vectors and the summation law exponent (α) to account for the aggregation of various unbalance emission levels which vary in magnitude and phase over time. A similar approach is used in [4] and [6] to derive $\mathrm{k_{uE}}$ using the well known IEC outcomes of VU emission due to load asymmetries and line asymmetries as given by (6) and (7) respectively. VU emission due to load asymmetries;

$$\left| \frac{U_{2,i(\mathrm{load})}}{U_1} \right| = \frac{S_i}{S_{sc}} \left| C_i \right| \tag{6}$$

where S_i is the VA loading level of the installation, S_{sc} is the short circuit capacity at the POE, and C_i is the negative sequence current unbalance factor (i.e., the ratio of negative sequence to positive sequence current) drawn by the installation under consideration.

VU emission due to line asymmetries;

$$\left| \frac{U_{2,i(\mathrm{line})}}{U_1} \right| = \frac{S_i}{S_{sc}} \left| \frac{Z_{12}}{Z_{11}} \right| \tag{7}$$

where, Z_{12} is the positive-sequence negative-sequence coupling impedance of the upstream network, and Z_{11} is the positive-sequence impedance of the upstream network.

Accordingly, $\mathrm{k_{uE}}$ can be calculated as shown in (8).

$$\mathrm{k_{uE}} = \frac{|C_i|^\alpha}{|C_i|^\alpha + \left(\left|\frac{Z_{12}}{Z_{11}}\right|\right)^\alpha} \tag{8}$$

III. Deterministic study on VU emission assessment

The new, deterministic approach presented in [5] follows the same basic guidelines given in the CIGRE/CIRED report on emission assessment techniques [4]. The evaluation of unbalance emission levels based on pre-connection and post-connection voltage measurements at the POE ($U_{2,\mathrm{post-connection}}$ and $U_{2,\mathrm{pre-connection}}$ respectively) as shown in [5] is given by (9).

$$U_{2,i} = U_{2,\mathrm{post-connection}} - U_{2,\mathrm{pre-connection}} \tag{9}$$

where, $U_{2,i}$ is the resultant VU emission which arise due to connection of i^{th} installation.

Accordingly, the emission level which arises as a result of a particular installation can lead to an increase or a decrease of the resultant unbalance level at the POE as illustrated by Fig. 1. If a decrease of the net unbalance level arises, no emission assessment is required for the particular installation. Conversely, if an increase of the net emission level is made by the connection of the installation, a fraction of the emission level which the installation is responsible for ($U_{2,i(\mathrm{load})}$) has to be evaluated.

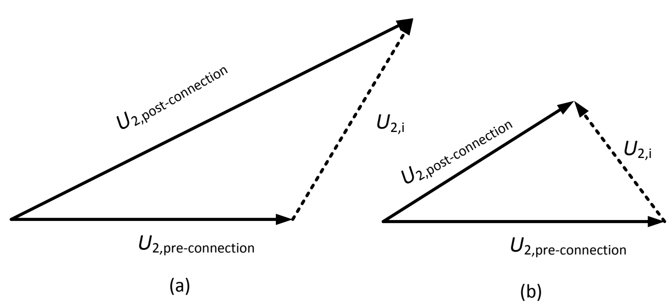

Fig. 1. Comparison of VU emission level at POE before and after the connection of installation

Referring to (9), the total emission $U_{2,i}$ has to be decomposed further to determine the individual contributions made by load asymmetry and line (or network) asymmetry and accordingly it can be rearranged as shown in (10) which shows the constituent parts of the total VU emission level at the POE.

$$U_{2,\mathrm{post-connection}} = k(U_{2,\mathrm{pre-connection}}) + U_{2,i(\mathrm{load})} + U_{2,i(\mathrm{line})} \tag{10}$$

In (10), k is a general, complex scaling factor.

The new, deterministic study presented in [5] forms the basis for evaluation of the individual contributions made by the installation asymmetry, upstream network asymmetry and the upstream source unbalance on the total voltage unbalance emission at the POE. The linearity property of negative sequence variables [1], [7] is employed in establishing the new methodology for the separation of different voltage unbalance contributors. That is, the resultant negative sequence voltage at the POE which arises as a result of the interaction of various sources of unbalance is equal to the phasor summation of the negative sequence components which arise due to individual sources of unbalance at the POE.

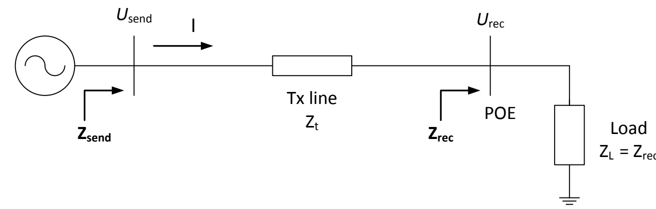

Fig. 2. Radial power system

Referring to the radial power system shown in Fig. 2, all power system elements (source, load and network) are analysed in a generalised manner in developing the post-connection emission assessment criteria noting that all of these components can contribute to the total unbalance emission at the POE. The reader should note that the POE is dedicated to the unbalanced installation under consideration only and zero sequence behaviour is ignored assuming three wire systems[1]. Different load types are considered separately in the evaluation procedure as discussed in the following section.

A. Separation of unbalance emission contributions: passive loads

A generalised expression for the total VU emission level at the POE (VUF_{POE}) as shown in (11) has been established in [5] which reflects the role played by all possible passive load configurations; constant impedance, constant current and constant power types.

$$\begin{aligned} VUF_{\mathrm{POE}} = VUF_{\mathrm{source}} &+ \frac{Z_{21,\mathrm{rec}}}{Z_{11,\mathrm{rec}}} \frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})} \\ &- \frac{Z_{21,t}}{Z_{11,t}} \frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})} \end{aligned} \tag{11}$$

where VUF_{source} is the upstream source VU factor which can be calculated using pre-connection voltage measurements at the POE, $Z_{xy,t}$ is the sequence impedance of the transmission line[2], $Z_{xy,\mathrm{rec}}$ is the sequence impedance seen at the POE (equal to load impedance), and $V_{\text{reg-line}}$ is the voltage regulation of the line defined as the ratio of positive sequence voltage drop in the network (line) to positive sequence voltage at the receiving end.

With balanced upstream source conditions, ($VUF_{\mathrm{source}} = 0$), if the load is also balanced or symmetrical (i.e., the coupling impedance $Z_{21,\mathrm{rec}} = 0$), then the unbalance at the POE arises only due to the network (line) asymmetry and it can be assessed using the factor $\frac{Z_{21,t}}{Z_{11,t}} \frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})}$. Conversely, for a symmetrical network, the positive-sequence negative-sequence coupling impedance $Z_{21,t} = 0$ and the voltage unbalance that arises at the POE due to load asymmetry can be established

[1]IEC/TR 61000-3-13 considers that zero sequence behaviour can be controlled through system design and maintenance.

[2]x and y are replaced by 1 and 2 which stand for positive sequence and negative sequence respectively.

using the factor $\frac{Z_{21,\text{rec}}}{Z_{11,\text{rec}}}\frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})}$. Further, VUF_{source} is the upstream source unbalance which is directly transferred to the POE without any attenuation. Thus, individual emission contributions on total VU factor at the POE for a passive load can be summarised as:

$$\text{Source contribution} = VUF_{\text{source}}$$

$$\text{Line contribution} = VUF_{\text{line}} = -\frac{Z_{21,t}}{Z_{11,t}}\frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})} \quad (12)$$

$$\text{Load contribution} = VUF_{\text{load}} = \frac{Z_{21,\text{rec}}}{Z_{11,\text{rec}}}\frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})}$$

This load contribution (VUF_{load}) can be further modified, in terms of voltage and current unbalance factors, by eliminating impedance terms associated with the installation (i.e., $Z_{21,\text{rec}}$ and $Z_{11,\text{rec}}$) to the form given in (13) to facilitate the evaluation of VU emission related to loads of which impedance details are not available such as constant current or constant power loads.

$$VUF_{\text{load}} = (VUF_{\text{POE}} - CUF)\frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})} \quad (13)$$

B. Separation of unbalance emission contributions: induction motors

Although induction motors are considered as symmetrical loads, this specific case is to examine their behaviour on VU emission compensation at the POE. For VU emission assessment studies, an induction motor is represented by three decoupled impedances in the sequence domain and total VU emission vector at the POE is obtained as shown in (14) similar to the use of passive load described in Section III-A.

$$VUF_{\text{POE}} = \left(\frac{Z_{2,m}}{Z_{1,m}}\right)\left(\frac{Z_{1,m}+Z_{11,t}}{Z_{2,m}+Z_{22,t}}\right)VUF_{\text{source}} - \left(\frac{Z_{2,m}}{Z_{1,m}}\right)\left(\frac{Z_{21,t}}{Z_{22,t}+Z_{2,m}}\right) \quad (14)$$

where $Z_{1,m}$ and $Z_{2,m}$ are positive sequence and negative sequence impedance of the motor respectively.

VU emission improvement provided by induction motors is reflected by (14), where the improvement made by the connection of three phase induction motors on an already unbalanced supply system can be noted by considering the special case where the transmission line is symmetrical (i.e., $Z_{21,t} = 0$). For this case, the voltage unbalance at the POE is the source voltage unbalance level (VUF_{source}), scaled by a factor $(\frac{Z_{2,m}}{Z_{1,m}})(\frac{Z_{1,m}+Z_{11,t}}{Z_{2,m}+Z_{22,t}})$, having a magnitude less than unity, which incorporates positive and negative sequence impedances of the line and the motor. Similarly, the influence made by the asymmetrical supply network (line) on the total unbalance is given by the factor $(\frac{Z_{2,m}}{Z_{1,m}})(\frac{Z_{21,t}}{Z_{22,t}+Z_{2,m}})$.

$$VUF_{\text{POE,IM}} = \left(\frac{Z_{2,m}}{Z_{1,m}}\right)\left(\frac{Z_{1,m}+Z_{11,t}}{Z_{2,m}+Z_{22,t}}\right)VUF_{\text{source}}$$

$$VUF_{\text{line}} = -\left(\frac{Z_{2,m}}{Z_{1,m}}\right)\left(\frac{Z_{21,t}}{Z_{22,t}+Z_{2,m}}\right)$$

IV. IMPLICATIONS OF 'k_{uE} FACTOR' APPROACH

The implications associated with the use of the k_{uE} factor in apportioning voltage unbalance emission is analysed in this section. The 'k_{uE} factor' used in here is considered as a vector quantity based on the formulations presented in Section III. Referring to (10), total VU factor the POE can be evaluated as a summation of VUF_{load}, VUF_{line} and VUF_{source}. If the upstream source is balanced (i.e. $VUF_{\text{source}} = 0$), VUF_{POE} gives the VU emission that arises due to the connection of unbalanced installation which is supposed to be apportioned to account for load asymmetries and line asymmetries as shown in (15).

$$VUF_{\text{POE}} = VUF_{\text{load}} + VUF_{\text{line}} \quad (15)$$

The factor 'k_{uE}' can be defined as a vector quantity as given by:

$$\text{k}_{\text{uE}} = \frac{VUF_{\text{load}}}{VUF_{\text{POE}}} \quad (16)$$

Similarly, k'_{uE} or the fraction that accounts for inherent system asymmetries as a vector quantity can be defined as:

$$\text{k}'_{\text{uE}} = \frac{VUF_{\text{line}}}{VUF_{\text{POE}}} \quad (17)$$

A. Passive loads

Normally, power system utilities control the VU emission level (in terms of magnitude of VUF) in MV (medium voltage) and LV (low voltage) networks under 2% compatibility level [1] while CUF which is a measure of the unbalance level of the load can be around 10% or even greater. This leads to a modification of the load contribution given in (13) as shown in (18) since the term $VUF_{\text{POE}} - CUF$ can be approximated to $-CUF$ noting that the magnitude of CUF is much larger than that of VUF.

$$VUF_{\text{load}} = (-CUF)\frac{V_{\text{reg-line}}}{(1+V_{\text{reg-line}})} \quad (18)$$

Therefore, the substitution of modified VUF_{load} and VUF_{POE} (as given in (15) under upstream source balanced condition) simplifies the k_{uE} (in (16)) as shown in (19).

$$\text{k}_{\text{uE}} = \frac{CUF}{CUF + \frac{Z_{21,t}}{Z_{11,t}}} \quad (19)$$

This reveals that the 'k_{uE}' or the fraction of total unbalance allocated to load asymmetry, depends not only on the line (network) characteristics, but also on the CUF or the level of load unbalance. As expected, for a perfectly symmetrical line $Z_{21,t} = 0$ and hence $\text{k}_{\text{uE}}= 1$.

The following case study results, which were obtained using an unbalanced load flow program developed in MATLAB, verify the above observation of the 'k_{uE} factor', resulting in varying emission levels (VUF_{load}) for different unbalance levels (measured in terms of CUF) for a constant power load. A 12.47 kV radial power system was established with a balanced source, an asymmetrical transmission line and three, 10 MVA single-phase loads which having different power factors to make it unbalanced. Test system details are given in Appendix A.

Case I: As shown in Table II, total VU emission at the POE ($VUF_{\rm POE}$) was evaluated by running the unbalanced load flow program while observing the constituent parts of $VUF_{\rm POE}$ ($VUF_{\rm load}$ and $VUF_{\rm line}$) using the deterministic approach described in Section III for different unbalance levels of the load. Power factor in phase C load was varied from 0.55 to 0.85 to obtain different current unbalance factors. $\rm k_{uE}$ is calculated as a vector quantity according to (16). Respective polar plots for representing the phasor behaviour of $VUF_{\rm POE}$ (total VU emission at the POE), $VUF_{\rm load}$ (VU emission at the POE caused by the load asymmetry) and $VUF_{\rm line}$ (VU emission at the POE caused by line asymmetry) are shown in Fig. 3.

TABLE II
$\rm K_{uE}$ FACTORS FOR CONSTANT POWER LOAD - CASE I

#	mag. CUF %	$VUF_{\rm POE}$ %	$VUF_{\rm line}$ %	$VUF_{\rm load}$ %	$\rm k_{uE}$	$\rm k'_{uE}$
a	3.3	1.17∠-170	0.79∠177	0.44∠-147	0.38∠23	0.68∠-12
b	5.2	1.24∠-158	0.79∠175	0.63∠-126	0.51∠31	0.64∠-26
c	8.3	1.46∠-150	0.78∠173	0.96∠-121	0.65∠28	0.53∠-37
d	13.0	1.87∠-141	0.78∠169	1.44∠-118	0.76∠22	0.42∠-49

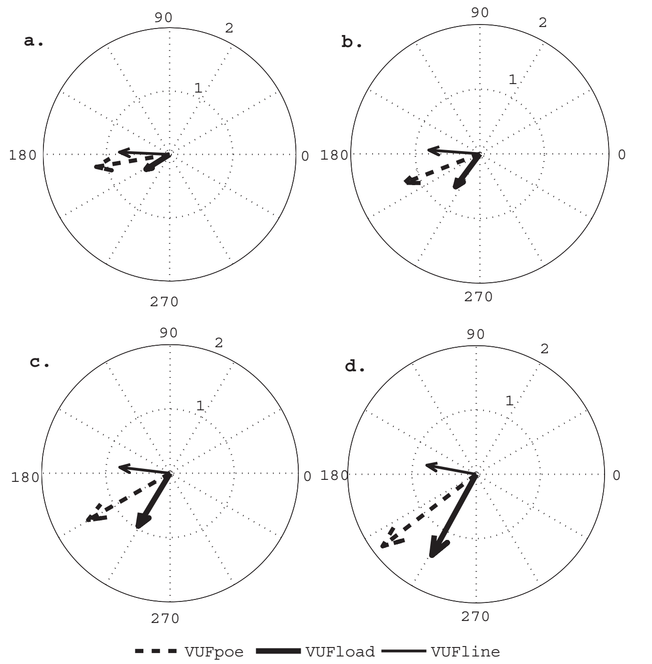

Fig. 3. Separation of VU emission levels at POE for different current unbalance levels: constant power load: Case I. (a) $|CUF|$ = 3.3%, (b) $|CUF|$ = 5.2%, (c) $|CUF|$ = 8.3%, (d) $|CUF|$ = 13.0%

Case II: The load configuration was established by swapping phase B and phase C loads in Case I. The corresponding outcomes as for Case II are given in Table III and illustrated in Fig. 4.

For both Cases I and II, the VU emission caused by line asymmetry ($VUF_{\rm line}$) seems to be constant in magnitude as well as in its phase angle since $VUF_{\rm line}$ is governed by the ratio $\frac{Z_{21,t}}{Z_{11,t}}$ which is an inherent property of a particular line. But, the emission contribution made by load asymmetry ($VUF_{\rm load}$) at the POE varies with the level of load unbalance (CUF) as well as with the relative phasor orientation of two the vectors $VUF_{\rm load}$ and $VUF_{\rm line}$ which is important in determining the total unbalance emission ($VUF_{\rm POE}$) at the POE. For Case I, the load configuration (as shown in Fig. 3), the phase angle between two vectors ($VUF_{\rm load}$ and $VUF_{\rm line}$) is less than 90 degrees and their summation leads to an increase the net unbalance emission at the POE. But, for Case II, where higher phase angle separations are large, the cancellation of unbalance emissions made by $VUF_{\rm load}$ and $VUF_{\rm line}$ helps to reduce the net emission at the POE as shown in Fig. 4. Therefore, although the emission contribution made by load asymmetry (for a fixed CUF in Case I and Case II) is approximately equal to each other, two different phasor orientations of $VUF_{\rm load}$ and $VUF_{\rm line}$ (for a fixed line emission vector) lead to two different net unbalance emission levels ($VUF_{\rm POE}$) and hence different $\rm k_{uE}$ factors.

TABLE III
k_{uE} FACTORS FOR CONSTANT POWER LOAD - CASE II

#	mag. CUF %	$VUF_{\rm POE}$ %	$VUF_{\rm line}$ %	$VUF_{\rm load}$ %	$\rm k_{uE}$	$\rm k'_{uE}$
a	2.5	0.95∠163	0.79∠177	0.25∠118	0.26∠-44	0.83∠14
b	4.0	0.81∠147	0.79∠175	0.38∠72	0.46∠-75	0.97∠28
c	6.5	0.65∠123	0.78∠178	0.61∠42	0.94∠-80	1.20∠50
d	10.7	0.64∠75	0.78∠168	1.05∠27	1.51∠-52	1.12∠89

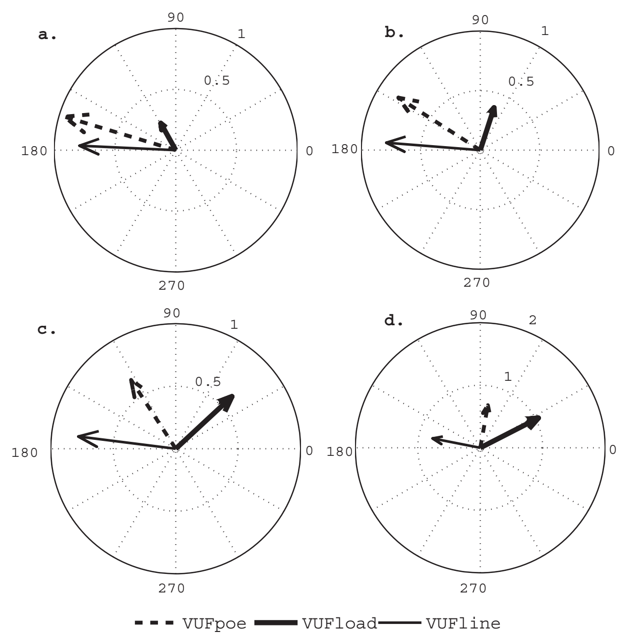

Fig. 4. Separation of VU emission levels at POE for different current unbalance levels: constant power load: Case II. (a) $|CUF|$ = 2.5%, (b) $|CUF|$ = 4.0%, (c) $|CUF|$ = 6.5%, (d) $|CUF|$ = 10.7%

B. Induction motor loads

Naturally, induction motor loads do not possess any inherent unbalance other than the fact that their operation is affected by the supply source unbalance. As shown by (14), the effective unbalance emission at the POE (at post connection stage) can be decomposed in to line contribution (VUF_{line}) and upstream source unbalance modification factor ($VUF_{\text{POE,IM}}$) which is given by upstream source VUF (VUF_{source}) multiplied by a scaling factor of which the magnitude is always less than unity. This is illustrated by (14) which proves that the induction motor improves the existing unbalance level at the POE and it seems incorrect to define or allocate a fraction of the total VU emission for the motor load itself. Thus, (16) or the existing 'k_{uE} factor' approach does not give rise to any meaningful unbalance emission allocation for induction motor loads.

Extensive simulation studies with unbalanced load flow studies carried out in relation to the induction motor VU emission assessment methodology [5] have shown that the scaling factor $\left(\frac{Z_{2,m}}{Z_{1,m}}\right)\left(\frac{Z_{1,m}+Z_{11,t}}{Z_{2,m}+Z_{22,t}}\right)$ associated with this emission reduction does not introduce any significant phase shift between pre- and post-connection emission vectors VUF_{source} and $VUF_{\text{POE,IM}}$. This enables the quantification of VU emission improvement by the connection of induction motor at the POE using known system and motor parameters as a scalar exercise.

C. Asymmetrical system (line) emission dependency on load types

Although VUF_{line} is almost constant (referring to Tables II and III), for different load unbalance levels (in terms of CUF), the normalised value over the VUF_{POE} which is calculated using (17) can vary since VUF_{POE} is not constant for different load unbalance levels. This behaviour can be illustrated by deriving k'_{uE} as given in (20) by substituting VUF_{line} and VUF_{POE} in (17).

$$\text{k}'_{\text{uE}} = \frac{\frac{Z_{21,t}}{Z_{11,t}}}{CUF + \frac{Z_{21,t}}{Z_{11,t}}} \tag{20}$$

Further, k'_{uE} can demonstrate some discrepancy when the phasor orientation between VUF_{load} and VUF_{line} is changed (as in Case II load with phase swapping or with some power factor changes) similar to 'k_{uE}' as shown above since it determines the net emission level at the POE.

The reader should also note that the line emission, and hence k'_{uE}, is also dependant on the load type as shown in Section III. Referring to (11) and (14), VUF_{line} depends on the voltage regulation of the line which is caused by the load current in case of a passive load and depends on the sequence impedances (Z_{m1} and Z_{m2}) in case of an induction motor load other than the positive sequence - negative sequence coupling impedance ($Z_{21,t}$) of the line. This variation is illustrated in Table IV. Line emissions (VUF_{line}) resulting from a 2.3 kV, 2250 hp induction motor load and a 1.67 MVA constant power load (same load capacity as the induction motor) which are connected to the same untransposed line are tabulated with normalised line emission vectors (k'_{uE}) for different source unbalance levels. Details of the asymmetrical line and the passive load (constant power type) are given in Appendix A and the induction motor specifications are given in Appendix B. A three-phase two-winding Yg-Yg connected transformer model was used as the motor service transformer with a voltage ratio: 12.47/2.3 kV and leakage reactance: 5% pu. Although the line emission levels are approximated for both load types, k'_{uE} values show a considerable difference due to the fact that the resultant VUF_{POE} is totally different for two load types.

V. CONCLUSIONS

This paper has demonstrated that the separation of total VU emission at the POE in to its constituent parts using pre-connection and post-connection voltage/current measurements allows the evaluation of 'k_{uE}' and 'k'_{uE}' independently. This process has revealed that these factors are highly dependent on the load type. In the case of passive loads, 'k_{uE}' has been shown to be dependent on the level of load asymmetry (expressed using current unbalance factor) even for a load with a fixed capacity. Further, the normalised VU emission values of load contribution and line contribution (ie. k_{uE} and k'_{uE}) are highly dependent on the phasor orientation of two vectors VUF_{load} and VUF_{line} which determines the net unbalance emission at the POE that is used for normalisation.

APPENDIX A
DETAILS OF THE RADIAL TEST SYSTEM WITH PASSIVE LOADS

- System details: 12.47 kV, 60 Hz, three wire
- 12.47 kV, 3.2187 km untransposed line:
  - Tower construction details: 1.143 m flat and horizontal
  - Conductor data:
    - Geometric mean radius = 7.7724 mm
    - AC resistance = 0.19014 Ω/km
    - Earth resistivity = 100 Ω.m
- Calculated line impedance matrix ($[Z_{abc}]$/km)

$$\begin{bmatrix} 0.2494 + j0.8748 & 0.0592 + j0.4985 & 0.0592 + j0.4462 \\ 0.0592 + j0.4985 & 0.2494 + j0.8748 & 0.0592 + j0.4985 \\ 0.0592 + j0.4462 & 0.0592 + j0.4985 & 0.2494 + j0.8748 \end{bmatrix}$$

- Constant power load: A set of three, 10 MVA/1.67 MVA single phase loads with lagging power factors of 0.85, 0.90 and 0.55 in phases a, b and c respectively.
- Voltage regulation of the line ($|V_{\text{reg-line}}|$) - 9.6% (for constant power load), - 5.5% (for induction motor load)

APPENDIX B
60 HZ, 4-POLE INDUCTION MOTOR PARAMETERS [10]

The induction motor used in this research was extracted from [10]. The parameters of this motor are presented here for convenience.

- Power rating - 2250 (hp)
- Line Voltage - 2300 (V)
- Motor speed - 1786 (rpm)
- r_s - 0.029 (Ω)
- X_{ls} - 0.226 (Ω)
- X_M - 13.04(Ω)
- X'_{lr} - 0.226(Ω)
- r'_r - 0.022(Ω)
- J - 63.87 (kg m^2)

TABLE IV
K'_{uE} CALCULATION FOR INDUCTION MOTOR AND CONSTANT POWER LOAD (SAME CAPACITY)

#	VUF_{source}	VUF_{POE} %		VUF_{line} %		k'_{uE}	
		IM load	Constant power load	IM load	Constant power load	IM load	Constant power load
a	$0.0\angle 0$	$0.17\angle -168$	$0.17\angle 21$	$0.16\angle -168$	$0.19\angle 171$	$0.91\angle 1$	$1.13\angle 143$
b	$0.58\angle 29$	$0.32\angle 45$	$0.75\angle 28$	$0.16\angle -168$	$0.19\angle 171$	$0.46\angle 146$	$1.11\angle 144$
c	$1.16\angle 29$	$0.87\angle 38$	$1.33\angle 29$	$0.16\angle -168$	$0.19\angle 171$	$0.19\angle 146$	$1.09\angle 144$
d	$2.33\angle 29$	$1.92\angle 35$	$2.50\angle 29$	$0.16\angle -168$	$0.19\angle 171$	$0.09\angle 156$	$1.05\angle 146$

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