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A review of recent investigations with reference to IEC/TR 61000-3-13 on voltage unbalance emission allocation

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A Review of Recent Investigations with Reference to IEC/TR 61000-3-13 on Voltage Unbalance Emission Allocation

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Abstract—The Technical Report IEC/TR 61000-3-13:2008 provides guiding principles for coordinating voltage unbalance between various voltage levels of a power system through the allocation of emission limits to installations. This report is based on widely accepted concepts and principles in relation to voltage unbalance. With regard to some of the key ideas used in this report, investigations have been carried out which have enabled the development of deeper insights making the voltage unbalance allocation process more comprehensive. The key aspects which have been considered in detail include: voltage unbalance which arises as a result of lines and voltage unbalance propagation in HV-MV, MV-LV power systems. In addition, a robust voltage unbalance allocation method has been developed which overcomes some difficulties associated where a uniform voltage unbalance planning level is adopted across all bus bars with the same voltage level classification (ie, MV or HV or EHV). With regard to voltage unbalance emission assessment a novel technique has also been developed which was verified through the application to an interconnected power system where the methodology allows identification of the contributors to voltage unbalance at a selected bus bar.

Index Terms—voltage unbalance, line asymmetries, power quality, voltage unbalance emission allocation, voltage unbalance emission level assessment, voltage unbalance propagation

I. INTRODUCTION

THE Technical Report IEC/TR 61000-3-13:2008 [1] is the only technical document available for coordination of voltage unbalance (negative sequence) in power systems. The primary objective of this report is to provide guiding principles to system operators and owners, to determine the connection requirements of unbalanced installations to MV, HV and EHV public power systems such that, adequate service quality to all connected customers is ensured. The report addresses the coordination of voltage unbalance between various voltage levels of a power system through apportioning of the global emission allowance to individual customers.

A comprehensive discussion on the voltage unbalance allocation procedure as presented in IEC/TR 61000-3-13:2008 is given in [2]. Similar to the counterpart IEC guidelines for harmonics (IEC/TR 61000-3-6 [3]) and flicker (IEC/TR 61000-3-7 [4]) allocation, voltage unbalance allocation approach given

in IEC/TR 61000-3-13:2008 employs planning levels, general summation law and voltage unbalance propagation that is taken into account through transfer and influence coefficients as some of the key aspects. In addition, the allocation methodology introduces a new factor, ‘Kue’, which takes the emission which arise as a result of line asymmetries into the account. However, the report does not cover a systematic approach for evaluating this ‘Kue’ factor. Further the method given for estimating the MV-LV unbalance transfer coefficient was noted to under estimate the level of propagation, particularly in the presence of commonly prevailing constant power loads. Also, the report does not elaborate a method for evaluating voltage unbalance influence coefficients. As in the case of harmonics and flicker [5, 6], the voltage unbalance allocation policy was found not to guarantee that the emission limits allocated to customers ensure non-exceedance of the set planning levels. In addition, assessment techniques associated with voltage unbalance emission has been a topic of interest to the CIGRE/CIREN Joint Working Group C4.109 with the objective of further developing the present version of IEC technical report on emission assessment techniques [7] at a future date. Sections II, III, IV and V of this paper summarises the significant outcomes of recent investigations carried out with regard to the ‘Kue’ factor, transfer and influence coefficients, a revised allocation policy and emission level assessment techniques respectively.

II. KUE FACTOR [2, 8]

The factor ‘Kue’, which represents the fraction of the total emission allowance (expressed in terms of voltage unbalance factor) that can be allocated to unbalanced installations, at any busbar x is defined as:

$$Kue_x = 1 - Kue'_x = 1 - \left[\frac{U_{lines-x}}{U_{gx}} \right]^\alpha \quad (1)$$

where,

$Kue'_x = 1 - Kue_x$ represents the fraction of the total emission allowance that arises from line asymmetries at busbar x

$U_{lines-x}$ - emission arising from line asymmetries at busbar x
 U_{gx} - total emission allowance at busbar x

α - summation law exponent

The Technical Report IEC/TR 61000-3-13:2008 gives only a rudimentary direction for evaluating the emission arising as

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a result of line asymmetries together with a set of indicative values for Kue' (in the range 0.1–0.5) from which a value can be selected depending on system characteristics.

Recent investigations show that the guidelines given in the IEC report to assess the influence of an asymmetrical radial line on the global emission can be applied only when the network supplies primarily passive loads. Presence of induction motors has been seen to make a noticeable influence on the level of emission determined using the IEC approach. This influence of motor loads, which depends primarily on the proportion of motor loads and secondarily on system and motor characteristics, can be seen in two forms:

(a) local emission or the emission arising from local lines (e.g. MV lines when assessing the global emission in MV systems) is influenced by motor loads supplied at downstream.

(b) the presence of motor loads makes the downstream emission or the emission arising from downstream lines (e.g. MV lines when assessing the global emission of HV systems) accountable for global emission. The influence of downstream MV lines can either decrease or increase the resultant emission levels at HV with respect to the local HV emission levels depending on impedance/admittance characteristics of the downstream lines relative to the local lines.

A generalised approach for evaluating the global emission caused by line asymmetries of radial and interconnected networks at nodal level has been developed as given by (2). The proposed method has been verified using unbalanced load flow analysis in relation to test systems.

$$[|V_{-:lines}|]_{n \times 1} = \left| [Y'_{++}]_{n \times n}^{-1} [Y'_{-+}]_{n \times n} [V_+]_{n \times 1} \right| \quad (2)$$

where,

$i, j - i^{th}$ and j^{th} bus bars

$Y_{++:ij} = Y_{++:ij} + Y_{--:i-im}$ for $i = j$

$Y'_{++:ij} = Y_{++:ij}$ for $i \neq j$

$Y_{-+:ij} = Y_{-+:ij} + Y_{-+:i}$ for $i = j$

$Y'_{-+:ij} = Y_{-+:ij}$ for $i \neq j$

$i, j = 1, 2, \dots, n$

In establishing the admittances listed above:

$Y_{++:ij}$ and $Y_{-+:ij}$ are the $(i, j)^{th}$ elements of the positive sequence and negative-positive sequence coupling nodal admittance matrices respectively. For $i = j$, $Y_{++:ii}$ (or $Y_{++:ij}$) is the sum of all respective network admittances connected to busbar i . For $i \neq j$, $Y_{++:ij}$ (or $Y_{++:ii}$) is equal to the respective admittance of the network element connecting busbars i and j . Admittance $Y_{--:i-im}$ is the downstream negative sequence admittance seen at busbar i taking into account only induction motors supplied by downstream LV systems. Note that this admittance can be approximated to a value of zero if busbar i supplies load bases containing primarily passive loads. Alternatively, when busbar i supplies load bases containing large proportions of induction motors, $Y_{--:i-im}$ can be expressed in terms of the motor proportion, system and load characteristics, system operating conditions and downstream load composition. Admittance $Y_{-+:i}$ is the downstream negative-positive sequence coupling admittance

seen at busbar i , which arises as a result of downstream line asymmetries together with the presence of large proportion of motor loads (thus, $Y_{-+:i} = 0$ in assessing MV systems).

Matrices $[V_{-:lines}]$ and $[V_+]$ are the nodal negative sequence (arising due to line asymmetries) and positive sequence voltage matrices respectively. The nodal positive sequence voltages can be considered as known quantities as they can be obtained from a conventional balanced load flow analysis.

As an example, Figure 1 illustrates the results (emission from line asymmetries in terms of the VUF), in relation to a simple three-bus interconnected MV test system, established using the proposed methodology compared with those obtained using unbalanced load flow analysis. In the test system considered: Busbar 1 connects to the upstream HV system (upstream voltage unbalance is considered to be zero) through a coupling transformer and all lines are untransposed. Busbars 1 and 3 supply passive loads at the MV level, busbar 2 supplies an LV load through an MV-LV transformer and accounts for 40% of the total load supplied by the system. Two cases are considered depending on the load type supplied by busbar 2 where: Case 1 - passive loads only and Case 2 - mixture of passive and motor loads. Figure 1 illustrates that the emission level at busbar 1 has increased for Case 2 compared to Case 1 whereas the opposite is true for busbars 2 and 3 thus indicating a link between contributions made by line asymmetries and load type as aspect which cannot be taken into account using the IEC methodology.

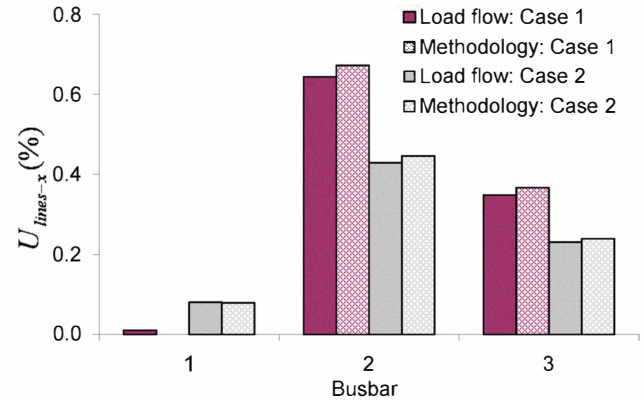


Fig. 1. Emission arising as a result of line asymmetries of a MV three-bus test system in the presence of: Case 1 - only passive loads, Case 2 - a mix of passive and motor loads

III. TRANSFER AND INFLUENCE COEFFICIENTS

A. Transfer coefficients [9, 10]

Transfer coefficient provides a quantitative measure of the propagation of voltage unbalance (in terms of the VUF) from an upstream higher voltage system to a downstream lower voltage system through the coupling transformer. IEC/TR 61000-3-13 gives a method for estimating the MV-LV transfer coefficient (T_{mv-lv}), which suggests a value less than unity in the presence of industrial load bases containing large proportions of mains connected three-phase induction motors

$$T_{mv-lv} \approx \frac{\left| 1 + j \frac{1}{k_{sc-lv}} \angle \theta_{pf} \right|}{\left[1 + \frac{k_m k_s}{k_{sc-lv}} \right] \left| 1 + j \frac{k_z}{k_{sc-lv}} \angle \theta_{pf:z} \right| \left| 1 + j \frac{k_{pq}}{k_{sc-lv}} \angle \theta_{pf:pq} \right|^\beta} \quad (3)$$

$$T_{hv-mv} \approx \frac{\left| 1 + j \frac{1}{k_{sc-mv}} \angle \theta_{pf:mv} \right|}{\left[1 + \left[\frac{k_m k_{lv}}{k_{sc-mv}} \right] \left[\frac{k_s}{1 + \frac{k_m k_s}{k_{sc-lvagg}}} \right] \right] \left| 1 + j \frac{k_{zmv}}{k_{sc-mv}} \angle \theta_{pf:zmv} \right| \left| 1 + j \frac{k_{pqmv}}{k_{sc-mv}} \angle \theta_{pf:pqmv} \right|^\beta} \quad (4)$$

(IM), and a value of unity in relation to passive loads in general.

Recent studies show that the transfer coefficient can be greater than unity in the presence of commonly prevailing constant power loads (PQ) whereas it is unity in the case of constant impedance type loads (Z). Incorporating the above findings, an improved method for estimating the MV-LV and HV-MV transfer coefficients are proposed as given by (3) and (4) respectively. These proposed formulations have been verified against the results obtained using unbalanced load flow analysis.

In relation to equations (3) and (4),

k_z, k_{pq} - ratios of constant impedance and constant power loads (in MVA) to the total load (in MVA) supplied by the LV busbar respectively (subscript mv in (4) for T_{hv-mv} indicates the load supplied by the MV busbar)

$\theta_{pf}, \theta_{pf:z}, \theta_{pf:pq}$ - power factor angles of the total load, constant impedance and constant power loads supplied by the LV system respectively (subscript mv in (4) for T_{hv-mv} indicates the load supplied by the MV busbar)

k_m - ratio between the rated motor load (in MVA) and the total load (in MVA) supplied by the LV system

k_s - ratio between positive and negative sequence impedances of the motor load supplied by the LV system (typically, $5 < k_s < 7$)

$\beta \approx -1$ and -2 for low (≈ 0.9) and high (≈ 1) lagging pf conditions respectively

k_{sc-lv} - ratio between the LV short circuit level (in MVA) and the total load (in MVA) supplied by the LV system (subscript mv in (4) for T_{hv-mv} indicates the corresponding factor at the MV busbar), $10 < k_{sc-lv} < 25$ and $5 < k_{mv-lv} < 15$ for practical systems

$k_{sc-lvagg}$ - ratio between the short-circuit capacity (in MVA) at the LV busbar (aggregation of all LV busbars supplied by the MV busbar under evaluation), and the total load (in MVA) supplied by the LV system.

Equations (3) and (4) suggest that the transfer coefficient < 1 for motor loads, and ≥ 1 for passive loads. However, its reduction for the case of motor loads, relative to unity, is significant compared to the increment shown for the case of passive loads. Noting that $k_{sc-mv} < k_{sc-lv}$, the amplification which takes place in the presence of passive loads in the HV to MV propagation is greater than that in the case of the MV to LV propagation. The reduction (for motor loads) in T_{hv-mv} is smaller than that of T_{mv-lv} for similar system and load characteristics. However, usually $k_{sc-mv} < k_{sc-lv}$, and thus a higher degree of reduction can be expected in the HV to

MV propagation than that in the MV to LV propagation.

As an example, Figures 2 and 3 illustrate the variation of T_{mv-lv} with k_{sc-lv} in relation to two load bases (0.9 lagging PF, $k_s = 6.7$ for motor loads):

(a) Z-10%, I-5%, PQ-15%, IM-70% and (b) Z-25%, I-5%, PQ-60%, IM-10% respectively ('I' represents constant current loads). These show the variations established using (3), IEC approach and unbalanced load flow analysis. These results demonstrate that although the IEC method provides an accurate estimation to T_{mv-lv} for load bases containing large proportions of induction motors, it is associated with a considerable degree of error for load bases dominated by passive elements.

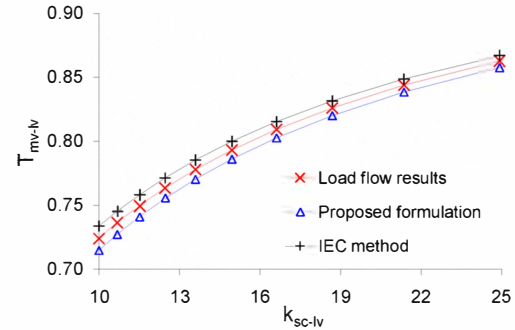


Fig. 2. Variation of T_{mv-lv} with k_{sc-lv} for a load base dominated by motor loads

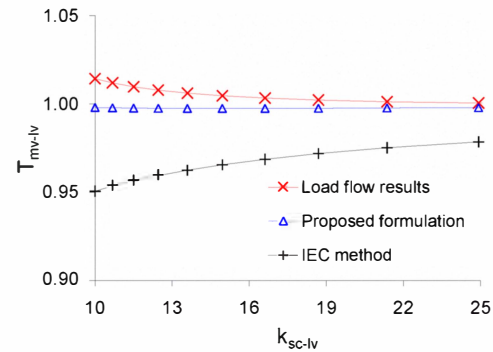


Fig. 3. Variation of T_{mv-lv} with k_{sc-lv} for a load base dominated by passive loads

B. Influence coefficients [11]

Influence coefficient gives a quantitative measure of the propagation of voltage unbalance from one busbar to another busbar of a system at a particular voltage level. The influence coefficient k_{i-x} between busbars i and x is defined as the voltage unbalance which arises at the busbar x when 1pu of negative sequence voltage source is applied at busbar i .

Recent investigations show that influence coefficients can be approximated to unity in the presence of passive loads in general. However, as in the case of transfer coefficients, they can be considerably smaller than unity when the network supplies a large proportion of three-phase induction motor loads at the downstream. Incorporating the above findings, a systematic approach for evaluating influence coefficients in relation to both radial and interconnected networks has been proposed as given by (5). The proposed method has been verified on test systems using unbalanced load flow analysis.

$$[k_{i-x}]_{(n-1) \times 1} = \left[[Y'_{++:xz}]_{(n-1) \times (n-1)}^{-1} [Y_{++:xi}]_{(n-1) \times 1} \right] \quad (5)$$

where,

$$Y'_{++:xz} = Y_{++:xz} + Y_{--:x-im} \text{ for } x = z$$

$$Y'_{++:xz} = Y_{++:xz} \text{ for } x \neq z$$

$$x, z = 1, 2, \dots, n \text{ and } x, z \neq i$$

All admittances are as defined and described for (2).

As an example, in relation to a simple three-bus interconnected MV test system, Figure 4 illustrates the influence coefficients k_{1-2} and k_{1-3} established using the proposed methodology and unbalanced load flow analysis. The test system is as described in Section II, except that all lines are taken as ideally transposed and busbar 2 supplies a mix of passive and motor loads (40% of the total load). Figure 4 shows the variation of the influence coefficients with the proportion of motor loads at busbar 2, demonstrating the impact of motor loads on influence coefficients.

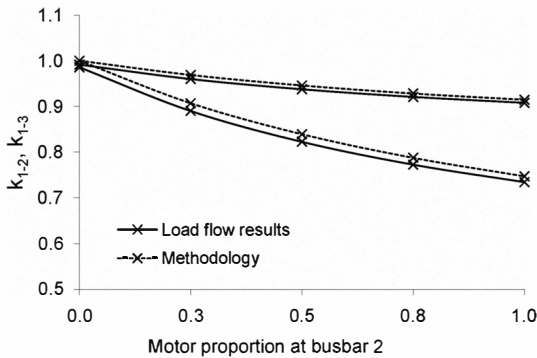


Fig. 4. Variation of influence coefficients with the proportion of motor load at busbar 2 of a MV three-bus test system

IV. A REVISED ALLOCATION TECHNIQUE BASED ON IEC/TR 61000-3-13 GUIDELINES [12]

The IEC allocation procedure in relation to harmonics and flicker has been seen to noted to exceed a set planning level even when no customer exceeds the allocated emission limit

TABLE I
RESULTS OF EXAMINATION OF THE IEC/TR 61000-3-13 PROCEDURE IN VOLTAGE UNBALANCE ALLOCATION

Global emission allowance (U_g)=1.4 (% VUF)				
Busbar	Load (Passive, 0.95 PF) (MVA)	Busbar allowance (% VUF)	Customer emission limit (% VUF)	$U_{result-x}$ (% VUF)
1	20	0.88	0.88	1.24
2	20	0.74	0.74	1.52
3	10	0.48	0.48	1.40

[5, 6]. References [5, 6] propose a revised allocation technique for harmonics and flicker which closely aligns with the IEC policy, whereby the emission levels at network busbars are explicitly forced to be at or below the set planning levels when all loads are injecting at their limits derived under the new approach. This new technique is known as the 'constraint bus voltage' (CBV) method.

Recent investigations revealed that the above problem is associated with the IEC/TR 61000-3-13:2008 voltage unbalance allocation approach as well. Table 1 gives the results of an examination of the IEC/TR 61000-3-13:2008 procedure carried out in relation to an HV three-bus test system (all lines are assumed to be ideally transposed, i.e. $Kue' = 0$). This examination procedure involves: (a) the calculation of emission limits of individual installations using the IEC/TR 61000-3-13:2008 prescribed formulae and influence coefficients calculated using the methodology covered in Section III-B, (b) the derivation of the resulting busbar emission when all individual installations inject their allocated limits using the general summation law ($\alpha = 1.4$). Note that although the resulting emission levels ($U_{result-x}$) at busbars 1 and 3 do not exceed the set planning level U_g of 1.4%, $U_{result-x}$ at busbar 2 exceeds that planning level by 8% approximately.

The CBV allocation method which has been suggested for harmonics and flicker cannot be applied in its present form to voltage unbalance as the additional aspect of emission arising as a result of system inherent asymmetries has to be taken into account. Thus, including appropriate revisions, the following alternative allocation policy is suggested to calculate the emission allocation limit E_{x-j} of a customer installation j of which the MVA load S_{x-j} is to be connected at any busbar x :

$$E_{x-j} = k_a \sqrt[\alpha]{Kue_x S_{x-j}} \quad (6)$$

The constant k_a known as the allocation constant can be determined using (7), which is chosen to be the largest value such that $U_{result-x} \leq U_g$ for every busbar x . The factor Kue_x can be determined using (8).

$$k_a = \min \left[\sqrt[\alpha]{\frac{(U_g)^\alpha + \sum_{i=1, i \neq x}^n (U_{lines-x})^\alpha}{S_x + \sum_{i=1, i \neq x}^n (k_{i-x})^\alpha S_i}} \right] \quad (7)$$

$$kue_x = 1 - \left[\frac{(U_{lines-x})^\alpha}{(k_a)^\alpha S_x} \right] \quad (8)$$

where,

i represent the i^{th} busbar of the considered system, S_i is the MVA demand at busbar i .

TABLE II

RESULTS OF AN EXAMINATION OF THE NEW CBV ALLOCATION METHOD

Busbar	RHS of (7)	k_a (minimum of column 2)	Customer emission limit (%VUF)	$U_{result-x}$ (% VUF)
1	0.110	0.088	0.75	1.12
2	0.088	0.088	0.75	1.40
3	0.096	0.088	0.46	1.28

Table 2 gives the results of the examination of the new CBV voltage unbalance allocation method applied to the HV three-bus test system considered above (with $U_g = 1.4\%$, $\alpha = 1.4$, $K_{ue} = 1$). Figure 5 provides a comparison of the resulting busbar emission levels established using the IEC/TR 61000-3-13 approach and the revised CBV allocation approach. This illustrates that the revised allocation technique restricts the resulting emission level at the constrained busbar (e.g. busbar 2 of the test system) to the set level ($= 1.4\%$ for the test case) while maintaining the emission levels at other busbars (e.g. busbars 1 and 3 of the test system) below the set limit.

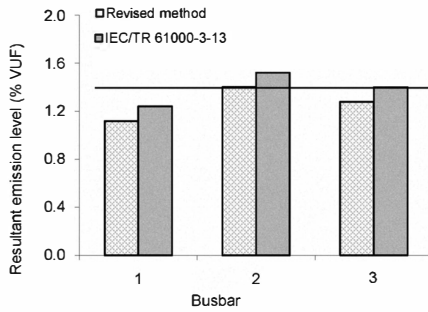


Fig. 5. Comparison of the resulting emission levels derived using the IEC/TR 61000-3-13 and CBV methods

V. CONTRIBUTION TOWARDS VOLTAGE UNBALANCE EMISSION LEVEL ASSESSMENT TECHNIQUES [13, 14]

A. Emission from line asymmetries

Recent investigations with regard to an interconnected sub-transmission (66kV) system which was known to experience excessive unbalance levels revealed the following:

- 1) The voltage unbalance introduced by an untransposed line can be treated as a vectorial quantity and in a global sense, can be ascertained by a single vector (referred to as 'global emission vector') of which:
 - The magnitude can be approximately assessed by referring to the product $|Z_- + I_+|$ associated with the line and its location (i.e. whether or not the line is in the direct path connecting the bulk supply point and central part and/or the downstream) in the network.
 - The phase angle can be approximately derived using the term $-Z_- + I_+$.
- 2) The behaviour of negative sequence variables is linear. That is, a resultant negative sequence voltage at a busbar, which arises as a result of the interaction of various

sources of unbalance is equal to the vector summation of negative sequence voltage components caused by individual sources at the considered busbar. Thus, the integration of global emission vectors of individual lines, as illustrated in Figure 6 for the lines (A-N) of study system, establishes a basis that provides a comprehensive understanding of the manner in which various asymmetrical lines interact with each other to form the resultant influence. This basis can be used to derive the following:

- The resultant influence of the interaction of all lines in terms of a single vector can be established by the summation of individual global emission vectors. This, for the study system, is illustrated by the vector R_{lines} in Figure 6.
- referring to Figure 6, lines *A* and *F* can be identified as dominant contributors to the resultant influence as the respective global emission vectors lie in close proximity to the resultant vector. Although the global emission vector of line *I* is displaced slightly away from the resultant vector, it being the line which introduces the highest level of emission on its own, can also make a significant contribution. The phase deviation close to 90° of the vector of line *J* with respect to the resultant vector can make it a less of a contributor. The positioning of the vector of line *D* with respect to the resultant vector suggests that it can make a negative contribution, or in other words it assists in counter balancing some of the emissions caused by the other lines. These assessments made on the study system using the proposed technique have been seen to be in agreement with the results obtained using unbalanced load flow analysis.
- Transposition options for managing the emission arising as a result of line asymmetries can be deduced using Figure 6. For this, the smaller global emission vectors of lines *B, C, L, M* and *N* are represented using a single vector (labeled as ' $B + C + L + M + N$ '). The most effective option to correct the network voltage unbalance through the transposition of a single line is seen to correspond to line *F* as it is represented by the largest vector among the group of vectors (i.e. $B + C + L + M + N$, *A* and *F*) clustered together. Further correction can be introduced to the network effectively by transposing lines *A* and *F*. It results in the vectors $B + C + L + M + N$, *D, I* and *J* to remain, out of which the vectors $B + C + L + M + N$ and *I* lie in close proximity. This is the case with the vectors *D* and *J* as well. The phase difference close to 90° between these two groups (i.e. $B + C + L + M + N$ and *I*, and *D* and *J*) suggests that the emissions arising as a result of lines *B, C, I* and $L - N$ assist in counter balancing some of the emissions of lines *D* and *J*. The outcomes of the transposition of line *F* only and lines *A* and *F* together are illustrated in Figures. 7 (II) and (III) respectively.

These demonstrate that the transposition of line F can introduce approximately 30% reduction in the resultant influence, whereas approximately 50 % reduction in the resultant influence can be expected by transposing both lines A and F.

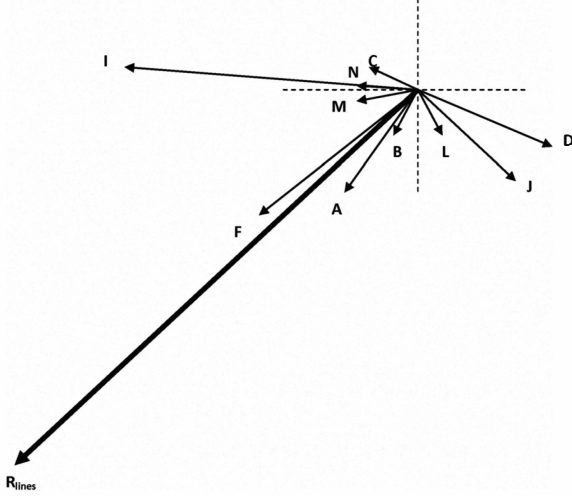


Fig. 6. Emission vectors of lines of the 66kV interconnected study network

B. Emission from load asymmetries

It has also been revealed that, as in the case of an asymmetrical line, the voltage unbalance behaviour exhibited by an unbalanced load of an interconnected network can be represented using a global emission vector of which:

- The magnitude can be approximately assessed by referring to the degree of asymmetry associated with the load and the location of the load (i.e. upstream, central part, downstream) in the network.
- The phase angle can be approximately derived by referring to the order of the distribution of power of the load across the three phases, and the X/R ratio associated with lines of the network.

Employing the linearity of negative sequence variables, as for line asymmetries, the global emission vectors of individual loads can be integrated to establish a basis that provides a comprehensive understanding of the manner in which various unbalanced loads interact with each other to form the resultant influence. Figure 8 illustrates this resultant influence for the study system using a single vector (R_{loads}) which can be established by the summation of the individual global emission vectors.

C. Emission from both load and line asymmetries

Employing the linearity of negative sequence variables, the global emission vectors of individual sources of unbalance (i.e. individual lines and loads) can be integrated to establish a basis that provides a comprehensive understanding of the manner in which various untransposed lines and unbalanced loads interact with each other to form the overall influence.

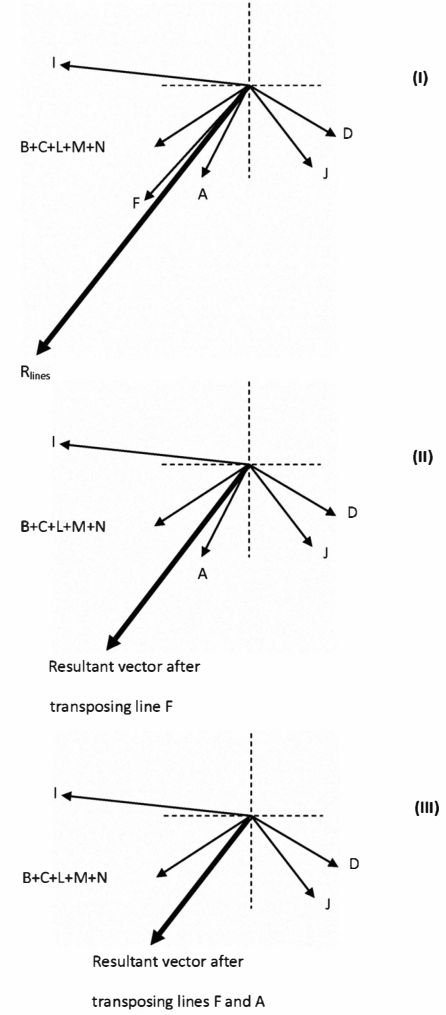


Fig. 7. Illustration of the use of the proposed emission vector approach for assessing various transposition options

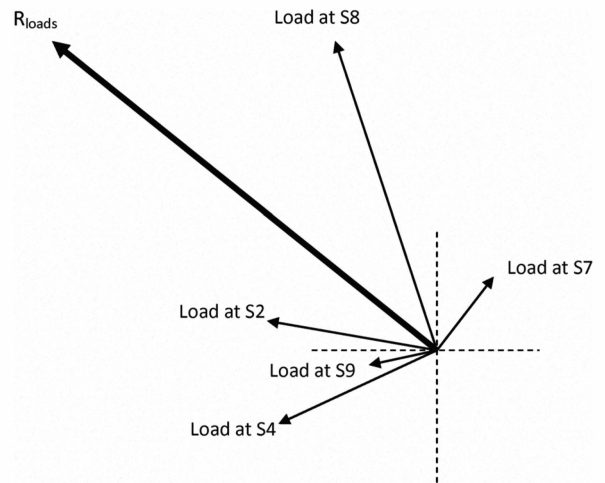


Fig. 8. Illustration of the use of proposed emission vector approach for assessing various transposition options

Figure 9 illustrates this overall influence for the study system using a single vector (R_{system}) which is obtained by the summation of the individual global emission vectors shown in Figures 6 (for lines) and 8 (for loads). Figure 9 also shows the vectors R_{lines} (Figure 6) and R_{loads} (Figure 8) where $R_{system} = R_{lines} + R_{loads}$. This basis can be used to derive the following:

- Referring to the vectors R_{system} , R_{lines} and R_{loads} , the component of R_{lines} which is in-phase with R_{system} accounts for approximately 60% of the magnitude of R_{system} , whereas that of R_{loads} is approximately 30%. That is, the asymmetry associated with the lines is the dominant contributor to the problem, whereas the load asymmetries play only a secondary role.
- Observation of the global emission vectors of the individual lines and loads illustrated in Figures 6 and 8 respectively together with the vector R_{system} (Figure 9) suggests that, among all sources of unbalance, lines F and I , these being represented by the largest and the closest vectors to R_{system} , can be identified as the major contributors to the overall voltage unbalance levels. In addition, the vectors of line A and the loads supplied by $S2$ and $S4$, having relatively large magnitudes and being closer to R_{system} , can contribute significantly to the problem supporting the two major contributors (i.e. lines F and I). The phase deviation close to 90° of the vector of the load supplied by $S8$ with respect to R_{system} can make it a less of a contributor. The positioning of the vectors of lines D and J and the load supplied by $S7$ with respect to R_{system} suggests that they can make negative contributions.

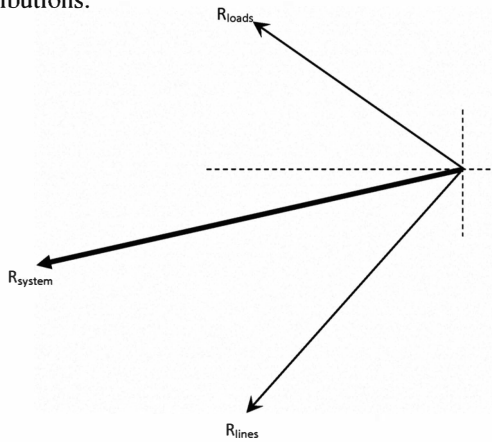


Fig. 9. Representation of the resultant voltage unbalance behaviour of the study 66kV interconnected network

VI. CONCLUSIONS

The paper has summarised the recent studies completed in relation to the Technical Report IEC/TR 61000-3-13:2008 on voltage unbalance emission limits allocation. Deeper insights into the aspects that influence of the 'Kue' factor, voltage unbalance transfer coefficients and influence coefficients have been developed. In addition, a robust voltage unbalance allocation methodology has been developed. A specific interconnected network case study has been carried out in order to

determine the contributors to voltage unbalance at each of its busbars thus paving a path for systematic selection of voltage unbalance mitigation options. All theoretical formulations that have been developed have been verified using unbalanced load flow analysis where close agreements have been noted. While it is expected that the recent work completed will help further develop the Technical Report IEC/TR 61000-3-13:2008, avenues for further research on the subject of voltage unbalance is also expected to open. It is expected that further real life case studies will help consolidate the outcomes reached. As in the case of harmonics and flicker, voltage unbalance emission assessment is seen to be an area which needs further development because of the complex interactions that take place between load asymmetry and line asymmetry noting the added complexity of load behaviour such as that of an induction motor.

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