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Contributions towards the development of the Technical Report IEC/TR 61000-3-13 on voltage unbalance emission allocation

Prabodha Paranavithana

University of Wollongong

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Contributions Towards the Development of the Technical Report IEC/TR 61000-3-13 on Voltage Unbalance Emission Allocation

A thesis submitted in fulfilment of the requirements for the award of the degree

Doctor of Philosophy

from

University of Wollongong

by

Prabodha Paranavithana, BSc(Eng)

School of Electrical, Computer and Telecommunications Engineering

March 2009
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Certification

I, Prabodha Paranavithana, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, is entirely my own work unless otherwise referenced or acknowledged. This manuscript has not been submitted for qualifications at any other academic institute.

Prabodha Paranavithana

Date: 31 March 2009
Abstract

Although voltage unbalance is a well understood concept, its presence as a power quality problem in electricity transmission and distribution networks has continued to be an issue of concerns primarily due to difficulties found by some network service providers in maintaining acceptable levels. This emphasises the lack of recommendations on engineering practices governing voltage unbalance that would facilitate the provision of adequate supply quality to connected customers.

The International Electrotechnical Commission (IEC) has recently released the Technical Report IEC/TR 61000-3-13 which provides guiding principles for coordinating voltage unbalance between various voltage levels of a power system through the allocation of emission limits to installations. Although the IEC report is based on widely accepted basic concepts and principles, it requires refinements and original developments in relation to some of the key aspects. This thesis primarily focuses on making contributions for further improvements to the IEC report so as to present a more comprehensive voltage unbalance allocation procedure.

Similar to the counterpart IEC guidelines for harmonics (IEC 61000-3-6) and flicker (IEC 61000-3-7) allocation, IEC/TR 61000-3-13 also apportions the global emission allowance to an installation in proportion to the ratio between the agreed apparent power, and the total available apparent power of the system seen at the busbar where it is connected. However, noting that voltage unbalance at a busbar can arise as a result of both load and system (essentially lines) asymmetries, IEC/TR 61000-3-13 applies an additional factor which is referred to as ‘$K_{ue}$’ to the apportioned allowance. This factor $K_{ue}$ represents the fraction of the global emission allowance that can be allocated to customers, whereas the factor $K'_{ue} = 1 - K_{ue}$ accounts for voltage unbalance which arises as a result of line asymmetries. Although
IEC/TR 61000-3-13 recommends system operators to assess the factors $K_{ue}$ and $K'_{ue}$ for prevailing system conditions, a systematic method for its evaluation is not provided other than a rudimentary direction. This thesis initially examines, employing radial systems, the influence of line asymmetries on the global emission levels in medium voltage (MV) and high voltage (HV) power systems in the presence of various load types/bases including three-phase induction motors. It is shown that the factor $K'_{ue}$ is seen to be dependant not only on line parameters as evident from IEC/TR 61000-3-13, but also on the downstream load composition. In essence, the global emission levels in HV power systems is seen to arise as a result of both the local HV lines and the downstream MV lines in the presence of considerable proportions of induction motor loads. Eventually, generalised methodologies, covering both radial and interconnected networks, for the assessment of the global emission in MV and HV power systems which arises due to line asymmetries are proposed.

In allocating voltage unbalance based on the IEC/TR 61000-3-13 recommendations, quantitative measures of its propagation from higher voltage to lower voltage levels in terms of transfer coefficients, and from one busbar to other neighbouring busbar of a sub-system in terms of influence coefficients are required. IEC/TR 61000-3-13 gives a method for evaluating the MV to LV transfer coefficient suggesting a value less than unity for industrial load bases containing large proportions of mains connected three-phase induction motors, and a value of unity for passive loads in general. Upon detailed examination, it is noted that a transfer coefficient $> 1$ can arise in the presence of commonly prevailing constant power loads. Incorporating these different influences exhibited by various load types under unbalanced supply conditions on the propagation, comprehensive methods for assessing the MV to LV and HV to MV transfer coefficients are proposed. A systematic approach for estimating influence coefficients for interconnected network environments taking their dependency on the
downstream load composition into account is developed.

The IEC allocation policy with regard to harmonics and flicker has been found not to guarantee that the emission limits allocated to customers ensure non-exceedance of the set planning levels. This thesis reports that the above is an issue with voltage unbalance as well. Overcoming this problem, an alternative allocation technique referred to as ‘constraint bus voltage’ (CBV) method which closely aligns with the IEC approach has been suggested for harmonics and flicker. The work presented in this thesis extends the suggested CBV method to voltage unbalance allocation adding appropriate revisions to address the additional aspect of the emission which arises as a result of line asymmetries.

In the application of the IEC/TR 61000-3-13 principles to better manage existing networks already experiencing excessive voltage unbalance levels, the initial development of insights into the influences made by various sources of unbalance is required. Employing an existing 66kV interconnected sub-transmission system as the study case, deterministic studies are carried out in a systematic manner considering each of the asymmetrical elements. Approaches for studying the voltage unbalance behaviour exhibited by various sources which exist in interconnected network environments are established. These are employed to identify the most favourable line transposition options for the study system. Further, this knowledge that facilitates the identification of contributions made by individual unbalanced sources forms a platform for developing techniques to assess the compliance with emission limits, which is another subject of relevance to future editions of IEC/TR 61000-3-13.

As an essential tool for carrying out the studies, an unbalanced load flow program based on the phase coordinate reference frame incorporating the component level load flow constraints and the three-phase modelling of system components is developed.
# List of Principal Symbols and Abbreviations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a, b, c)</td>
<td>refer to the three phases</td>
</tr>
<tr>
<td>(\alpha)</td>
<td>summation law exponent</td>
</tr>
<tr>
<td>CBV</td>
<td>constraint bus voltage</td>
</tr>
<tr>
<td>CIGRE</td>
<td>International Council on Large Electric Systems</td>
</tr>
<tr>
<td>CIRED</td>
<td>International Conference on Electricity Distribution</td>
</tr>
<tr>
<td>(E_{s,x})</td>
<td>emission limit of any busbar (x) of any sub-system (S) [VUF]</td>
</tr>
<tr>
<td>(E_{s,x-j})</td>
<td>emission limit of any installation (j) to be connected at any busbar (x) of any sub-system (S) [VUF]</td>
</tr>
<tr>
<td>EHV</td>
<td>extra high voltage</td>
</tr>
<tr>
<td>(h_m)</td>
<td>refers to a HV-MV coupling transformer</td>
</tr>
<tr>
<td>HV</td>
<td>high voltage</td>
</tr>
<tr>
<td>(I)</td>
<td>refers to a constant current load</td>
</tr>
<tr>
<td>([I])</td>
<td>matrix of nodal currents</td>
</tr>
<tr>
<td>(I_{\lambda t})</td>
<td>(\lambda = 0, +, -) sequence current in any line (t) [A]</td>
</tr>
<tr>
<td>(I_{\lambda x})</td>
<td>(\lambda = 0, +, -) sequence component of (I_x) [A]</td>
</tr>
<tr>
<td>(I_x)</td>
<td>nodal current at any busbar (x) [A]</td>
</tr>
<tr>
<td>(I_{-\lambda x/e})</td>
<td>negative sequence current in any system element (e) (e = t, tf, busbar x) caused by any source of unbalance (c) (c = t, t_d, lines, U_x) [A]</td>
</tr>
<tr>
<td>IEC</td>
<td>International Electrotechnical Commission</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>(IM)</td>
<td>refers to a three-phase induction motor load</td>
</tr>
<tr>
<td>(k_a)</td>
<td>allocation constant</td>
</tr>
<tr>
<td>(k_{i-x})</td>
<td>influence coefficient from any busbar (i) to any other busbar (x)</td>
</tr>
</tbody>
</table>
\( k_{lv} \) fraction of LV loads supplied by any higher voltage (MV, HV) busbar

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

\( k_{mv} \) ratio between the rated motor load (in MVA) and the total load (in MVA) supplied by an MV system

\( k_{pq} \) ratio between the constant power load (in MVA) and the total load (in MVA) supplied by an LV system

\( k_{pqmv} \) ratio between the constant power load (in MVA) and the total load (in MVA) supplied by an MV system

\( k_s \) ratio between the positive and negative sequence impedances of the aggregated motor load supplied by an LV system

\( k_{sc-s} \) ratio between the short-circuit capacity (in MVA) at any busbar \( S \) and the total load (in MVA) supplied by the busbar \( S \)

\( k_z \) ratio between the constant impedance load (in MVA) and the total load (in MVA) supplied by an LV system

\( k_{zmv} \) ratio between the constant impedance load (in MVA) and the total load (in MVA) supplied by an MV system

\( K_{ue_{s,x}} \) fraction of the busbar emission allowance at any busbar \( x \) of any sub-system \( S \) that can be allocated to installations

\( K'_{ue_{s,x}} \) fraction of the busbar emission allowance at any busbar \( x \) of any sub-system \( S \) that accounts for the emission arising as a result of system inherent asymmetries

LF load flow

LV low voltage

\( ml \) refers to a MV-LV coupling transformer

MV medium voltage

NECA National Electricity Code Australia

NEMA National Equipment Manufacturer’s Association

PCC point of common coupling

\( PQ \) refers to a constant power load

\( PS \) refers to a passive load
rec receiving end busbar of any line \( t \)

\( S \) represents any sub-system (\( S = HV, MV, LV \))

\( S_{sc, S} \) short-circuit capacity at any busbar \( S \) [MVA]

\( S_{s,x} \) total apparent power to be supplied by any busbar \( x \) of any sub-system \( S \) [MVA]

\( S_{s,x-ds} \) part of \( S_{s,x} \) supplied at the downstream (DS) [MVA]

\( S_{s,x-j} \) agreed apparent power of any installation \( j \) to be connected at any busbar \( x \) of any sub-system \( S \) [MVA]

\( S_{s,x-local} \) part of \( S_{s,x} \) supplied locally [MVA]

\( S_{s,x-total} \) total apparent power, as seen at any busbar \( x \) of any sub-system \( S \), to be supplied by the sub-system \( S \) [MVA]

\( send \) sending end busbar of any line \( t \)

\( t \) any radial local line of any sub-system under evaluation

\( t_d \) any radial downstream line of any sub-system under evaluation

\( t_{ij} \) any line between busbars \( i \) and \( j \) of any sub-system under evaluation

\( tf \) refers to a coupling transformer

\( T_{us-S} \) US to S transfer coefficient

\( \theta_{pf-x} \) power factor angle at any busbar \( x \) [deg.]

\( \theta_{pf:z, pf:pq} \) power factor angle of the constant impedance and constant power loads respectively supplied by an LV system [deg.]

\( \theta_{pf:zmv, pf:pqm} \) power factor angle of the constant impedance and constant power loads respectively supplied by an MV system [deg.]

\( \theta_{Y_{-+:x}} \) phase angle of the admittance \( Y_{-+:x} \) [deg.]

\( \theta_{Z_{-+:t_d}} \) phase angle of the impedance \( Z_{-+:t_d} \) [deg.]

\( \theta_{Z_{\lambda\Delta:t}} \) phase angle of the impedance \( Z_{\lambda\Delta:t} \) [deg.]

\( \theta_{I_{\lambda:t}} \) phase angle of the current \( I_{\lambda:t} \) [deg.]

\( U_{g/s} \) global emission allowance of any sub-system \( S \) [VUF]

\( U_{g/s:x} \) emission allowance of any busbar \( x \) of any sub-system \( S \) [VUF]

\( U_{loads_{g/s:x}} \) global emission arising as a result of unbalanced installations at any busbar \( x \) of any sub-system \( S \) [VUF]
$U_{\text{lines}}_{g/s:x}$: global emission arising as a result of system inherent asymmetries at any busbar $x$ of any sub-system $S$ [VUF]

$U_{j/s:x}$: emission level caused by any source of unbalance $j$ at any busbar $x$ of any sub-system $S$ [VUF]

$U_{\text{result}}_{s:x}$: resultant emission level at any busbar $x$ of any sub-system $S$ [VUF]

$U_s$: voltage unbalance at any busbar $x$ [VUF]

UIE: International Union for Electricity Applications

US: represents any upstream system of any sub-system $S$ (US = EHV, HV, MV)

$[V]$: matrix of nodal voltages

$V_{\lambda x}$: $\lambda (= 0, +, -)$ sequence component of $V_x$ [V]

$V_{\lambda:us}$: $\lambda (= 0, +, -)$ sequence voltage, referred to US, at any busbar $S$ [V]

$V_n$:$s$: nominal line-line voltage of any sub-system $S$ [V]

$V_s$: voltage at any busbar $x$ [V]

$V_{\text{lines}}_{-g/s:x}$: global negative sequence voltage arising as a result of line asymmetries at any busbar $x$ of any sub-system $S$ [V]

$V_{-U_i/x}$: negative sequence voltage at any busbar $x$ caused by the voltage unbalance $U_i$ that exists at any other busbar $i$

$VR_t$: voltage regulation of any line $t$

$VR_{td}$: voltage regulation of any line $t_d$

VUF: voltage unbalance factor [%]

$[Y]$: matrix of nodal admittances

$Y_{\lambda\Delta:xy}$: $\lambda - \Delta (\lambda, \Delta = 0, +, -)$ sequence coupling admittance component of $Y_{xy}$ [S]

$Y_{xy}$: nodal admittance between any busbar $x$ and any other busbar $y$ [S]

$Y_{-\Delta;x-im}$: downstream negative sequence admittance seen at any busbar $x$ taking only induction motors into account [S]

$Y_{-+:x}$: downstream negative-positive sequence coupling admittance seen at any busbar $x$ [S]
$Z$ refers to a constant impedance load

$Z_{\lambda\Delta:t}$ $\lambda - \Delta$ ($\lambda, \Delta = 0, +, -$) sequence coupling impedance of any line $t$ [Ω]

$Z_{\lambda:x}$ downstream $\lambda$ ($\lambda = 0, +, -$) sequence impedance seen at any busbar $x$ [Ω]

$Z_{\lambda:tf-s}$ $\lambda$ ($\lambda = 0, +, -$) sequence impedance, referred to $S$, of any coupling transformer [Ω]

$Z_{-:-x-im}$ downstream negative sequence impedance seen at any busbar $x$ taking only induction motors into account [Ω]

$Z_{-:+t_d}$ negative-positive sequence coupling impedance of any line $t_d$ [Ω]

$Z_{-:+t_d-us}$ negative-positive sequence coupling impedance, referred to US, of any line $t_d$ [Ω]

0, +, − refer to zero, positive and negative sequences respectively
Publications Arising from the Thesis


# Table of Contents

1 Introduction
   1.1 Statement of the Problem .................................................. 1
   1.2 Research Objectives and Methodologies .................................. 4
   1.3 Outline of the Thesis ....................................................... 6

2 Literature Review
   2.1 Introduction ................................................................. 10
   2.2 Definition of Voltage Unbalance .......................................... 11
   2.3 Sources of Voltage Unbalance .......................................... 13
   2.4 Effects of Voltage Unbalance .......................................... 14
   2.5 Mitigation Techniques of Voltage Unbalance ......................... 17
   2.6 Measurement and Indices of Voltage Unbalance ..................... 18
   2.7 Limits of Voltage Unbalance ............................................. 21
      2.7.1 Compatibility Levels ................................................ 21
      2.7.2 Voltage Characteristics ......................................... 22
      2.7.3 Planning Levels .................................................... 25
      2.7.4 Customer Emission Limits ....................................... 26
   2.8 Guiding Principles of IEC/TR 61000-3-13 [1] for Voltage Unbalance
      Emission Allocation ...................................................... 27
      2.8.1 Basic Concepts Used in IEC/TR 61000-3-13 .................. 28
      2.8.2 Emission Limits: Stages 1, 2 and 3 .......................... 30
      2.8.3 Development of Stage 2 Emission Limits ..................... 31
      2.8.4 Voltage Unbalance Transfer Coefficients .................... 39
      2.8.5 Factor $K'ue$ ....................................................... 41
   2.9 A Revised Harmonics/Flicker Allocation Technique Based on the IEC
      Guidelines - A Preamble to Voltage Unbalance Allocation .......... 43
   2.10 Chapter Summary .......................................................... 47

3 Global Voltage Unbalance in MV Power Systems due to System Inherent
   Asymmetries ................................................................. 49
   3.1 Introduction ................................................................. 49
   3.2 Influence of Line Asymmetries on the Global Emission and its Depen-
      dency on Load Types/Bases ......................................... 52
      3.2.1 Constant Impedance ($Z$) Loads ................................ 54
      3.2.2 Constant Current ($I$) Loads .................................... 55
      3.2.3 Constant Power ($PQ$) Loads .................................... 55
      3.2.4 Induction Motor ($IM$) Loads .................................... 56
      3.2.5 Discussion ........................................................... 57
      3.2.6 Mixes of Passive and Induction Motor Loads ................ 58
   3.3 Methodology for Evaluating the Global Emission Arising Due to Line
      Asymmetries ............................................................... 60
3.4 Verification of the Methodology .............................................. 66
3.5 Chapter Summary ................................................................. 68

4 Global Voltage Unbalance in HV Power Systems due to System Inherent Asymmetries ................................................................. 70
4.1 Introduction ................................................................. 70
4.2 Influence of Line Asymmetries on the Global Emission in the Presence of Induction Motor Loads ...................................................... 74
4.3 Methodology for Evaluating the Global Emission Arising Due to Line Asymmetries ................................................................. 79
4.4 Verification of the Methodology Using a Three-bus Test System ... 85
4.5 Verification of the Methodology Using the IEEE 14-bus Test System . 89
4.6 Chapter Summary ................................................................. 90

5 Propagation of Voltage Unbalance ................................................... 94
5.1 Introduction ................................................................. 94
5.2 Voltage Unbalance Transfer Coefficients ..................................... 97
  5.2.1 MV to LV Transfer Coefficient, $T_{mv-lv}$ .................................. 103
  5.2.2 HV to MV Transfer Coefficient, $T_{hv-mv}$ .................................. 110
5.3 Voltage Unbalance Influence Coefficients .................................... 117
  5.3.1 Preliminary Investigations - Dependency of Influence Coefficients on Load Types/Bases ...................................................... 117
  5.3.2 Methodology for Evaluating Influence Coefficients ..................... 121
  5.3.3 Verification of the Methodology Using a Three-bus MV Test System ................................................................. 125
  5.3.4 Verification of the Methodology Using the IEEE 14-bus Test System ................................................................. 126
5.4 Chapter Summary ................................................................. 129

6 A Revised Voltage Unbalance Allocation Technique Based on the IEC/TR 61000-3-13 Guidelines ................................................... 131
6.1 Introduction ................................................................. 131
6.2 Examination of the IEC/TR 61000-3-13 Approach ......................... 132
  6.2.1 Calculation of Individual Emission Limits .................................. 134
  6.2.2 Resulting Busbar Emission Levels and Examination Remarks 138
6.3 A Revised Voltage Unbalance Allocation Technique Based on the CBV Allocation Principles ................................................... 139
6.4 Examination of the Revised Voltage Unbalance Allocation Technique ................................................... 142
  6.4.1 Calculation of Individual Emission Limits .................................. 142
  6.4.2 Resulting Busbar Emission Levels and Examination Remarks 144
6.5 Chapter Summary ................................................................. 146
7 Analysis of the Problem of Voltage Unbalance in Interconnected Power Systems 147
  7.1 Introduction ............................................................. 147
  7.2 Voltage Unbalance Behaviour of Line Asymmetries ............... 150
    7.2.1 Impact of the Line Asymmetries of the Study System on the
          Voltage Unbalance Problem .................................... 150
    7.2.2 Voltage Unbalance Behaviour of the Individual Lines of the
          Study System - as Standalone Lines ............................ 152
    7.2.3 Voltage Unbalance Behaviour of the Individual Lines of the
          Study System - as Elements in the Interconnected Network . 155
    7.2.4 General Outcomes - Representation of the Voltage Unbalance
          Behaviour of an Asymmetrical Line as an Element in an Inter-
          connected Network ............................................... 160
    7.2.5 General Outcomes - Representation of the Interaction of All
          Asymmetrical Lines ................................................. 160
  7.3 Voltage Unbalance Behaviour of Load Asymmetries ............... 167
    7.3.1 Impact of the Load Asymmetries of the Study System on the
          Voltage Unbalance Problem .................................... 167
    7.3.2 Voltage Unbalance Behaviour of the Individual Loads of the
          Study System - as Elements in the Interconnected Network . 169
    7.3.3 General Outcomes ............................................... 174
  7.4 Combined Voltage Unbalance Behaviour of Line and Load Asymmetries176
    7.4.1 Combined Impact of the Line and Load Asymmetries of the
          Study System on the Voltage Unbalance Problem .......... 176
    7.4.2 Representation of the Voltage Unbalance Behaviour of the En-
          tire System ....................................................... 176
  7.5 Chapter Summary .................................................... 181

8 Conclusions and Recommendations for Future Work 184
  8.1 Conclusions ............................................................ 184
  8.2 Recommendations for Future Work .................................. 191

Appendices
A Derivation of (3.5) ...................................................... 204
B Radial MV-LV Test System
   (Fig. 3.2) ............................................................... 207
C Derivation of (3.14) ...................................................... 209
D $Y_{--:x--:im}$ for an MV Network .................................... 212
E Application of the Methodology Given by (3.25) to the Three-bus MV Test
   System (Fig. 3.7) ...................................................... 214
# List of Figures

2.1 Derating of three-phase induction motors (UIE) .......................... 15
2.2 Statistical interpretation of the compatibility level (IEC 61000-2-2, IEC 61000-2-12) .................................................. 22
2.3 Statistical interpretation of the planning level (IEC 61000-2-2, IEC 61000-2-12) .................................................. 25
2.4 Interpretation of the emission level (IEC/TR 61000-3-13) ......... 30
2.5 Illustration of the global emission allowance (IEC/TR 61000-3-13) ... 35
2.6 Interconnected sub-system S .................................................. 37
2.7 System representation of any busbar $x$ of the system $S$ shown in Fig. 2.6 37
2.8 Variation of $T_{mv-tv}$ with $k_m$ established using (2.17) for various combinations of $k_s$ and $k_{sc-tv}$ values ......................... 40
3.1 Simple MV network .......................................................... 51
3.2 Radial MV-LV system ...................................................... 53
3.3 Variation of $|V_{g/mv-rec}^{t}|$ with $|I_{t-d}^{t}|$ (2.14) values corresponding to various $|I_{t-d}^{t}|$ are indicated) for the four basic load types 57
3.4 Variation of $U_{g/mv-rec}^{t}$ with $k_m$ for the cases where $k_{tv} = 1$, $k_{tv} = 0.5$ and $k_{tv} = 0$ ............................................. 61
3.5 Interconnected MV sub-system ......................................... 61
3.6 System representation of any busbar $x$ of the MV system shown in Fig. 3.5 ................................................................. 62
3.7 Three-bus MV test system considered for applying the proposed methodology .............................................................. 67
3.8 Emissions $U_{g/mv:2}$ for the three-bus MV test system for the two cases where $k_{m:2} = 0$ and $k_{m:2} = 1$ .................................. 68
4.1 Simple HV network .......................................................... 72
4.2 Radial HV-MV-LV system .................................................. 75
4.3 Variation of $U_{g/hv-rec}^{t+k} + I_{g/hv-rec}^{t+k}$ with $k_{fr}$ for the two cases where $k_{mr} = 0$ and $k_{mr} = 1$ ................................... 79
4.4 Interconnected HV sub-system ......................................... 80
4.5 System representation of any busbar $x$ of the HV system shown in Fig. 4.4 ................................................................. 81
4.6 Three-bus HV test system considered for applying the proposed methodology .............................................................. 86
4.7 Emissions $U_{g/hv:2}$ for the three-bus HV test system for the cases where $k_{m:2} = 0$ and $k_{m:2} = 1$ .................................. 88
4.8 Emissions $U_{g/hv:2}$ for the three-bus HV test system for the case where $k_{m:2} = 1$ in relation to the Phase arrangements I and II of the MV lines 89
4.9 IEEE 14-bus test system ...................................................... 91
4.10 Emissions $U_{g/hv:2}$ for the IEEE 14-bus test system 91
5.1 Variation of $T_{mv-lv}$ with $k_{sc-lv}$ obtained for constant power loads using unbalanced load flow analysis ........................................ 95
5.2 Radial system considered for the illustration of transfer coefficients ........ 97
5.3 Variation of $T_{mv-lv}$ with $k_{sc-lv}$ for constant current loads: I - 0.99 lagging pf, II - 0.9 lagging pf .................................................. 104
5.4 Variation of $T_{mv-lv}$ with $k_{sc-lv}$ for constant power loads: I - 0.99 lagging pf, II - 0.9 lagging pf .................................................. 104
5.5 Variation of $T_{mv-lv}$ with $k_{sc-lv}$ for induction motor loads with $k_s = 6.7$ and pf = 0.9 lagging ......................................................... 106
5.6 Variation of $T_{mv-lv}$ with $k_{sc-lv}$: I - for a load base dominated by induction motors, II - for a load base dominated by passive elements .... 108
5.7 Variation of $T_{mv-lv}$ with $k_m$ for $k_{sc-lv} = 25$ and $k_{sc-lv} = 10$: I - for load mixes of Z and IM loads, II - for load mixes of PQ and IM loads 109
5.8 Variation of $T_{mv-lv}$ with $k_m$ established using the IEC method, (5.19), (5.20) and unbalanced load flow analysis ........................................ 110
5.9 Variation of $T_{hv-mv}$ with $k_{mv}$ for $k_{sc-mv} = 12$ (loads are supplied directly at the MV busbar): I - for load mixes of Z and IM loads, II - for load mixes of PQ and IM loads ................................................ 115
5.10 Variation of $T_{hv-mv}$ with $k_{mv}$ for $k_{sc-mv} = 4$ (loads are supplied directly at the MV busbar): I - for load mixes of Z and IM loads, II - for load mixes of PQ and IM loads ................................................ 116
5.11 Variation of $T_{hv-mv}$ with $k_{mv}$ (LV loads are supplied through MV lines): I - for $k_{sc-mv} = 12$, II - for $k_{sc-mv} = 4$ ................................................ 116
5.12 Radial MV-LV system (reproduction of Fig. 3.2) .................................... 117
5.13 Variation of $k_{send-rec}$ with $k_m$ for the cases where $k_{mv} = 1$, $k_{mv} = 0.5$ and $k_{mv} = 0$ ......................................................... 121
5.14 Interconnected sub-system S (reproduction of Fig. 2.6) .......................... 122
5.15 System representation of any busbar $x$ of the MV system shown in Fig. 5.14 (reproduction of Fig. 3.6) .............................................. 124
5.16 Three-bus MV test system considered for applying the proposed methodology (reproduction of Fig. 3.7) .......................................... 127
5.17 Variations of $k_{1-2}$ and $k_{1-3}$ with $k_{m;2}$ for the three-bus MV test system 127
5.18 IEEE 14-bus test system (reproduction of Fig. 4.9) .............................. 128
5.19 Influence coefficients $k_{4-x}$ ($x = 1 - 14$, $x \neq 4$) for the IEEE 14-bus test system ................................................................. 128

6.1 Three-bus HV test system considered for examining the IEC/TR 61000-3-13 approach ............................................................. 133
6.2 A comparison of the influence coefficients for the test system derived using the proposed method: (5.37), and unbalanced load flow analysis 135
6.3 A comparison of the $K'_{ue_x}$ factors for the test system derived using the proposed method: (4.16), and unbalanced load flow analysis ........ 138
6.4 Comparison of the busbar emission limits $E_{hv;x}$ derived according to IEC/TR 61000-3-13 and the revised method for the test system: I - for Case 1, II - for Case 2 ................................. 144
6.5 Comparison of the resulting emission levels $U_{reulx}$ derived according to IEC/TR 61000-3-13 and the revised method for the test system: I - for Case 1, II - for Case 2 ................................. 145

7.1 66kV sub-transmission interconnected system under study ................. 148
7.2 Measured nodal VUF values for the study system ............................... 149
7.3 Nodal VUF values (load flow results) which arise as a result of the line asymmetries, in comparison to the measured values .............................. 151
7.4 Variation of $|V_{t-rec}^{−}|$ with $|I_{+,t}^{−}|$ for the individual lines ............... 153
7.5 Variation of $\theta_{V_{t-rec}}$ with $|I_{+,t}|$ for the individual lines ...................... 154
7.6 Nodal VUF values arising as a result of the individual lines ................. 157
7.7 Phase angles of the nodal negative sequence voltages introduced by the individual lines ................................................................. 158
7.8 Global emission vectors of the individual lines (drawn approximately to a scale) ................................................................. 161
7.9 Resultant influence of the interaction of all asymmetrical lines (drawn approximately to a scale) ................................................................. 162
7.10 Nodal contributions made by the individual lines to the resultant voltage unbalance levels ................................................................. 164
7.11 (I) Deduced from Fig. 7.8 (II) Effect of the transposition of line F only (III) Effect of the transposition of lines A and F together (drawn approximately to a scale) ................................................................. 165
7.12 Effects, obtained using unbalanced load flow analysis, of the transposition of line F only, and lines A and F together ................................. 166
7.13 Nodal VUF values which arise as a result of the load asymmetries, in comparison to that of the line asymmetries ........................................ 168
7.14 Nodal VUF values which arise as a result of the individual loads ............ 170
7.15 Phase angles of the nodal negative sequence voltages introduced by the individual loads ................................................................. 171
7.16 Global emission vectors of the individual loads (drawn approximately to a scale) ................................................................. 173
7.17 Resultant influence of the interaction of all unbalanced loads (drawn approximately to a scale) ................................................................. 175
7.18 Nodal VUF values which arise as a result of both the line and load asymmetries, in comparison to that of the line asymmetries alone, and the load asymmetries alone, and also to the measured values ................................. 177
7.19 Resultant influence of the interaction of all lines and loads (drawn approximately to a scale) ................................................................. 178
7.20 Nodal contributions made by the line and load asymmetries to the overall voltage unbalance levels ................................................................. 179
7.21 Nodal contributions made by the individual sources of unbalance to the overall voltage unbalance levels ........................................ 181

O.1 Synchronous generator model ........................................... 252
O.2 Load model ................................................................. 255
O.3 Equivalent circuit of a voltage regulator/transformer ............. 257
O.4 Three-phase induction motor model proposed in [4, 5] .......... 257
O.5 Variation of the real (P) and reactive (Q) power with the supply voltage level for a typical three-phase induction motor ............. 259
O.6 Variation of the real (P) and reactive (Q) power with $k_p$ (motor loading levels corresponding to various $k_p$ is also given as a percentage to the rated output power) for a 2250hp induction motor .................. 260
O.7 Variation of the speed with $k_p$ (motor loading levels corresponding to various $k_p$ is also given as a percentage to the rated output power) for a 2250hp induction motor .................. 261
O.8 Impedance type induction motor model ............................ 261
O.9 PQ type induction motor model ....................................... 262
O.10 Sequence equivalent circuits of a three-phase induction motor: I - positive sequence, II - negative sequence ......................... 263
O.11 Variation of $P'_x - xx$ with $\omega_{rt}$ for the 3hp, 220V motor 270
O.12 Variation of $Q'_x - xx$ with $\omega_{rt}$ for the 3hp, 220V motor 271
O.13 Variation of $\eta_{im}$ with $\omega_{rt}$ for the 3hp, 220V motor 275
O.14 Variation of the per phase input active and reactive power with the motor loading level for the 3hp, 220V motor excited at the rated voltage (balanced) ......................................................... 277
O.15 Variation of the per phase input active and reactive power components with the motor loading level for the 3hp, 220V motor excited at reduced and unbalanced voltages ................................. 277
O.16 Variation of the per phase input active and reactive power components with the motor loading level for a 2250hp, 2.3kV motor excited at reduced and unbalanced voltages ................................. 278
O.17 Variation of $P_{im,a}$ with $k_p$ for the existing and proposed induction motor models ...................................................... 278
O.18 Variation of $Q_{im,a}$ with $k_p$ for the existing and proposed induction motor models ...................................................... 279
List of Tables

2.1 Requirements of background disturbances in assessing the uncertainty of Class A instruments for the measurement of voltage unbalance (IEC 61000-4-30) .......................................................... 20
2.2 Indicative planning levels given in IEC/TR 61000-3-13 .......................... 29
2.3 Indicative values for the factor $K'u_e$ given in IEC/TR 61000-3-13  .... 42

6.1 Influence coefficients for the test system shown in Fig. 6.1 ..................... 135
6.2 $S_{hv,x}$, $S_{hv,x-total}$ and $U_{g/hv,x}$ for the test system shown in Fig. 6.1 .... 135
6.3 $U_{lines}^{g/hv,x}$, $K'u_e$ and $K'u_e$ for Case 2 of the test system shown in Fig. 6.1 137
6.4 $E_{hv,x}$ according to IEC/TR 61000-3-13 for the test system shown in Fig. 6.1 ................................................................. 137
6.5 $U_{reult}^{g/hv,x}$ arising as a result of the IEC/TR 61000-3-13 allocation procedure for the test system shown in Fig. 6.1 ................................. 139
6.6 Values of the RHS of (6.8) in relation to the test system shown in Fig. 6.1 .......................... 143
6.7 $k_a$ for the test system shown in Fig. 6.1 ........................................ 143
6.8 $K'u_e$ and $E_{hv,x}$ according to the revised allocation method for the test system shown in Fig. 6.1 ................................................................. 143
6.9 $U_{reult}^{g/hv,x}$ arising as a result of the revised allocation procedure for the test system shown in Fig. 6.1 ................................................................. 144

7.1 Ranking of the sub-transmission lines based on the associated degree of asymmetry ................................................................. 154
7.2 Parameters, operating features and emission levels of the individual lines ................................................................. 159
7.3 Distribution of the active and reactive power across the three phases at each of the load busbars of the study system ............................................. 167
7.4 Operating features and emission levels of the individual loads of the study system ................................................................. 171

H.1 Values of $k_{sc-lvr-agg}$ and $\sigma$ for various $k_{lvr}$ .................................. 226

K.1 Voltage controlled bus data ............................................................... 233
K.2 Static capacitor data: susceptances ........................................................ 233
K.3 Generator and load bus data: three-phase MW and MVAr values ....... 234
K.4 Transformer data: impedances and secondary tap settings (1st and 2nd bus numbers refer to the primary and the secondary respectively) .... 234
K.5 Nodal positive sequence voltages ........................................................ 235
K.6 Transmission line data: lengths and impedances .................................... 236

L.1 Replacement factors for a mix of various load types .............................. 239

N.1 System details ........................................................................ 243
N.2 Voltage controlled bus data ........................................... 244
N.3 Generator and load bus data: three-phase MW and MVAr values .. 244
N.4 Voltage regulator data: impedances and secondary tap settings .... 245
N.5 Static capacitor data: susceptances .................................. 245
N.6 Generator impedance data .............................................. 245
N.7 Lengths and impedances ($Z_{-+}$ and $Z_{++}$) of the sub-transmission lines 246
N.8 Negative sequence voltages $V_{t:S2}^{-}$ caused by the individual lines A - N at the busbar S2 .................................................. 248
N.9 Resultant negative sequence voltage $V_{lines}^{-:S2}$ at the busbar S2 . . . 248

O.1 Parameters of a 60Hz, 3hp, 220V induction motor .................... 270
O.2 Power components $P_{x-xx}^{n}$ - $Q_{x-xx}^{n}$ for the 3hp, 220V motor ........ 270
O.3 Speed coefficients corresponding to the power components $P_{x-xx}$ - $Q_{x-xx}$ for a range of induction motors ............................. 272
O.4 Efficiency coefficients for a range of induction motors ............... 275