

2009

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

Prabodha Paranavithana
University of Wollongong

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author.

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Paranavithana, Prabodha, Contributions towards the development of the Technical Report IEC/TR 61000-3-13 on voltage unbalance emission allocation, PhD thesis, School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, 2009. <http://ro.uow.edu.au/theses/834>

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

**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 Parनावithana, BSc(Eng)

**School of Electrical, Computer and Telecommunications
Engineering**

March 2009

Acknowledgements

It is a pleasure to be able to thank many people to whom I am indebted for the development of this thesis.

First and foremost, I wish to express my utmost gratitude to my principal supervisor, Associate Professor Sarath Perera of the University of Wollongong (UoW), for enabling me to pursue postgraduate studies at the University of Wollongong and the support given throughout the study period in many ways. Your dedication, patience, knowledge and experience could not have been surpassed. I admire your guidance towards growing me up academically and personally over last few years.

Thanks to my co-supervisor, Professor Danny Sutanto of the UoW, for the assistance provided. I would also like to offer many appreciations to Dr. Duane Robinson of Beca, Australia for proofreading this thesis. To Mr. Robert Koch of Eskom Holdings Limited, South Africa and Dr. Zia Emin of National Grid Electricity Transmission, United Kingdom go many thanks for their insightful technical contributions and helpful attitude. LATEX assistance received from Dr. Timothy Browne, previously with the Integral Energy Power Quality and Reliability Centre (IEPQRC) at the UoW, is much appreciated.

Funding for this project was provided by SP AusNet, Victoria and the IEPQRC. I am grateful to Mr. Dhammika Adihetti, Mr. Shiva Bellur and Mr. Sanath Peiris of SP AusNet for arraigning this. Many thanks to Mr. Jeff Sultana, Mr. Shem Cardosa and Mr. Mahinda Wickramasuriya of SP AusNet for the support given in collecting the required data for Chapter 7 of this thesis.

Thanks to Dr. Vic Smith and Sean Elphick of the IEPQRC who have graciously responded to many administrative and software related requests. My thanks also go to Roslyn Causer-Temby of the School of Electrical, Computer and Telecommunications

Engineering (SECTE) at the UoW, Tracey O'Keefe and Maree Burnett who are former members of the SECTE staff, and Esperanza Riley of the IEPQRC for solving many administrative problems and providing perspective. The SECTE workshop staff have cheerfully provided the technical assistance.

Very special thanks go to my friend Dr. Sankika Tennakoon, previously with the IEPQRC, for being generously supportive especially during hard times along the way. Your contribution to my PhD experience is also appreciated.

My heartiest gratitude goes to my parents Mithrananda and Manike for all encouragements, guidance and sacrifices made on behalf of me to come this far. Finally, my thanks go to the rest of my family and friends particularly Pinky, Dimuthu, Radley, Matthew and Nishad for being supportive in many ways.

Certification

I, Prabodha Paronavithana, 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 Paronavithana

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 ' Kue ' to the apportioned allowance. This factor Kue represents the fraction of the global emission allowance that can be allocated to customers, whereas the factor $K'ue$ ($= 1 - Kue$) 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

a, b, c	refer to the three phases
α	summation law exponent
CBV	constraint bus voltage
CIGRE	International Council on Large Electric Systems
CIRED	International Conference on Electricity Distribution
$E_{s:x}$	emission limit of any busbar x of any sub-system S [VUF]
$E_{s:x-j}$	emission limit of any installation j to be connected at any busbar x of any sub-system S [VUF]
EHV	extra high voltage
hm	refers to a HV-MV coupling transformer
HV	high voltage
I	refers to a constant current load
$[I]$	matrix of nodal currents
$I_{\lambda:t}$	λ ($= 0, +, -$) sequence current in any line t [A]
$I_{\lambda:x}$	λ ($= 0, +, -$) sequence component of I_x [A]
I_x	nodal current at any busbar x [A]
$I_{-:c/e}$	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]
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IM	refers to a three-phase induction motor load
k_a	allocation constant
k_{i-x}	influence coefficient from any busbar i to any other busbar x

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
$k_{m_{mv}}$	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
$k_{pq_{mv}}$	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
$k_{z_{mv}}$	ratio between the constant impedance load (in MVA) and the total load (in MVA) supplied by an MV system
$Kue_{s:x}$	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.]
$\theta_{pf:z}, \theta_{pf:pq}$	power factor angle of the constant impedance and constant power loads respectively supplied by an LV system [deg.]
$\theta_{pf:z_{mv}}, \theta_{pf:pq_{mv}}$	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]
$U_{g/s:x}^{loads}$	global emission arising as a result of unbalanced installations at any busbar x of any sub-system S [VUF]

$U_{g/s:x}^{lines}$	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]
$U_{s:x}^{result}$	resultant emission level at any busbar x of any sub-system S [VUF]
U_x	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
$V_{\lambda:x}$	λ ($= 0, +, -$) sequence component of V_x [V]
$V_{\lambda:s-us}$	λ ($= 0, +, -$) sequence voltage, referred to US, at any busbar S [V]
V_{n-s}	nominal line-line voltage of any sub-system S [V]
V_x	voltage at any busbar x [V]
$V_{-:g/s:x}^{lines}$	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_{t_d}	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]
$Y_{--:x-im}$	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]
$Z_{\lambda\lambda:x}$	downstream λ ($\lambda = 0, +, -$) sequence impedance seen at any busbar x [Ω]
$Z_{\lambda\lambda:tf-s}$	λ ($\lambda = 0, +, -$) 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

1. Prabodha Paranavithana, Sarath Perera, and Danny Sutanto. Impact of Untransposed 66kV Sub-transmission Lines on Voltage Unbalance. In *Proc. Australasian Universities Power Engineering Conference (AUPEC 2006)*, paper 28, Melbourne, Australia, December 2006.
2. P. Paranavithana, S. Perera, and D. Sutanto. Analysis of System Asymmetry of Interconnected 66kV Sub-transmission Systems in relation to Voltage Unbalance. In *Proc. IEEE Power Engineering Society Conference and Exposition in Africa (PowerAfrica '07)*, Johannesburg, South Africa, July 2007.
3. Prabodha Paranavithana, Sarath Perera, Danny Sutanto, and Robert Koch. A Systematic Approach Towards Evaluating Voltage Unbalance Problem in Interconnected Sub-transmission Networks: Separation of Contribution by Lines, Loads And Mitigation. In *Proc. 13th IEEE International Conference on Harmonics and Quality of Power (ICHQP 2008)*, Wollongong, Australia, September-October 2008.
4. Prabodha Paranavithana, Sarath Perera, and Robert Koch. An Improved Methodology for Determining MV to LV Voltage Unbalance Transfer Coefficient. In *Proc. 13th IEEE International Conference on Harmonics and Quality of Power (ICHQP 2008)*, Wollongong, Australia, September-October 2008.
5. Robert Koch, Alex Baith, Sarath Perera, and Prabodha Paranavithana. Voltage Unbalance Emission Limits for Installations - General Guidelines and System Specific Considerations. In *Proc. 13th IEEE International Conference on Harmonics and Quality of Power (ICHQP 2008)*, Wollongong, Australia, September-October 2008.

6. Prabodha Parनावithana, Sarath Perera, and Danny Sutanto. Management of Voltage Unbalance Through Allocation of Emission Limits to Installations. In *Proc. Australasian Universities Power Engineering Conference (AUPEC 2008)*, paper 017, Sydney, Australia, December 2008.
7. Prabodha Parनावithana, Sarath Perera, and Robert Koch. Propagation of Voltage Unbalance from HV to MV Power Systems. In *Proc. 21st International Conference on Electricity Distribution (CIRED 2009)*, paper 0497, Prague, June 2009.
8. Prabodha Parनावithana, Sarath Perera, and Robert Koch. A Generalised Methodology for Evaluating Voltage Unbalance Influence Coefficients. In *Proc. 21st International Conference on Electricity Distribution (CIRED 2009)*, paper 0500, Prague, June 2009.
9. Prabodha Parनावithana and Sarath Perera. Location of Sources of Voltage Unbalance in an Interconnected Network. In *Proc. IEEE Power Engineering Society General Meeting (panel session on “Developments in Determining Power Quality Disturbance Sources and Harmonic Source Contributions”)*, Calgary, Alberta, Canada, July 2009.
10. Prabodha Parनावithana and Sarath Perera. A Robust Voltage Unbalance Allocation Methodology Based on the IEC/TR 61000-3-13 Guidelines. In *Proc. IEEE Power Engineering Society General Meeting*, Calgary, Alberta, Canada, July 2009.
11. P. Parनावithana, S. Perera, R. Koch, and Z. Emin. Global Voltage Unbalance in MV Power Systems due to Line Asymmetries. Accepted for publication in *IEEE Trans. on Power Delivery*.

12. P. Parnavithana, S. Perera, R. Koch, and Z. Emin. Global Voltage Unbalance in HV Power Systems due to Line Asymmetries: Dependency on Loads And an Evaluation Methodology. Accepted for publication in *IEEE Trans. on Power Delivery*.
13. Prabodha Parnavithana, Sarath Perera, and Danny Sutanto. Management of Voltage Unbalance Through Allocation of Emission Limits to Installations. Accepted for publication in Australian Journal of Electrical and Electronics Engineering (reproduction of *Proc. AUPEC 2008*).

Table of Contents

1	Introduction	1
1.1	Statement of the Problem	1
1.2	Research Objectives and Methodologies	4
1.3	Outline of the Thesis	6
2	Literature Review	10
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 Interconnected 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 Asymmetries	176
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 Entire 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

	xx
F Derivation of (4.7)	218
G Derivation of (4.9)	221
H Test Case Description of the Radial HV-MV-LV System (Fig. 4.2)	224
I $Y_{-+:x}$ for an HV Network	227
J Application of the Methodology Given by (3.22) to the Three-bus HV Test System (Fig. 4.6)	229
K Data of the IEEE 14-bus Test System (Fig. 4.9)	233
L Derivation of (5.18)	237
M Application of the Methodology Given by (5.37) to the Three-bus MV Test System (Fig. 5.16)	240
N 66kV Sub-transmission Interconnected Study System (Fig. 7.1) - Additional Data/Information	243
N.1 Operating Conditions at the Considered Time Stamp	243
N.2 Line Data	246
N.3 An Explanation on the Influence of the Location of an Asymmetrical Line of an Interconnected Network on the Voltage Unbalance Behaviour of the Line	246
N.4 A Demonstration of the Linearity of Negative Sequence Voltages	247
O Development of a Method for Unbalanced Load Flow Analysis	249
O.1 Introduction	249
O.2 Symmetrical Component Versus Phase Coordinate Reference Frames for Unbalanced Load Flow Analysis	250
O.3 Special Considerations in Developing an Unbalanced Load Flow Program	250
O.4 Representation of System Components	251
O.4.1 Synchronous Generators	251
O.4.2 Passive Loads	254
O.4.3 Overhead Lines	255
O.4.4 Capacitor Banks	256
O.4.5 Three-phase Voltage Regulators/Transformers	256
O.4.6 Three-phase Induction Motors	256
O.4.7 Network Interactions	280
O.5 Load Flow Solution	280
O.6 Related References	281

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-lv} with k_m established using (2.17) for various combinations of k_s and k_{sc-lv} 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} $ (VR_t values corresponding to various $ I_{+:t} $ are also indicated) for the four basic load types	57
3.4	Variation of $U_{g/mv:rec}^t$ with k_m for the cases where $k_{lv} = 1$, $k_{lv} = 0.5$ and $k_{lv} = 0$	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 $U_{g/mv:x}^{lines}$ 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 $U_{g/hv:rec}^{t+td}$ with k_{lvr} 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 $U_{g/hv:x}^{lines}$ for the three-bus HV test system for the cases where $k_{m:2} = 0$ and $k_{m:2} = 1$	88
4.8	Emissions $U_{g/hv:x}^{lines}$ 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 $U_{g/hv:x}^{lines}$ 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 $k_{sc-lv} \approx 25$ and $k_{sc-lv} \approx 10$: 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_{lv} 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_{lv} 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_{lv} (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 $k_{lv} = 1$, $k_{lv} = 0.5$ and $k_{lv} = 0$	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 $U_{g/hv:x}^{reult}$ 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_{-:rec}^t $ with $ I_{+:t} $ for the individual lines	153
7.5	Variation of $\theta_{V_{-:rec}^t}$ 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 $\frac{ Y_{im:s} \cos(-\theta_{im:s})}{ Y_{im:s}^n \cos(-\theta_{im:s}^n)}$ of P'_{x-xx} with $\frac{\omega_{rt}}{\omega_{rt}^n}$ for the 3hp, 220V motor	270
O.12	Variation of $\frac{ Y_{im:m2} \sin(-\theta_{im:m2}-120^0)}{ Y_{im:m2}^n \sin(-\theta_{im:m2}^n-120^0)}$ of Q'_{x-xz} with $\frac{\omega_t}{\omega_{rt}^n}$ for the 3hp, 220V motor	271
O.13	Variation of η_{im} with ω_{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 $K'ue$ 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	$U_{g/hv:x}^{lines}$, $K'ue_x$ and Kue_x 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	$U_{g/hv:x}^{result}$ 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	Kue_x and $E_{hv:x}$ according to the revised allocation method for the test system shown in Fig. 6.1	143
6.9	$U_{g/hv:x}^{result}$ 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 $k_{sc-lvragg}$ and σ 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 (1^{st} and 2^{nd} 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 $V_{-,S2}^t$ caused by the individual lines A - N at the busbar S2	248
N.9	Resultant negative sequence voltage $V_{-,S2}^{lines}$ at the busbar S2	248
O.1	Parameters of a 60Hz, 3hp, 220V induction motor	270
O.2	Power components $P_{x-xx}^n - Q_{x-xz}^n$ for the 3hp, 220V motor	270
O.3	Speed coefficients corresponding to the power components $P_{x-xx} -$ Q_{x-xz} for a range of induction motors	272
O.4	Efficiency coefficients for a range of induction motors	275