University of Wollongong
Research Online

University of Wollongong Thesis Collection
1954-2016

University of Wollongong Thesis Collections

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

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

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

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 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 '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 Kue 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 $(e = t, tf, \text{busbar } x)$ 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 $[\Omega]$
$Z_{\lambda\lambda:x}$	downstream λ $(\lambda = 0, +, -)$ sequence impedance seen at any busbar x $[\Omega]$
$Z_{\lambda\lambda:tf-s}$	λ $(\lambda = 0, +, -)$ sequence impedance, referred to S, of any coupling transformer $[\Omega]$
$Z_{--:x-im}$	downstream negative sequence impedance seen at any busbar x taking only induction motors into account $[\Omega]$
$Z_{-+:t_d}$	negative-positive sequence coupling impedance of any line t_d $[\Omega]$
$Z_{-+:t_d-us}$	negative-positive sequence coupling impedance, referred to US, of any line t_d $[\Omega]$
$0, +, -$	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 P*roc.* 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 Paranavithana, 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 Paranavithana, Sarath Perera, and Robert Koch. Propagation of Voltage Unbalance from HV to MV Power Systems. In *Proc.* 21^{st} *International Conference on Electricity Distribution (CIRED 2009)*, paper 0497, Prague, June 2009.

8. Prabodha Paranavithana, Sarath Perera, and Robert Koch. A Generalised Methodology for Evaluating Voltage Unbalance Influence Coefficients. In *Proc.* 21^{st} *International Conference on Electricity Distribution (CIRED 2009)*, paper 0500, Prague, June 2009.

9. Prabodha Paranavithana 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 Paranavithana 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. Paranavithana, 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. Paranavithana, 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 Paranavithana, 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

Appendices

List of Figures

List of Tables