University of Wollongong

Research Online

University of Wollongong Thesis Collection 1954-2016

University of Wollongong Thesis Collections

2008

Flicker propagation in radial and interconnected power systems

Sankika Tennakoon
University of Wollongong

Follow this and additional works at: https://ro.uow.edu.au/theses

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

Tennakoon, Sankika, Flicker propagation in radial and interconnected power systems, PhD thesis, School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, 2008. http://ro.uow.edu.au/theses/96

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

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.

Flicker Propagation in Radial and Interconnected Power Systems

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

Doctor of Philosophy

from

University of Wollongong

by

Sankika Tennakoon, BSc(Eng)

School of Electrical, Computer and Telecommunications
Engineering

March 2008

Dedicated to my parents...

Acknowledgements

This thesis would not have become a realisation without the contributions from many people.

First and foremost I wish to express my utmost gratitude to my supervisor, Associate Professor Sarath Perera for enabling me to pursue postgraduate studies at the University of Wollongong. You have always been more than a supervisor to me. I admire your commitment, patience and the academic and moral support given throughout my postgraduate studies. I am indebted to you for guiding me to grow up academically and personally over last few years.

I would also like to thank Dr. Duane Robinson, former co-supervisor for his assistance during the early stages of the project. Thanks also go to my current co-supervisor Professor Danny Sutanto as well for assistance provided. I am grateful to TransGrid for financially supporting the project and to Dr. Don Geddey for providing valuable technical inputs. The assistance received from Sean Elphick in setting up the laboratory experiments and data analysis is appreciated. Many thanks to Tracey and Roslyn in School office for their generous support at various occasions.

Very special thanks go to my friends Prabodha, Radley, Kalyani and Nishad for all the support given during good times as well as hard times along the way. I was lucky to have you all around me to share memories over the last few years in Wollogong.

I would also like to thank my husband, Chaminda who became a part of my life recently for being supportive and understanding especially during the final stages of the research.

Finally, my heartiest gratitude goes to my parents, sister, brother-in-law and two nephews for being such a wonderful family to me. Thank you so much for your endless love, encouragement, guidance and all the sacrifices you all made on behalf of me to come this far. I owe my success to you.

Certification

I, Sankika Tennakoon 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.

Sankika Tennakoon

Abstract

Voltage fluctuations which cause lamp flicker tend to propagate from the point of origin to various parts of a power system exhibiting some level of attenuation depending on factors such as system impedances, composition of loads and frequency components of the fluctuating waveform. Maintaining the flicker levels at various busbars below the planning limits specified by the standards is crucial, and in this regard it is important to develop an insight into the manner in which the flicker propagates via systems operating at different voltage levels. This thesis presents flicker transfer analysis methodologies applicable for radial and interconnected power systems particularly considering the influence of induction motor loads on flicker attenuation.

In the first phase of the work, development of the foundations towards flicker transfer analysis methodologies is carried out by investigating the stand-alone behaviour of induction motors that are subjected to regular supply voltage fluctuations. The electrical and mechanical response of induction motors to two types of sinusoidal fluctuations in the supply voltage where (a) a positive or negative sequence sinusoidal frequency component is superimposed on the mains voltage and (b) mains voltage amplitude is sinusoidally modulated are examined. State space representation of induction motors is used to develop a linearised induction motor model describing the response of the stator current and the rotor speed to small voltage variations in the supply voltage. The results from the model reveal that various sub-synchronous and/or super-synchronous frequency components that exist in the supply voltage as small voltage perturbations can influence the dynamic response of the machine in relation to flicker. In particular, oscillations in the electromagnetic torque and rotor speed arising as a result of the applied voltage perturbations are found to be the key influencing factors controlling the stator current perturbations. It has been noted that, the speed fluctuation caused by a superimposed positive sequence voltage perturbation tends to produce extra emf components in the rotor which in turn can reflect back to the stator. This concept of multiple armature reaction has been found to be significant in large motors especially when the superimposed frequencies are closer to the fundamental frequency.

The second phase of the work covers the development of systematic methods for evaluation of flicker transfer in radial and interconnected power systems taking the dynamic behaviour of induction motors into account. In relation to radial systems, small signal models are developed which can be used to establish the flicker propagation from a higher voltage level (upstream) to a lower voltage level (downstream) where induction motor loads are connected. Although this method can be applied for regular or irregular voltage fluctuations, emphasis has been given to sinusoidal voltage fluctuations arising from conventional sinusoidal amplitude modulation of upstream voltage. Moreover, the method examines the propagation of sub-synchronous and super-synchronous frequency components that exist in the supply voltage as side bands and hence determines the overall attenuation in the voltage envelope. The contribution of induction motors of different sizes and other influential factors such as system impedance, loading level of the motor are examined. It has been noted that in general higher frequency components of the upstream fluctuating voltage envelope tend to attenuate better at the downstream. A method is also presented which allows aggregation of induction motors at the load busbars in relation to flicker transfer studies.

In relation to interconnected systems, a frequency domain approach which can be used to investigate the flicker transfer is presented. This approach can be considered as an extension to the impedance matrix method as described in the literature and can overcome some of the limitations of the latter method. In the proposed approach, induction motor loads are modelled in a more realistic manner to replicate their dynamic behaviour, thus enabling the examination of the frequency dependent characteristics of flicker attenuation due to induction motors and the influence of tie lines in compensating flicker at remote load busbars consisting of passive loads.

To verify some of the theoretical outcomes real time voltage waveforms captured from a large arc furnace site have been used, in addition to the experimental work using a scaled down laboratory set up of a radial power system.

List of Principal Symbols

δ_i	voltage angle of i$^{\text{th}}$ node [degree]
Δi	variation in stator current [pu]
Δi_{ds}, Δi_{qs}	d-q axes stator current variations [pu]
ΔP	active power drawn by the motor at frequency f_i [kW]
ΔQ	reactive power drawn by the motor at frequency f_i [kVAr]
Δv	magnitude of voltage fluctuation [pu]
Δv_s	variation in amplitude of the supply voltage [pu]
E_{Psti}	flicker emission limit of an individual load
F	coincidence factor
f_b	fundamental frequency [Hz]
f_c	cut-off frequency [Hz]
f_i	superimposed sub-synchronous or super synchronous frequency [Hz]
f_m	modulation frequency [Hz]
f_r	rotor speed (electrical) [Hz]
ϕ_b	phase angle of fundamental frequency [rad]
ϕ_m	phase angle of modulating signal [rad]
G_{Pst}	global flicker contribution
H	inertia constant
I_p	amplitude of line current
J	moment of inertia [kgm^2]
k	load torque constant
L_{Pst}	short term flicker planning level
m	modulation depth (factor)
ω_b	base angular frequency [rad/s]

ω_e	synchronous speed (angular) [elec rad/sec]
ω_m	modulation frequency (angular) [rad/sec]
ω_r	rotor speed (angular) [elec rad/sec]
p	$\frac{d}{dt}$ operator
P_{it}	instantaneous flicker sensation
P_{st}	short term flicker severity index
P_{lt}	long term flicker severity index
r'_r	rotor resistance (referred to the stator) [Ω]
r_s	stator resistance [Ω]
ψ_d, ψ_q	d-q axes flux linkages per second [V]
ψ'_d, ψ'_q	d-q axes flux linkages per second referred to the stator [V]
s	Laplace operator
S_i	consumer's agreed power [MVA]
S_{tMV}	total supply capacity at a MV busbar [MVA]
S_{tHV}	total supply capacity at a HV busbar [MVA]
T_e	electromagnetic torque [Nm]
T_L	load torque [Nm]
$T_{Pst_{AB}}$	flicker transfer coefficient from A to B
T_{LSB}, T_{USB}	transfer coefficients of lower and upper side band voltages
u	control (input) vector
v_d, v_q	dq axes voltages [V]
v'_d, v'_q	dq axes voltages referred to stator [V]
V_m	peak value (amplitude) of the modulating signal [V]
V_p	amplitude of line-to-neutral voltage [V]
x	state vector
X'_{lr}	stator leakage reactance (referred to the stator) [Ω]

X'_d	sub transient reactance of the generator
X_{ls}	stator leakage reactance [Ω]
X_M	mutual reactance [Ω]
y	output vector

subscripts:

s stator variables

r rotor variables

o steady state values

Publications arising from this Thesis

1. S. Tennakoon, L. Perera, S. Perera and D. Robinson, *Flicker Transfer Analysis in Radial Power System*, Proc. Auastralasian Universities Power Engineering Conference (AUPEC 2004), Paper ID: 190, September 2004, Brisbane, Australia.

2. S. Tennakoon, S. Perera and D. Robinson, *Response of Mains Connected Induction Motors to Low Frequency Voltage Fluctuations from a Flicker Perspective*, Proc. Auastralasian Universities Power Engineering Conference (AUPEC 2005) (ISBN: 1 86295 277 9), Volume 2 pp 610-614, September 2005, Hobart, Australia.

3. S. Tennakoon, and S. Perera, and D. Robinson, *Attenuation of Flicker by Induction Motor Loads: A Laboratory Investigation*, Proc. 12th International Conference on Harmonics and Quality of Power (ICHQP 2006), October 2006, Cascais, Portugal.

4. S. Tennakoon, S. Perera, and D. Robinson, *Flicker Attenuation Part I: Response of Three-Phase Induction Motors to Regular Voltage Fluctuations*, Paper ID: TPWRD-00828-2006, IEEE Transactions on Power Delivery (in print).

5. S. Tennakoon, and S. Perera, and D. Robinson, *Flicker Attenuation - Part II: Transfer Coefficients for Radial Power Systems with Induction Motor Loads*, Paper ID: TPWRD-00829-2006, IEEE Transactions on Power Delivery (in print).

6. S. Tennakoon and S. Perera, and D. Sutanto, *Flicker Propagation in Interconnected Power Systems*, Proc. of IEEE PES PowerAfrica 2007, Conference and Exposition in Africa (ISBN: 1 4244 1478 4), July 2007, Johannesburg, South Africa.

Table of Contents

1 Introduction 1
  1.1 Statement of the Problem . . . 1
  1.2 Research Objectives and Methodologies . . . 3
  1.3 Outline of the Thesis . . . 4

2 Literature Review 7
  2.1 Introduction . . . 7
  2.2 Voltage Fluctuations and Flicker . . . 8
  2.3 IEC Flickermeter and Flicker Measurement . . . 10
  2.4 Flicker Propagation and Attenuation . . . 13
    2.4.1 An Overview on General Aspects . . . 13
    2.4.2 Radial Systems - Downstream to Upstream Flicker Transfer . 14
    2.4.3 Radial Systems - Upstream to Downstream Flicker Transfer . 16
    2.4.4 Flicker Transfer in Interconnected Systems . . . 17
  2.5 Electromagnetic Compatibility Standards for Flicker Allocation . . . 20
    2.5.1 The IEC Technical Report Type III (IEC 61000-3-7)/ Australian Standard (AS/NZS 61000.3.7) . . . 20
    2.5.2 Global Flicker Emission in Radial Systems . . . 21
    2.5.3 Interconnected Systems . . . 22
  2.6 Measurement of Emission and Establishment of Flicker Transfer Coefficient . . . 23
  2.7 Summary . . . 25

3 Preliminary Investigations on Flicker Transfer in Radial Systems using Time Domain Simulations 26
  3.1 Introduction . . . 26
  3.2 Simulation of a Hypothetical Radial Network Consisting of two Voltage Levels using PSCAD/EMTDC . . . 27
    3.2.1 Description of the Network and Flicker Measurement Criteria 27
    3.2.2 Dependency of Flicker Attenuation on Different Downstream Load Compositions . . . 31
    3.2.3 Dependency of Flicker Measurement on Modulation (Flicker) Frequency of Upstream Voltage . . . 33
    3.2.4 Dependency of Flicker Attenuation on the Magnitude of the Upstream Voltage Fluctuation . . . 35
    3.2.5 Dependency of Flicker Transfer on Mechanical Load type . . . 35
  3.3 Simulation of Flicker Propagation in a Real System . . . 37
    3.3.1 Network Configuration and Data Capturing System . . . 37
    3.3.2 Reconstruction of Voltage Envelope at 132kV Upstream Busbar (Site A) and Simulations on Reduced Network Model . . . 38
    3.3.3 Envelope Detection at Downstream . . . 41

3.3.4 Propagation of Flicker from Site A to Sites E and F 42
3.4 Summary 46

4 Response of Three Phase Induction Motors to Regular Voltage Fluctuations 48
4.1 Introduction 48
4.2 Small Signal Modelling for Dynamic Performance Studies 49
4.2.1 Existing Applications 49
4.2.2 Small Signal Modelling for Flicker Studies 50
4.3 State Space Analysis of Induction Motors 51
4.3.1 Linearised Machine Equations 51
4.3.2 Incorporation of Load Dynamics 53
4.3.3 Combining the Machine Equations for State Space Representation 54
4.4 Supplementary Material used in Present Work 55
4.5 Type I Voltage Fluctuations: Superimposed Positive Sequence Frequency Component on the Mains Voltage Waveform 57
4.5.1 Identification of Voltage Perturbations 57
4.5.2 Small Signal Modelling of Rotor Speed Fluctuations 58
4.5.3 Speed Fluctuations derived from Small and Large Signal Models 59
4.5.4 Generation of Additional emf Components on Stator 60
4.6 Type II Voltage Fluctuations: Sinusoidal Amplitude Modulation of Mains Voltage 67
4.6.1 Rotor Speed Oscillations: Large Signal Behaviour 67
4.6.2 Modelling the Response of the Stator Current using Small Signal Analysis 69
4.7 Summary 72

5 Analysis of Flicker Transfer in Radial Systems 75
5.1 Introduction 75
5.2 Small Signal Modelling of a Radial Network for Flicker Transfer Analysis 76
5.2.1 Description of the Network Model 76
5.2.2 Modification to the Small Signal Model of an Induction Motor to accommodate the Radial Network 77
5.3 Implementation of the Small Signal Model 80
5.3.1 Transfer Coefficients for a Network having a 2250hp Induction Motor at Downstream 80
5.3.2 Determination of Effective Sub-Synchronous and Super-Synchronous Impedances, Active and Reactive Power Variations 81
5.3.3 Discussion on the Attenuation Levels exhibited by the 2250hp Motor 85
5.3.4 Dependency of Transfer Coefficient on the Induction Motor Rating 87
5.3.5 Dependency of Transfer Coefficient on System Impedance . . . 87
5.4 Correlation between the Attenuation of Side Bands and Flicker Attenuation 90

5.4.1 Determination of flicker transfer coefficient using the small signal model 90
5.4.2 Accuracy of Small Signal Modelling 93
5.5 Summary 94

6 Experimental Validation of Flicker Attenuation due to Induction Motor Loads 96
6.1 Introduction 96
6.2 Experimental Set-up and Practical Matters 97
6.2.1 Experimental Set-up 97
6.2.2 Generation of Voltage Fluctuations at Upstream (A) 98
6.2.3 Practical Matters 100
6.3 Measurements and Results 100
6.3.1 Propagation and Attenuation of Voltage Side Bands with Induction Motor Load 100
6.3.2 Determination of Effective Sub-Synchronous and Super-Synchronous Impedances of 3hp Induction Motor 103
6.3.3 Flicker Transfer Coefficient at a Fixed Modulation Depth and Variable Modulation Frequency 106
6.3.4 Influence of Modulation Depth on Flicker Transfer Coefficient 108
6.4 Summary 109

7 Analysis of Flicker Propagation in Interconnected Systems 111
7.1 Introduction 111
7.2 Impedance Matrix Method - Overview 112
7.3 A Frequency Domain Method of Analysis of Flicker Transfer 114
7.3.1 Methodology 114
7.3.2 Modelling the System Components 114
7.3.3 The Complete System 118
7.3.4 Voltage Transfer Coefficients for d-q axes ($T_{q_{mi}}, T_{d_{mi}}$) and Flicker Transfer Coefficient ($T_{Pst_{mi}}$) 120
7.3.5 Implementation of the Proposed Method 122
7.3.6 Multiple Modulation Frequencies - Composite Modulating Signals 138
7.4 Summary 140

8 Conclusions and Recommendations for Further Work 142
8.1 Conclusions 142
8.2 Recommendations for Further Work 148

Appendices

A Major Building Blocks of the Simulink based d-q domain Induction Motor 156

B Discussion on the Positive and Negative Damping 159

C Theory of Induced EMF Components 163
C.1 Per Phase Equivalent Circuit of an Induction Motor 163
C.2 Superimposed Upper Side Band (Super-synchronous) Frequency Component ($f_i = f_b + f_m$) and Fluctuations in Rotor Speed 164
C.3 Induced emf Components due to Fundamental Frequency ($\omega_b = 2\pi f_b$) in Stator 165
C.4 Induced emf Components due to Super-synchronous Frequency, $\omega_b + \omega_m = 2\pi(f_b + f_m)$ in Stator 166

D Derivation of $G_1(s)$ and $G_2(s)$ for the 2250hp Squirrel Cage Induction Motor 169

E Aggregation of Induction Motors for Flicker Studies 171
E.1 Introduction 171
E.2 A Method based on Steady State Equivalent Circuit Theory 172
E.2.1 Determination of Electrical Parameters 172
E.2.2 Determination of Steady State Slip 176
E.2.3 Determination of Inertia 177
E.2.4 Determination of Load Torque Characteristics 177
E.2.5 Criterion for Aggregation of Individual Motors 179
E.3 Implementation 179
E.3.1 Case I: Aggregation of two induction motors 179
E.3.2 Case II: Aggregation of Group of Induction Motors 180

F Aggregation of 35 500hp Induction Motors 187

G IEEE 14 Bus System Data 189

List of Figures

2.1 Sinusoidal flicker due to amplitude modulation of fundamental frequency with a single modulating component 8
2.2 IEC flicker curve 11
2.3 Major blocks of the IEC flickermeter 12
2.4 Radial system 14
2.5 Scatter plot of the P_{st} values measured at two locations (1 and 2) . . 25

3.1 Radial system used for the simulations 27
3.2 Control blocks used for amplitude modulation of upstream voltage in PSCAD/EMTDC 29
3.3 Upstream voltage fluctuations generated by amplitude modulating the three phase source voltage 29
3.4 Variation of $T_{Pst_{AB}}$ with induction motor percentage 32
3.5 Variation of $\mathrm{T_{Pst_{AB}}}$ with induction motor percentage and loading level 33
3.6 Variation of flicker transfer coefficient ($T_{Pst_{AB}}$) with modulation frequency (f_m) 34
3.7 Variation of flicker transfer coefficient ($T_{Pst_{AB}}$) with modulation frequency (f_m) and the proportion of the induction motors downstream 34
3.8 Variation of $T_{Pst_{AB}}$ with modulation depth (m) 36
3.9 Variation of $T_{Pst_{AB}}$ with modulation frequency for two different load types 36
3.10 Single line diagram of the sub-transmission network used for the simulation 38
3.11 Reduced network model used in simulation 39
3.12 Process of reconstructing the voltage envelope (modulating signal) of the 132kV busbar at site A ($m'_a(t)$) using the waveform data captured at 22kV busbar at site C 40
3.13 Time domain characteristics of a Hamming window 43
3.14 Variation of the instantaneous flicker sensation (P_{it}) 43
3.15 Voltage envelope and its frequency spectrum at site A 44
3.16 Frequency spectra of voltage envelopes at sites E and F 45
3.17 Variation of voltage transfer coefficient ($T_{\Delta v}$) with modulation frequencies that exist in voltage envelope 46

4.1 Simulink induction motor model 56
4.2 Rotor speed fluctuation of the 2250hp motor with superimposed frequency established using small and large signal analyses 60
4.3 Variation of rotor speed fluctuations of the 2250hp motor with superimposed frequency for three different values of inertia 61
4.4 Variation of rotor speed fluctuation with superimposed frequency for four different motors with superimposed frequency 61

4.5 Variation of stator current side bands for a superimposed lower side band for 2250hp motor: $f_i = f_b - f_m$ 64
4.6 Variation of stator current side bands for upper side band injection, 2250hp motor: $f_i = f_b + f_m$ 65
4.7 Comparison of stator current side bands of different motors for lower side band injection 66
4.8 Comparison of stator current side bands of different motors for upper side band injection 66
4.9 Rotor speed fluctuation of the 2250hp motor for amplitude modulation 68
4.10 Variation of stator side band current components (as a percentage of the fundamental) with side band frequency ($f_b - f_m$ or $f_b + f_m$) established for amplitude modulation and superimposition of a single frequency component 69
4.11 Recovery of stator current perturbation (Δi_s) 71
4.12 Variation of stator side band current components (as a percentage of the fundamental) established using small and large signal analyses for amplitude modulation 72
4.13 Comparison of the side band currents caused by amplitude modulation for motors of different sizes 73

5.1 Radial system 76
5.2 Block diagram of the small signal model which represents the process of recovering the stator current perturbation 78
5.3 Variation of transfer coefficients of voltage side bands (T_{LSB} and T_{USB}) with modulation frequency (f_m) for the 2250hp motor 80
5.4 Variation of transfer coefficients of voltage side bands (T_{LSB} and T_{USB}) at low modulation frequencies for the 2250hp motor 81
5.5 Variation of transfer coefficients of voltage side bands (T_{LSB} and T_{USB}) with side band frequency ($f_b \pm f_m$) for the 2250hp motor 82
5.6 Variation of (a) the magnitude and (b) angle of the effective impedance of the 2250hp motor and an equivalent passive load with frequency of the voltage side band ($f_b \pm f_m$) 84
5.7 Active (ΔP) and reactive (ΔQ) power consumed by the 2250hp motor for voltage side bands at f, where $f = f_b \pm f_m$ 85
5.8 Variation of transfer coefficients of voltage side bands (T_{LSB} and T_{USB}) with side band frequency ($f_b \pm f_m$) for the three motors 88
5.9 Variation of transfer coefficients of voltage side bands (T_{LSB} and T_{USB}) with side band frequency ($f_b \pm f_m$) for three system impedance ($Z_s = jX_s$) magnitudes - 2250hp motor 89
5.10 Variation of transfer coefficients of voltage side bands (T_{LSB} and T_{USB}) with side band frequency ($f_b \pm f_m$) for three line ($Z_s = jX_s$) impedance magnitudes at for low modulation frequencies values - 2250hp motor . 90

5.11 Variation of transfer coefficients of voltage side bands (T_{LSB} and T_{USB}) with side band frequency ($f_b \pm f_m$) for $\psi_s = 90°$ and $\psi_s = 60°$ for the 2250hp motor 91
5.12 Comparison of the transfer coefficients of the side bands (T_{LSB} and T_{USB}) and flicker transfer coefficient, T_{Pst} 92
5.13 Comparison of flicker transfer coefficients (T_{PstAB}) established using small and large signal models 93
5.14 Percentage error involved in determining flicker transfer coefficient using the small signal model 94

6.1 Experimental set-up of the scaled down radial network 97
6.2 Modulating the rotor excitation current of the synchronous generator 99
6.3 Amplitude modulated terminal voltage (line-to-line) of the synchronous generator 101
6.4 Frequency spectrum of the voltage waveform in Figure 6.3 101
6.5 Variation of the transfer coefficients of the voltage side bands 102
6.6 Variation of the magnitude of the effective impedance of the motor with frequency of the voltage side band 104
6.7 Variation of the voltage transfer coefficients of the side bands with frequency of the voltage side band 105
6.8 Variation of flicker transfer coefficients established using measurements 1 and 2 for downstream induction motor and passive loads 107
6.9 Variation of flicker transfer coefficient T_{PstAB} with modulation depth (m) 108

7.1 Series impedance 115
7.2 Process used to determine the voltage fluctuation at i$^{\text{th}}$ node 122
7.3 Simple interconnected network with three nodes 123
7.4 Variation of q-axis transfer coefficient with modulation frequency . . 125
7.5 Variation of d-axis transfer coefficient with modulation frequency . . 126
7.6 Variation of flicker transfer coefficient with modulation frequency for Case I together with those established using impedance matrix method 127
7.7 A simple three node interconnected network consisting of a generator node (derived from IEEE 14 bus system) 129
7.8 Variation of flicker transfer coefficient with modulation frequency for Case II 130
7.9 Difference between the T_{Pst} values established using impedance matrix method and frequency domain method for the network shown in Figure 7.8 131
7.10 IEEE 14 bus network 132
7.11 Flicker transfer coefficients of the 14 bus system established using frequency domain method 134
7.12 Variation of flicker transfer coefficient (T_{Pst}) with modulation frequency (f_m) at node 2 135

7.13 Variation of flicker transfer coefficient (T_{Pst}) with modulation frequency (f_m) at node 13 136
7.14 Reduction in flicker due to induction motor load at node 13 137
7.15 Error involved in T_{Pst} determined using Z-matrix method 138
7.16 Comparison of transfer coefficients of the modulation frequencies in a composite signal with individual modulation frequencies 140

A.1 Conversion of three phase voltages from a-b-c domain to d-q domain . 156
A.2 Establishment of d-q axes currents using voltages-flux linkages 157
A.3 Determination of q-axis flux linkage 157
A.4 Generation of sinusoidally amplitude modulated three phase supply . 158
A.5 Generation of three phase supply consisting a superimposed positive or negative sequence frequency component 158

B.1 Rotor speed fluctuation of the 2250hp motor with superimposed frequency established using small and large signal analyses 160
B.2 Variation of stator current side bands for a superimposed lower side band for 2250hp motor: $f_i = f_b - f_m$ 160
B.3 Variation of stator current side bands for upper side band injection, 2250hp motor: $f_i = f_b + f_m$ 161

C.1 Per phase equivalent circuit of an induction motor 163
C.2 Spectrum of the stator induced emf components 167

E.1 Per phase equivalent circuits of the first induction motor (T-model) . 173
E.2 Per phase equivalent circuit of the first induction motor (Π-model) . . 173
E.3 Equivalent circuits of the both motors 174
E.4 Hypothetical equivalent circuit of the aggregate machine 175
E.5 Steady state equivalent circuit of the aggregate motor 176
E.6 Electromagnetic torque (T_e) and load torque ($T_{L_{agg}}$) characteristics of the aggregate induction motor 181
E.7 Comparison of the response of the aggregate motor and the cluster of individual motors to a step change of 0.2pu in the supply voltage . . 183
E.8 Comparison of the response of the aggregate motor and the cluster of individual motors to a sinusoidal fluctuation in the supply; frequency of voltage fluctuation=5Hz 184
E.9 Comparison of the response of the aggregate motor and the cluster of individual motors to a sinusoidal fluctuation in the supply; frequency of voltage fluctuation=10Hz 184
E.10 Variation of T_{Pst} with modulation frequency (f_m) for aggregate induction motor and the cluster of individual motors 185
E.11 Error involved in T_{Pst} established for the aggregate machine 186

List of Tables

2.1 Indicative values of planning levels of flicker for HV and MV systems; 1kV<MV<35kV;35kV<HV<230kV 20

4.1 60Hz induction motor parameters 57
4.2 Frequency components of emf components in rotor and stator caused by rotor speed oscillation at angular speed of $\omega_m = 2\pi f_m$ and a superimposed positive sequence frequency component $(2\omega_b + \omega_m)$; * extra side band frequencies 63

7.1 Magnitude and angle of bus voltages of IEEE 14 bus system 133

C.1 Frequency components of emf components in rotor and stator caused by rotor speed oscillation at angular speed of $\omega_m = 2\pi f_m$ and a superimposed positive sequence frequency component $(2\omega_b + \omega_m)$; * extra side band frequencies 167

E.1 Ratings and parameters of individual motors: Case I 180
E.2 Electrical and mechanical parameters of the aggregate motor established using the proposed method and Kataoka's method: Case I - aggregation of two low voltage machines 181
E.3 Ratings and parameters of individual motors: Case II 182
E.4 Electrical and mechanical parameters of aggregate motor 182
E.5 Comparison of the input power of aggregate machine and the group of individual machines at full load steady state operation 183

F.1 Ratings and parameters of an individual 500hp motor 187
F.2 Electrical and mechanical parameters of the aggregate motor representing 35 individual motors 188

G.1 Generator and load bus data 189
G.2 Transmission Line and Transformer Data; Impedances and line charging susceptance in pu on a 100MVA base 190
G.3 Voltage-controlled bus data 190
G.4 Tap settings of fixed-tap transformers 191
G.5 Static capacitor data; Susceptance in pu on a 100MVA base 191