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Sankika Tennakoon
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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...

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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^{th} node [degree]
Δi	variation in stator current [pu]
$\Delta i_{ds}, \Delta i_{qs}$	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_{PstAB}	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)/ Aus- tralian 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 Coef- ficient	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 Fre- quency 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 Sig- nal 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 Atten- uation	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 $T_{Pst_{AB}}$ 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 $\psi_s = 90^\circ$ and $\psi_s = 60^\circ$ 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^{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_{Lagg}) 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 super- imposed 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 super- imposed 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 estab- lished 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 repre- senting 35 individual motors	188
G.1	Generator and load bus data	189
G.2	Transmission Line and Transformer Data; Impedances and line charg- ing 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