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# Flicker propagation in radial and interconnected power systems

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# Flicker Propagation in Radial and Interconnected Power Systems

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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

| | |
|---|---|
| $\delta_i$ | voltage angle of $i^{th}$ node [degree] |
| $\Delta i$ | variation in stator current [pu] |
| $\Delta i_{ds}$, $\Delta i_{qs}$ | d-q axes stator current variations [pu] |
| $\Delta P$ | active power drawn by the motor at frequency $f_i$ [kW] |
| $\Delta Q$ | reactive power drawn by the motor at frequency $f_i$ [kVAr] |
| $\Delta v$ | magnitude of voltage fluctuation [pu] |
| $\Delta v_s$ | 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] |
| $\phi_b$ | phase angle of fundamental frequency [rad] |
| $\phi_m$ | 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) |
| $\omega_b$ | base angular frequency [rad/s] |

| | |
|---|---|
| $\omega_e$ | synchronous speed (angular) [elec rad/sec] |
| $\omega_m$ | modulation frequency (angular) [rad/sec] |
| $\omega_r$ | 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] |
| $\psi_d$, $\psi_q$ | d-q axes flux linkages per second [V] |
| $\psi'_d$, $\psi'_q$ | 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 [$\Omega$] |
| $X_M$ | mutual reactance [$\Omega$] |
| $y$ | 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. 12$^{\text{th}}$ 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

**Appendices**

# List of Figures

# List of Tables