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Flicker Transfer in Radial Power Systems

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Abstract

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Keywords

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FLICKER TRANSFER IN RADIAL POWER SYSTEMS

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Abstract

Loads which exhibit continuous and rapid variations in their current can cause voltage fluctuations that are often referred to as flicker. One good example for such loads is arc furnaces which are usually fed by dedicated feeders from the high voltage busbars in transmission systems. The flicker generated from such loads will propagate to the upstream HV point of common coupling (PCC), and from there to the downstream through the transmission and sub transmission systems. This paper demonstrates how the generated flicker is propagated from the HV PCC to the downstream in radial networks exhibiting different levels of attenuation depending upon the load composition of the downstream. Theoretical investigations on flicker transfer have been carried out using simple and more advanced modelling of loads and simulations of radial transmission and sub transmission networks having different load types. The behaviour predicted by the theoretical work is supported through field measurements that have been carried out in an actual network.

1. INTRODUCTION

The rapid expansion of power systems and the vast usage of modern load types have caused the area of power quality to become a major issue from an obscurity within few years. Amongst many power quality problems voltage flicker has gained a growing concern from utilities, especially in the areas of transmission and distribution planning. Voltage flicker is a common term used to describe systematic fluctuations in the voltage envelope or a series of random voltage changes that can cause perceptible variations in the illumination of lighting devices. The perceptibility of light flicker depends upon the magnitude and the frequency of the variation.

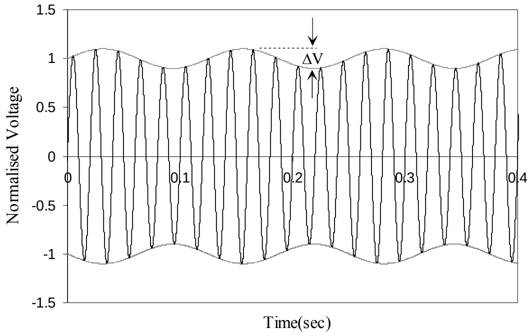

Figure 1: Sinusoidal voltage flicker: 50Hz ac voltage modulated with 8Hz sinusoidal waveform and a modulation factor of 0.1

The most basic flicker phenomenon can be explained by amplitude modulating the ac voltage waveform by a sine wave seen as the envelope of the waveform, as shown in Figure 1 [1]. The resulting instantaneous voltage can be expressed as per (1).

$$v(t) = V(1 + m\sin(2\pi f_m t))\sin(2\pi f_o t) \qquad (1)$$

where
V – nominal amplitude of the ac voltage,
f_o – fundamental frequency of the ac voltage,
f_m – modulating frequency, and
$m = (\Delta V/2V)$ – modulation factor

The adverse effect of flicker is not only the irritation caused by the visible perception of illumination variation of the lights, but also the risk of voltage magnitude being outside the accepted tolerances and its consequences. On the other hand, since the flicker originates at one point and propagates through the transmission and sub transmission systems, a single source of flicker can easily affect a large number of customers in the MV and LV systems. For example, in a radial network, flicker due to arc furnaces that are normally connected to the HV system through dedicated feeders can propagate easily to the PCC and from there to the downstream of the network.

The paper will discuss how the flicker that originates in an HV system propagates through the PCC to the downstream and how the flicker attenuates at different voltage levels when downstream busbars contain different load compositions. Furthermore, the paper discusses the dependency of flicker transfer and flicker attenuation on the modulation frequency and the loading level of the downstream.

2. FLICKER PROPAGATION & ALLOCATION IN RADIAL SYSTEMS

Flicker related criteria are generally expressed in terms of P_{st} and P_{lt} and the IEC flickermeter provides these two quantities. P_{st}, the short term flicker severity, is calculated for each 10 minute period and the P_{lt}, long term flicker severity, is calculated for any two hour period and can be calculated using 12 consecutive P_{st} values [2]. The threshold for perceptible flicker is $P_{st}=1$. As stated previously, flicker disturbances that originate at one point can propagate into the power system according to the system impedances. In radial systems downstream flicker transfer to upstream is seen to be small compared to upstream to downstream flicker transfer. This is due to the fact that impedances in the upstream are much less than those of the downstream and hence gives rise to smaller voltage drops in the upstream. Nevertheless, the flicker transfer from the upstream to the downstream can easily take place with a certain attenuation factor which is determined by the downstream impedances. The level of attenuation of flicker at one point (B) with respect to the other (A) is determined by the flicker transfer coefficient, T_{PstAB}, and is defined as the ratio between the P_{st} values measured simultaneously at the two locations [3].

$$T_{PstAB} = \frac{P_{stB}}{P_{stA}} \qquad (2)$$

Assessment and allocation of flicker emission limits for fluctuating loads in the MV and HV systems are addressed in the Australian standard AS/NZS 61000.3.7 [4] and planning levels for flicker are discussed in the Standards Australia guidebook [5]. Maintaining the flicker levels at or below the planning levels at different voltage levels in transmission and sub transmission systems is crucial though it is not a mandatory requirement for utilities at the moment unless called upon by state codes or the regulator. The emission level of a fluctuating load is the flicker level which would be produced at the PCC if no other fluctuating loads were present. In order to determine the total emission limit of all individual loads at a selected voltage level (e.g. MV), the flicker transfer from the HV system has to be known. For the MV system the total flicker emission limit is referred to as the 'Global contribution of flicker (G_{PstMV})' and can be determined using (3) in which it gives the total headroom available for the local loads for flicker emission [4]:

$$G_{PstMV} = \sqrt[3]{L_{PstMV}^{3} - \left(T_{PstHM} \times L_{PstHV}\right)^{3}} \qquad (3)$$

where

G_{PstMV} – maximum global contribution of the local loads to the flicker level in the MV system,

L_{PstMV} – short term planning level of the flicker level in MV system,

L_{PstHV} – short term planning level of the flicker level in HV system, and

T_{PstHM} – flicker transfer coefficient from HV system (upstream) to the MV system (downstream).

Global flicker emission level can also be expressed in terms of long term flicker severity (P_{lt}) and the corresponding equation is similar to (3).

Knowledge of the transfer coefficient is crucial when determining the emission levels of flicker. Based on the indicative short term planning levels given in AS/AZS 61000.3.7 (i.e. $L_{PstMV}=0.8$, $L_{PstHV}=0.9$) [4], and considering a unity flicker transfer coefficient for upstream to downstream flicker transfer (i.e. $T_{PstHM}=1$), global short term flicker emission (G_{PstMV}) can be determined as 0.6. For a transfer coefficient of 0.8 the global short term flicker emission would be 0.78. Thus, precise evaluation of the flicker transfer coefficient is needed when deciding on flicker emission levels for the MV fluctuating loads.

Once the global flicker emission limit is determined, allocation of emission limits for individual fluctuating local loads (E_{Psti}) can be carried out based on the consumer's agreed power (S_i) and the total supply capacity (S_{MV}) of the MV system [4]. Further, all MV fluctuating loads may not be in operation at the same time and a coincidence factor ($0<F_{MV}\leq 1$) is introduced in determining the individual customer emission limit as per (4).

$$E_{Psti} = G_{PstMV} \cdot \sqrt[3]{\frac{S_i}{S_{MV}} \cdot \frac{1}{F_{MV}}} \qquad (4)$$

3. FLICKER TRANSFER ANALYSIS USING A SIMPLE RADIAL SYSTEM

As mentioned in Section 2, flicker propagating in the upstream transfers to the downstream with certain attenuation factor. In order to illustrate this phenomenon, consider the following simple radial system which consists of a fluctuating supply that represents the flicker propagating from the upstream. Note that fluctuating loads such as arc furnaces are usually supplied by dedicated feeders from the HV busbars, hence the flicker originated by them is significantly present at the HV bus in the upstream.

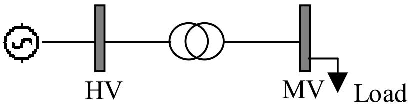

Figure 2: Simple radial network used for flicker transfer analysis

This simple radial network shown in Figure 2 can be modelled using an approximate equivalent circuit as given in Figure 3 where,

V_1 – upstream voltage (HV)
V_2 – downstream voltage (MV)
Z_S – equivalent impedance of the system which connects the upstream and the downstream (e.g. transformer)
Z_L – equivalent steady state impedance of the load.

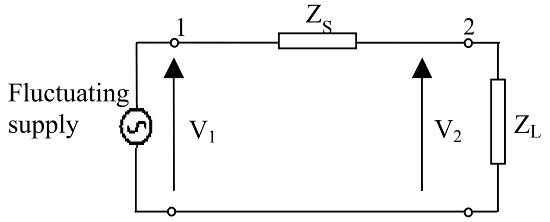

Figure 3: Equivalent circuit for the radial system shown in Figure 2

In the steady state the voltages V_1 and V_2 are related according to the simple relationship:

$$V_2 = \frac{Z_L}{Z_L + Z_S} V_1 \Rightarrow \frac{V_2}{V_1} = \frac{Z_L}{Z_L + Z_S} \tag{5}$$

But for small voltage fluctuations (ΔV_1) in the upstream, the corresponding fluctuations in the downstream voltage (ΔV_2) can be established using (6).

$$\Delta V_2 = \frac{Z_L^{'}}{Z_L^{'} + Z_S} \Delta V_1 \Rightarrow \frac{\Delta V_2}{\Delta V_1} = \frac{Z_L^{'}}{Z_L^{'} + Z_S} \tag{6}$$

In deriving (5) and (6) it is assumed that the system impedance Z_S remains constant under fluctuating conditions and load impedance becomes the dynamic impedance (Z_L'). From (5) and (6),

$$\frac{\left(\frac{\Delta V_2}{V_2}\right)}{\left(\frac{\Delta V_1}{V_1}\right)} = \frac{Z_L^{'}}{Z_L^{'} + Z_S} \times \frac{Z_L + Z_S}{Z_L} \tag{7}$$

Assuming that the P_{st} values are proportional to the relative voltage changes ($\Delta V/V$) [3], flicker transfer coefficient from upstream to the downstream is given by,

$$T_{Pst12} = \frac{P_{st2}}{P_{st1}} = \frac{\left(\frac{\Delta V_2}{V_2}\right)}{\left(\frac{\Delta V_1}{V_1}\right)} = \frac{Z_L^{'}}{Z_L^{'} + Z_S} \times \frac{Z_L + Z_S}{Z_L} \tag{8}$$

For passive loads dynamic impedance is nearly equal to the steady state impedance ($Z_L \approx Z_L$') and hence $T_{Pst12} \approx 1$ using (8). In an induction motor, the rotor flux cannot change instantaneously and hence tends to react in dynamic state for small voltage variations. This dynamic state impedance is smaller than the equivalent impedance of the motor under steady state (i.e. $Z_L' < Z_L$) and hence, $T_{Pst12} < 1$ using (8). In practice, Z_L' is approximately equal to the locked rotor impedance of the motor. In other words, the flicker that originates and transferred from the upstream (HV) will be attenuated to a greater extent if the downstream load contains a large proportion of induction motors. Equation (8) can also be used to examine the dependency of flicker transfer from upstream to downstream on the loading level at the downstream busbars. If the downstream busbars are lightly loaded flicker transfer coefficient would be close to unity.

Based on the above formulation a simple simulation has been carried out to determine the behaviour of flicker transfer coefficient with variable load composition and variable transformer loading levels [6]. Figure 4 shows the variation of the T_{PstHM} from upstream to downstream with respect to induction motor load percentage for five different transformer loading levels. In establishing these curves, as the percentage of induction motor load is decreased, the total transformer loading level is kept constant by adding an equivalent passive load component.

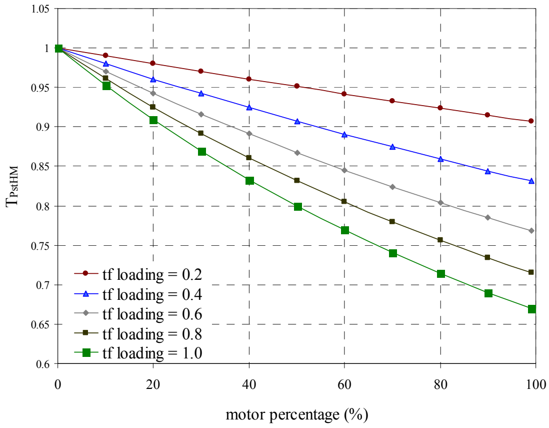

Figure 4: Variation of flicker transfer coefficient with percentage of induction motor load

It is clear from Figure 4 that for a given transformer loading level, as the motor load content is increased with respect to the passive load content, the flicker transfer coefficient decreases. Further, for a given motor load percentage, as the transformer loading level is increased the flicker transfer coefficient decreases. The above formulation assumes that upstream flicker comprises of one modulating frequency component only and hence relative voltage changes are directly proportional to the corresponding P_{st} values [3]. It is however imperative to notice that the modulating envelope of the upstream voltage fluctuations in practice would contain numerous frequency components. Therefore it is generally not possible to state that the relative voltage changes are directly proportional to P_{st} values, without knowing whether all frequency components are equally attenuated or not. Hence, further investigations on flicker transfer and attenuation have been carried out by considering the normalised (relative) voltage fluctuation ($\Delta V/V$) at downstream with respect to that of upstream for different flicker frequencies. This would provide a more rational perception of flicker transfer.

4. SIMULATION OF THE RADIAL SYSTEM IN PSCAD™/EMTDC®.

In order to examine the flicker transfer and its attenuation with different load compositions, simulations have been carried out using PSCAD™/EMTDC®. The single line diagram of a simple radial network used for the simulation is given in Figure 5. For simplicity only two voltage levels are considered (230kV/2.3kV) in this network.

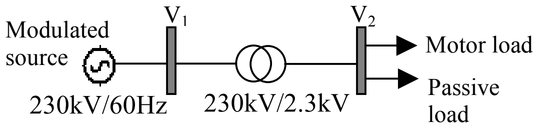

Figure 5: Simple radial network used for PSCAD™/EMTDC® simulation

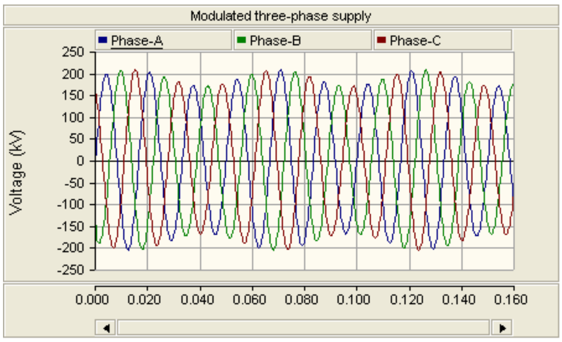

Figure 6: Upstream flicker generated by modulating the three phase source voltage

Upstream flicker was generated by amplitude modulating the 230kV voltage source. The modulating frequency (f_m) and the modulation factor (m) were controlled externally, and the flicker transfer analysis can be easily carried out in a wide scope by varying the modulating frequency and/or modulation factor. Load comprises of a composite load. This composite load contains a total induction motor load of forty 2250hp/60Hz machines [7] and an equivalent passive load which has the same rating as the total motor load. The step-down transformer is a 76MVA transformer that can be fully loaded by appropriately apportioning induction motors and the passive loads. Flicker transfer analysis in this system was done by measuring the absolute voltage fluctuation and determining the relative voltage change at the load end (downstream) envelope of the voltage waveform.

4.1 Flicker transfer simulation with different load compositions

Simulation with different load compositions was carried out in order to investigate the dependency of the flicker transfer and flicker attenuation on the load composition at downstream. The proportional content of the induction machine (IM) load and the passive load were varied such that, the total MVA drawn by the two loads from the transformer is a constant. This keeps the transformer at constant rated loading level. Three load compositions were considered as given in the Table I.

Table I: Load compositions used for flicker analysis

Case	IM load	Passive load
1	100%	0%
2	50%	50%
3	0%	100%

For each load composition in Table I modulation frequency (f_m) was varied from 2Hz – 36Hz while keeping the modulation factor (m) at a constant value of 0.1. At each frequency absolute voltage change at the load end (ΔV_2) and the amplitude of the fundamental ac voltage (V_2) were measured. Therefore, referring to (1), the relative voltage change at the source end ($\Delta V_1/V_1$) can be derived as follows:

$$m = \frac{\Delta V_1}{2V_1} \Rightarrow \frac{\Delta V_1}{V_1} = 2m \qquad (9)$$

Using (9), the relative voltage at the upstream is forced to be a constant value throughout. Fluctuation in the voltage at downstream with respect to the upstream can then be calculated by taking the ratio $(\Delta V_2/V_2)/(\Delta V_1/V_1)$ which is plotted against the modulating frequency in Figure 7 which shows three cases of different load compositions.

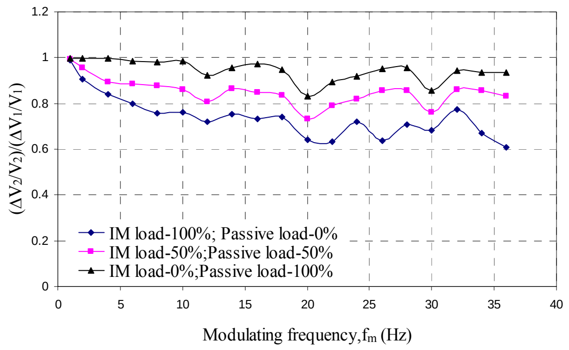

Figure 7: Variation of flicker transfer from upstream to downstream for different load compositions

Figure 7 indicates that the greater the IM load content in the downstream, the lower the flicker transfer from upstream to downstream. Further, for each load composition as the modulation frequency (i.e. flicker frequency) increases, the flicker transfer tends to decrease. Peaks and valleys in the curves indicate that flicker transfer has a non-uniform frequency dependency.

4.2 Flicker transfer simulation with different loading levels

Simulation has been further extended to examine the dependency of flicker transfer on the downstream loading level. Three different load compositions used for the simulation under Section 4.1 (Table I) have been used for this section as well. Modulating frequency (f_m) and modulation factor (m) were held at 8Hz and 0.1 respectively. For each load composition transformer loading level was increased from 0% to 100% by varying the total downstream load appropriately. For each transformer loading level the relative voltage change was determined as per Section 4.1. Figure 8 shows the ratio $(\Delta V_2/V_2)/(\Delta V_1/V_1)$ plotted against the percentage of the transformer loading level.

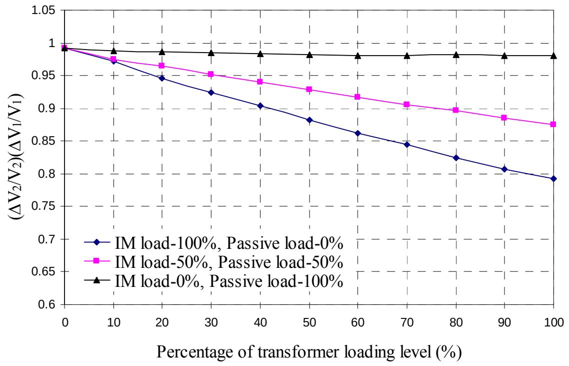

Figure 8: Variation of upstream to downstream flicker transfer for different loading levels

It is evident from Figure 8 that as the transformer loading level increases the flicker transfer from upstream to downstream decreases uniformly and will be minimum at the highest loading level.

5. FIELD MEASUREMENTS

Figure 9 illustrates the actual network in which field measurements have been carried out [6]. This network contains a large arc furnace that is fed by a dedicated feeder connected to the upstream HV bus. Note that flicker originated by the arc furnace will propagate to the HV busbar at A which would be the PCC for the downstream MV feeders. Busbar D is classified as mainly industrial and busbar E is classified as mainly residential.

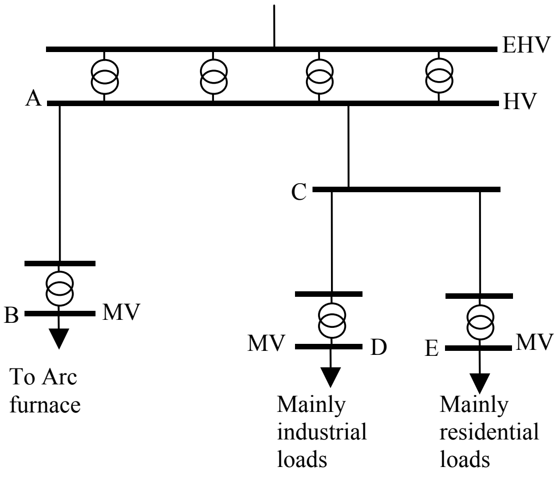

Figure 9: Simplified single line diagram of the actual network

Synchronised flicker measurements have been carried out at busbars A to E over a period of seven days in order to establish the flicker transfer between various busbars. Short term and long term flicker severity indices have been determined to obtain the flicker transfer coefficient. The flicker transfer and the flicker transfer coefficient can be examined by correlating the flicker measurements at the different busbars. For example, Figure 10 shows the scatter plot of the P_{st} values of the MV side of the downstream bus at D and the HV bus at A. Similarly Figure 11 shows the scatter plot of the P_{st} values of the MV side of the downstream bus at E and the HV bus at A. The regression lines have been forced to pass through zero, which makes it possible to determine the flicker transfer coefficient by determining the gradient of the regression lines. The gradient of the scatter plots corresponding to the MV busbar, which predominantly carries an industrial load base is 0.63. On the other hand, the gradient of the scatter plot corresponding to the MV busbar, which predominantly carries a residential load base is 0.82.

Thus the argument that the industrial load bases containing large proportions of induction motors help to reduce the flicker transfer from the upstream to downstream is seen to be supported (0.66 against 0.84).

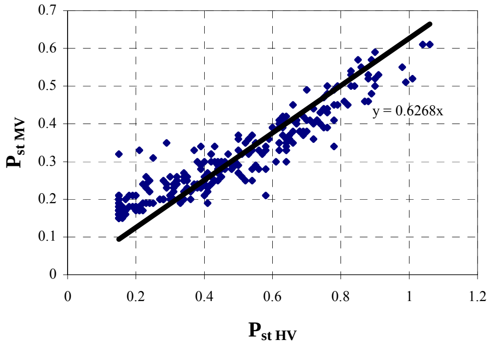

Figure 10: Scatter plot of P_{st} values of MV industrial load at D versus HV at A

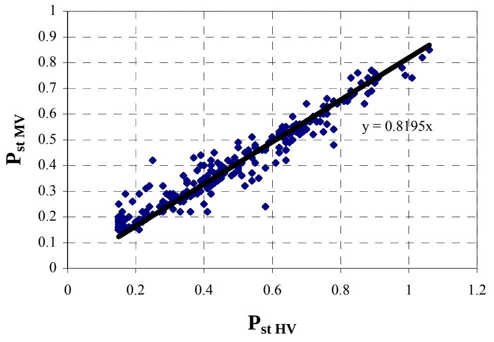

Figure 11: Scatter plot of P_{st} values of MV residential load at E versus HV at A

6. CONCLUSIONS

Based on theoretical modelling, simulations and the field measurements carried out following conclusions can be drawn in relation to flicker transfer in radial networks.

1. Flicker does attenuate when it propagates from upstream to downstream.
2. Upstream to downstream flicker transfer is seen to be dependent on the load composition, i.e. whether the downstream consists of an industrial load base (containing large proportion of induction motors) or residential load base. Presence of the industrial load base tends to attenuate the flicker to a greater extent than the residential load base.
3. Loading levels of the downstream busbars have an impact on the flicker transfer coefficient (T_{PstHM}). Higher the loading level of the downstream bus bars, the greater the flicker attenuation.
4. Flicker attenuation depends on the frequency and from the simulations carried out it is seen that flicker transfer from upstream to downstream decreases as the flicker frequency increases. However, this decrease is not uniformly related to flicker frequency and this non-uniform behaviour of the flicker attenuation has to be further investigated.
5. Synchronous field measurements tend to support the conclusions 1 and 2 above.

Flicker that originates from the fluctuating loads normally contain more than one frequency component and whether all frequency components are equally attenuated or not at the downstream is a question yet to be answered in full. Hence, further investigations on the dependency of the flicker attenuation level on the modulating frequency are being carried out. Exploration of new methodologies to examine flicker transfer and development of load models that are suitable for flicker analysis are being investigated. Experimental work will be carried out to support the theoretical work.

7. ACKNOWLEDGEMENTS

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