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Abstract

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Flicker Propagation in Interconnected Power Systems

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Abstract – ***Voltage fluctuations leading to lamp flicker can propagate from the point of origin to various parts of the power system with some attenuation depending on the system impedances and load composition. Field measurements and theoretical studies suggest that the industrial loads containing large proportions of induction motors assist in attenuating flicker compared to residential loads consisting of passive devices. This paper describes a frequency domain approach which can be used to determine the propagation of voltage fluctuations when there are induction motor loads in the vicinity of the disturbing load. The method involves linearization of the network in d-q domain to evaluate various voltage transfer coefficients. Induction motor loads are modelled as a matrix of transfer functions developed between node voltages and currents. The proposed method has been applied to a simple meshed system and the results clearly show the influence of the induction motors on flicker attenuation and the dependency of the flicker transfer coefficient on the frequency of voltage fluctuations. Results are in close agreement with results obtained from time domain simulations.***

I. INTRODUCTION

Flicker is a power quality problem that arises as result of voltage fluctuations caused by random variations in active and reactive power drawn by loads such as electric arc furnaces (EAFs). Such fluctuating loads are normally supplied through dedicated feeders from high voltage (HV) or medium voltage (MV) busbars, yet the generated voltage fluctuations can penetrate into neighbouring parts of the power system with some level of attenuation depending on factors such as feeder and transformer impedances, load composition and the frequency components that are present in the voltage waveform [1]-[7].

Recent theoretical work and field measurements related to flicker propagation suggest that the industrial loads containing large proportions of induction motors assist in attenuating flicker compared to residential loads consisting of essentially passive devices [3]-[5]. Extensive theoretical investigations carried out by the authors recently on the dynamic response of induction motors in relation to flicker attenuation clearly indicate that induction motors offer a relatively small effective impedance at flicker related frequencies. The magnitude of the effective impedance has also been found to be very much dependent on the frequency of voltage fluctuations and hence the attenuation of flicker also becomes frequency dependent. This theoretical work is further supported by experimental validation in relation to radial power systems as discussed in [9].

Theoretical investigation on flicker propagation in interconnected systems is relatively more complex compared to what has been recently carried out by the authors due to the interacting behaviour of the various bus bars and the connected loads. Possible methods of analysis for interconnected systems include impedance matrix method, load flow and short circuit methods [2],[11],[12]. However, these methods are primarily based on the rms voltage variations in the system hence do not take the frequency of voltage fluctuations into account in determining the flicker transfer coefficient. Moreover, the induction motor loads are represented by hypothetical static impedances.

This paper describes a frequency domain approach for flicker transfer analysis in interconnected systems, which takes the frequency of voltage fluctuation into account. The influence of the induction motor loads on flicker attenuation has been incorporated by modelling the induction motors in a more realistic and rigorous manner using small signal analysis. The proposed method can be considered as an extension to the impedance matrix method described in [2].

The paper is organised as follows: Section II gives an overview of the flicker propagation in radial and interconnected systems and emphasises on the relevance of the flicker transfer coefficient in deciding emission limits to new loads. Section III presents the frequency domain analysis of the flicker propagation in interconnected systems which describes the methodology of the proposed approach. Section IV illustrates the implementation of the proposed method and analysis of results for a simple 3 node system. Finally, Section V gives the conclusions derived from the work presented in the paper.

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II. FLICKER TRANSFER ANALSYIS AND ALLOCATION OF EMISSION LIMITS

A. *Flicker propagation in radial and interconnected systems*

Propagation of flicker in radial systems can be attributed to the system impedances based on the assumption that flicker severity is proportional to the relative voltage change. With reference to the radial system illustrated in Fig. 1, flicker propagation from a lower voltage level (downstream bus bar-4) to a higher voltage level (upstream bus bar-2) can be estabslished using the fault levels. Due to the relatively high fault levels at the upstream bus bars, flicker would be substantially attenuated at the upstream [4],[10]. Conversely, flicker propagation from the upstream point of common coupling (PCC - bus bar-2) to the downstream bus bars (bus bar-3)would be mainly governed by composition of the downstream load apart from the line and the transformer impedances. Compared to the radial systems, investigation of flicker propagation in interconnected networks requires more refined methods which take the interaction between various bus bars into account. The possible methods of analsysis include impedance matrix method [2], load flow method [2] and simplified short circuit method [12],[2]. Impedance matrix method suggested in [2] determines the flicker transfer coefficient from one bus bar to another based on the system impedance matrix defined at mains frequency. In this method, induction motors are represented by their dynamic impedances. Dynamic impedance is defined for the mains frequency and hence the analysis will be based on the rms variations in the bus voltage. Thus, the determination of flicker transfer using impedance matrix method would be frequency independent. Furthermore, the assumption of nearly equal impedance angle in relation to the impedance matrix elements would not be valid for all cases. The load flow and simplified short circuit methods are also based on the static load representation and hence do not account for frequency of voltage fluctuations. Therefore, a need exits for the development of refined analytical methods for detailed investigations in relation flicker propagation in meshed networks.

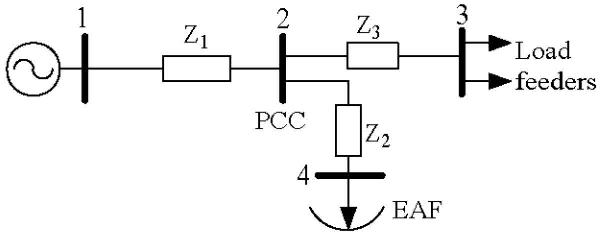

Fig. 1. A simple radial power system with an EAF

B. *AS/NZS61000.3.7 and allocation of emission limits*

As stipulated by the electromagnetic compatibility standards [11], [12], determination of planning limits for various voltage levels requires a knowledge on the manner in which the voltage fluctuations propagate through the system. Especially, when allocating emission limits to new customers the flicker transfer coefficient plays an important role. In relation to radial systems this can be explained using (1) which determines the global flicker emission level for the medium voltage (G_{PstMV}) fluctuating loads where L_{PstMV} is the flicker planning level for the medium voltage level (downstream), L_{PstHV} is the flicker planning level for the high voltage (upstream) level and T_{PstHM} is the flicker transfer coefficient between HV and MV systems.

$$G_{PstMV} = \sqrt[3]{L^3_{PstMV} - T^3_{PstHM} L^3_{PstHV}} \qquad (1)$$

A conservative value of unity can be used for T_{PstHM} without giving due consideration to the actual flicker transfer coefficient in the system. A transfer coefficient less than unity (ie. $T_{PstHM} < 1$) can be expected if the downstream (MV busbar) consists of a significant proportion of induction motor loads and consequently as per (1) more headroom would be available for medium voltage fluctuating loads for flicker emission.

In interconnected HV systems the flicker contributions from neighbouring busbars, eg. busbars B and C on another busbar A, are taken into account by the use of influence coefficients K_{B-A} and K_{C-A} in (2) for the calculation of the total available power S_{tHVA} at A for allocating the fluctuating load at A (S_{tHV}),

$$S_{tHV} = S_{tHVA} + K_{B-A}S_{tHVB} + K_{C-A}S_{tHVC} + ... \qquad (2)$$

where S_{tHVB} and S_{tHVC} are the available power levels at busbars B and C respectively. Similar to a radial system the influence coefficients K_{B-A} and K_{C-A} will depend on the composition of the loads connected at the various busbars.

III. FREQUENCY DOMAIN ANALYSIS OF INTERCONNECTED SYSTEMS

A. *Methodology*

In order to overcome the limitations of conventional flicker transfer analysis methods that are used for interconnected systems, a frequency domain based approach is introduced. The proposed method can be considered as an extension to the impedance matrix method. The main objective is to incorporate the influence of the induction motors on attenuation of flicker in a more pragmatic manner.

The methodology involves linearisation of the network around the operating point in d-q domain in synchronously rotating reference frame. The system components have been analysed as individual linear time invariant systems and combined to form a system matrix in the frequency domain describing the network. Where there are more than one flicker source, superposition can be used as suggested by [11], [12]. The node at which the fluctuating load is connected has been assumed to be the reference bus. This is due to the fact that fluctuating load can be considered as the source of voltage disturbance for the small signal analysis. Modelling of system components and the steps involved in deriving the flicker transfer coefficients at various nodes are discussed in following sections.

B. Modelling the network components

1) Line Impedances, Generators, Residential Loads: Following a-b-c to d-q domain transformation applied to a network element having a series reactance (X) and resistance (R) the voltage across and current can be written in the form (3):

$$[\Delta i] = [M][\Delta v] \tag{3}$$

where, $[\Delta v]$ and $[\Delta i]$ are the d-q axes voltage and current vectors and;

$$[M] = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \tag{4}$$

where a, b, c and d are 2^{nd} order transfer unctions.

Line impedances can be expressed as per (3) using the node voltages and line currents. Residential loads are assumed to be series R-X type impedances and hence transformation of such a passive load from a-b-c to d-q domain would be again similar to (3). Generators are represented by their subtransient reactance (X_g) with short circuited source voltage hence representation X_g would also be similar to that of the line impedances.

2) Industrial Loads: Industrial loads are represented by aggregated induction motors. A suitable aggregation method has to be implemented and one or more aggregated motors may have to be used to best represent the total industrial load. In the present work, motor loads are considered to be the major contributing factor in flicker attenuation and hence an appropriate dynamic modelling method has to be adopted. As the analysis is based on the linearisation, small signal induction motor models are used. State space representation of the voltage-flux linkage equations of induction motors in d-q domain are utilised to derive 5^{th} order transfer functions $(G_1(s) - G_4(s))$ between the d-q axes bus voltages and the currents which incorporate the motor load dynamics as well assuming a pump type load.

$$\begin{bmatrix} \Delta i_q \\ \Delta i_d \end{bmatrix} = \begin{bmatrix} G_1(s) & G_2(s) \\ G_3(s) & G_4(s) \end{bmatrix} \begin{bmatrix} \Delta v_q \\ \Delta v_d \end{bmatrix} \tag{5}$$

C. Combining the network components

Conventional nodal analysis is used to relate the node voltages and currents to combine the individual linear time invariant systems in an interconnected network containing n number of nodes as below:

$$[\Delta i_{sys}] = [Y][\Delta v_{sys}] \tag{6}$$

where, $[\Delta i_{sys}]$ and $[\Delta v_{sys}]$ are the respective voltage and current vectors for small voltage variations. For for the n bus system $[\Delta i_{sys}]$ and $[\Delta v_{sys}]$ consist of 2n number of elements.

Y defines the system transfer matrix and can be considered as a frequency domain non-linear admittance matrix where all the other systems components such as generators, industrial loads and residential loads are included in it. The effect of fluctuating load at m^{th} bus bar is reflected in the corresponding node current.

The nodal voltages can be expressed as:

$$[\Delta v_{sys}] = [Z][\Delta i_{sys}] \tag{7}$$

where, Z = $[\text{Y}]^{-1}$. The three phase bus voltage at m^{th} node can be defined as:

$$v_{a,b,c} \quad = \quad V_p(1 + \Delta v_m)\cos(\omega_b t - (n-1)\frac{2\pi}{3} + \phi) \tag{8}$$

where, V_p is nominal peak line-ground voltage, Δv_m is the voltage fluctuation in m^{th} node , ω_b = $2\pi f_b$ f_b being the mains frequency, ϕ is the bus voltage angle and n = 1,2,3. The d-q axes voltage changes can be derived as:

$$\begin{bmatrix} \Delta v_{qm} \\ \Delta v_{dm} \end{bmatrix} = \begin{bmatrix} \Delta v_m \\ 0 \end{bmatrix} \tag{9}$$

Using (7) and (9), two voltage transfer coefficients can be established for the i^{th} node with respect to q-axis voltage change in m^{th} (noting d- axis voltage change at m^{th} node is zero) as:

$$Tq_{mi} = \left|\frac{\Delta v_{qi}}{\Delta v_{qm}}\right| = \left|\frac{Z_{i,m} - Z_{i,n+m}[\frac{Z_{n+m,m}}{Z_{n+m,n+m}}]}{Z_{m,m} - Z_{m,n+m}[\frac{Z_{n+m,m}}{Z_{n+m,n+m}}]}\right| \tag{10}$$

$$Td_{mi} = \left|\frac{\Delta v_{di}}{\Delta v_{qm}}\right| = \left|\frac{Z_{i+n,m} - Z_{i+n,n+m}[\frac{Z_{n+m,m}}{Z_{n+m,n+m}}]}{Z_{m,m} - Z_{m,n+m}[\frac{Z_{n+m,m}}{Z_{n+m,n+m}}]}\right| \tag{11}$$

Tq_{mi} and Td_{mi} express the q and d axes voltage change at i^{th} node with respect to the q- axis voltage change in m^{th} node. Note that in (11), d-axis voltage change in i^{th} node is expressed as a fraction of q-axis voltage change in m^{th} node. Δv_m is defined as a sinusoidal signal as per (12) in order to represent a typical modulating signal enabling the investigation of the frequency dependent characteristics of the transfer coefficients (Tq_{mi}) and (Td_{mi}).

$$\Delta v_m = m\sin(2\pi f_m t) \tag{12}$$

where, f_m, modulation frequency frequency and m is the modulation depth. As Tq_{mi} and Td_{mi} are established as functions of ‘s’ their values at a given modulation frequency can be determined by taking their frequency response. The commonly used perceptible flicker frequency range is covered by varying the modulation frequency (f_m) between 0.05Hz and 40Hz. As illustrated in Fig. 2 if the voltage fluctuation at m$^{\text{th}}$ node ($\Delta v_m = \Delta v_{qm}$) and the voltage angles (δ_i) of the other nodes are known, d-q axes voltage changes at all other nodes can be determined using (10) and (11) which in turn can be used to establish

(a) the instantaneous phase voltages and hence determine the voltage transfer coefficient at each node, and/or
(b) the fluctuation in voltage envelope (Δv_i) at any node using (13) or (14):

$$\Delta v_i = \frac{\Delta v_{qi}}{\cos \delta_i} \tag{13}$$

$$\Delta v_i = -\frac{\Delta v_{di}}{\sin \delta_i} \tag{14}$$

A conventional load flow study will provide the voltage angle (δ_i) of each node required for (a) and (b) above.

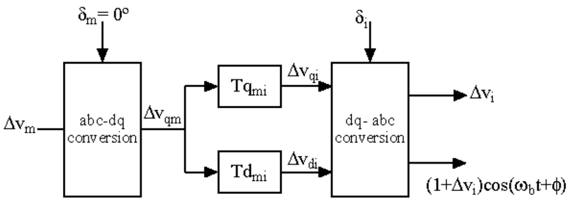

Fig. 2. Evaluation of voltage fluctuations at the bus bars

IV. ILLUSTRATIVE EXAMPLE

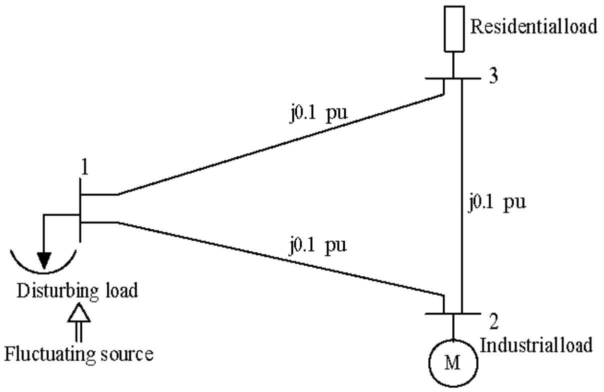

Fig. 3. Three node system

The proposed method has been applied to a simple interconnected system that contains one industrial load node and one residential load node as shown in Fig. 3. As the disturbing load at node 1 is the source of voltage fluctuation, node-1 can be considered as an ideal fluctuating voltage source in the small signal system. Furthermore, as any generator node will simply be replaced by its subtransient impedance, absence of a separate generator node does not affect the analysis of the network.

The system voltage is 2.3kV and the industrial load and the residential load are equivalent in terms of their kVA and power factor. A 2250hp induction motor of which the data is given in [13] is used to represent the industrial load. Line impedances are given on a 5kVA base. However, the induction motor transfer functions are developed using its own base values. Therefore all the system components including line impedances have been converted into a common per unit system applicable to the induction motor. Node 1 which contains the disturbing load produces a voltage fluctuations of Δv_1 which gives rise to a q-axis voltage change of Δv_{q1}. For comparison of the results obtained from the frequency domain approach, the network was simulated in time domain using PSCAD$^{\text{TM}}$EMTDC ®. Figs. 4 and 5 illustrate the variations in the magnitudes of the q axis (T_{q12} and T_{q13}) and d axis (T_{d12} and T_{d13}) transfer coefficients respectively with modulation frequency(f_m). According to Fig. 4, q-axis voltage attenuation prediction from the frequency domain method is in close agreement with the time domain simulation. A relatively significant difference can be seen between the predicted d-axis voltage attenuation and the time domain simulation results, yet this discrepancy does not affect the the overall attenuation of the voltage envelope as result of the extremely small values of d-axis voltages arising at nodes 2

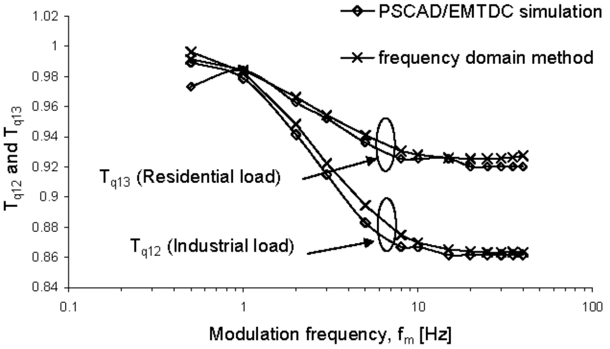

Fig. 4. Variation of q-axis voltage transfer coefficients (T_{q12} and T_{q13}) with the modulation frequency (f_m)

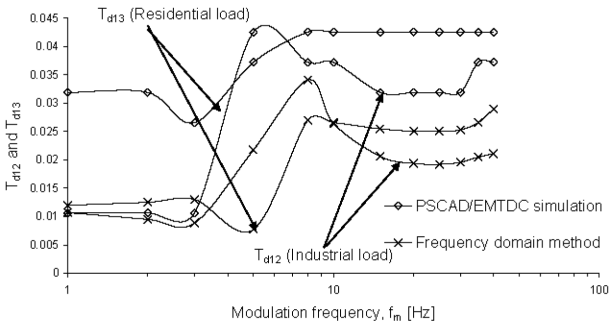

Fig. 5. Variation of d-axis voltage transfer coefficients (T_{d12} and T_{d13}) with the modulation frequency (f_m)

and 3. It is evident that both q and d axes voltage perturbations are attenuated to a better extent at node 2 where the induction motor load is connected. Despite the static bahaviour of passive load, the interconnecting line between nodes 2 and 3 has assisted in attenuating voltage fluctuations at node 3. D-q axes voltage changes which have been determined using the calculated voltage transfer coefficients are utilised to establish the transfer coefficients of the voltage envelope at nodes 2 and 3 as:

$$T_{\Delta v_{12}} = \left|\frac{\Delta v_2}{\Delta v_1}\right| \tag{15}$$

$$T_{\Delta v_{13}} = \left|\frac{\Delta v_3}{\Delta v_1}\right| \tag{16}$$

where, Δv_2 and Δv_3 are the per unit voltage fluctuations at nodes 2 and 3 derived from 13 or14. Variations in magnitude of $T_{\Delta v_{12}}$ and $T_{\Delta v_{13}}$ with f_m are illustrated in Figure 6. It also depicts the magnitude variations of the voltage transfer coefficient ($T_{\Delta v}$) and the flicker transfer coefficient (T_{Pst}) determined using time domain simulation. If the impedance matrix method is used, assuming the locked rotor impedance of the induction motor to be its dynamic impedance, the transfer coefficients $T_{\Delta v_{12}}$ and $T_{\Delta v_{13}}$ are found to be 0.86 and 0.92 respectively which are also indicated in Fig. 6. As the modulation frequency increases the transfer coefficients established using the frequency domain method and time domain simulation are seen to converge to the transfer coefficient determined employing the impedance matrix method. The threshold frequency of voltage fluctuations (f_{m-th}) at which a transfer coefficient reaches its steady value would depend on the characteristics of the aggregate induction motor(s) and the network parameters. For the system under consideration, f_{m-th} is about 20Hz.

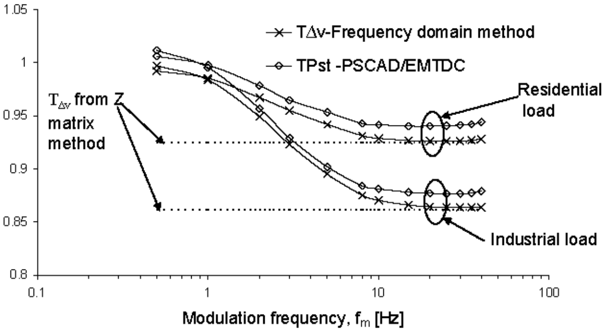

Fig. 6. Variation of voltage transfer coefficients ($T_{\Delta v12}$ and $T_{\Delta v13}$) with the modulation frequency (f_m)

V. CONCLUSIONS

This paper presented the methodology, implementation and analytical results of a frequency domain approach that can be used to examine flicker propagation in interconnected systems. The proposed method employs a detailed representation of induction motor loads and hence enables determination of frequency dependant characteristics of flicker as it propagates in a meshed network. Propagation of flicker in a simple 3-node network was examined using the proposed approach and the results were compared with the impedance matrix method and the results from time domain simulation work.

With reference to the flicker frequency range of interest (i.e 0.05Hz $<$ f_m $<$ 40Hz), the results suggest that the flicker transfer coefficient T_{Pst} is mainly governed by the composition of the load as well as the relative proportions of dominant flicker frequencies that exist in the voltage envelope. Therefore, the validity of the assumption of frequency independency of T_{Pst} which has been made in the impedance matrix method can be examined by investigating the variation of T_{Pst} over the modulation frequency range. It has been found that, where voltage envelope contains a significant level of low frequency components (below the threshold frequency f_{m-th}), frequency dependency has to be taken into account in determining the flicker transfer coefficients in the network hence the impedance matrix method is found to be less accurate. Conversely, if the frequency components which appear at or less than the threshold frequency, f_{m-th} are relatively small, frequency dependance of flicker attenuation can be neglected. However, in practice the flicker generated by typical fluctuating loads may contain random combinations of numerous flicker frequencies and hence the actual T_{Pst} would lie between unity and the minimum value of T_{Pst} determined from T_{Pst} vs f_m curve. The tie lines of the meshed systems seem to have a significant impact on compensating flicker at remote bus bars that contains passive loads.

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