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Methodology of calculating harmonic distortion from multiple traction loads

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ABSTRACT

This paper presents a methodology for studying and specifying incremental and aggregated harmonic distortion emission limits from multiple harmonic sources that are connected to the utility network in close proximity and/or electrically are close to each other. The methodology specifically concentrates on traction loads and includes the development of combined equivalent circuits for the harmonic sources for evaluating their impact on power quality. This methodology has been used successfully to represent an electrified traction load and can be extended and applied to the assessment of multiple embedded generators such as from PV solar or wind farms.

1. Introduction

As part of the requirements for Distribution Code and Grid Code compliance in the United Kingdom, harmonic voltage distortion must be kept below specified limits. In terms of the requirements both documents refer the reader to Engineering Recommendation G5/4-1 [5]. The assurance of compliance is provided through undertaking of harmonic voltage distortion studies and measurements. The voltage distortion study method described in this paper is based on the harmonic load flow procedure. The harmonic load flow procedure calculates the propagation of harmonic currents at each harmonic frequency resulting in the combined harmonic current through branches of interest and more importantly in harmonic voltage distortion at each node of interest.

This paper presents a methodology for studying and specifying incremental and aggregated harmonic distortion emission limits from multiple harmonic sources that are connected to the utility network in close proximity and/or electrically are close to each other. This methodology has been developed to represent an electrified traction load with multiple feeder stations connected to the utility network in the same area and each connection consisting of several traction units supplied through the railway power distribution system. The methodology can be extended and applied to the assessment of multiple embedded generators such as from PV solar or wind farms.

The methodology includes the development of combined electrical equivalent circuits for the harmonic sources for evaluating their impact on power quality. The combined electrical equivalent circuits are based on the network electrical parameters and statistical aggregation of harmonic distortion contributions from different sources. This enables integration of all the harmonic sources such that harmonic load flow studies can be undertaken with a conservative approach without exaggerating their effects on the network. Furthermore, this enables the separation of the complex load modelling from the mainstream power system harmonic load flow analysis. It must be emphasised that the paper does not cover a review of literature on traction load integration onto electric systems. Specific examples of such analysis can be found in [6,7].

The system considered for the study consisted of three main parts: the traction system; the utility (transmission/distribution) network; and the interface between them which may consist of traction transformers, compensation equipment, harmonic filters, etc. The system representation has to be sufficiently detailed and include suitable model representation of the trains' operations. Detailed representation of the trains in harmonic studies can be very complex and it is common to employ simplified methods while maintaining accuracy.

A method based on aggregation of traction loads and construction of a Norton equivalent circuit and its integration to the utility network is described in this paper. The Norton equivalent accounts for the effects of the 25 kV impedance on the harmonic propagation through the system and the aggregated traction load. The paper also describes the modification of utility network equipment to properly represent harmonic behaviour, according to recommended industry practices such as CIGRE.

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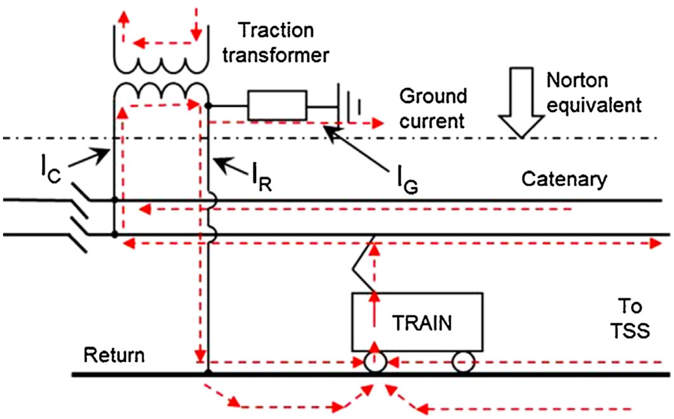

Fig. 1. Flow of harmonic currents through the traction system.

2. Traction system

2.1. Flow of harmonic currents

In an electric traction system, each train acts as a harmonic current source. The harmonic currents will propagate through the catenary system, traction transformer and into the EHV/HV system, as illustrated in Fig. 1. The harmonic current distribution will depend on the catenary system parameters, train parameters and train location.

The Norton equivalent has to adequately represent the traction system at each traction power supply point in order to account for all parameters. The Norton equivalent must account for a number of trains (potentially of different types) operating to a given timetable. Therefore, different Norton equivalents are required to model the different sections, modes of operation, timetables, rolling stock, etc. Based on previous experience, some averaging methods can be employed by the designer to simplify the process.

The Norton equivalent circuit will depend on the type of electrification system such as autotransformer system, booster transformer system or rail return system etc. The traction system considered here is the rail return system (and it may include additional return conductors) with the related Norton equivalent circuit shown in Fig. 2. To derive the complete Norton equivalent circuit, both admittance matrix and equivalent current sources have to be determined. With reference to Fig. 2, the following equations are used to derive the equivalent circuit parameters:

$$I_1 + I_{n1} = V_1 \times Y_{n11} + (V_1 - V_2) \times Y_{n12} \tag{1}$$

$$I_2 + I_{n2} = V_2 \times Y_{n22} - (V_1 - V_2) \times Y_{n12} \tag{2}$$

To calculate the Norton equivalent circuit admittance matrix for conductor "*i*", it is necessary to:

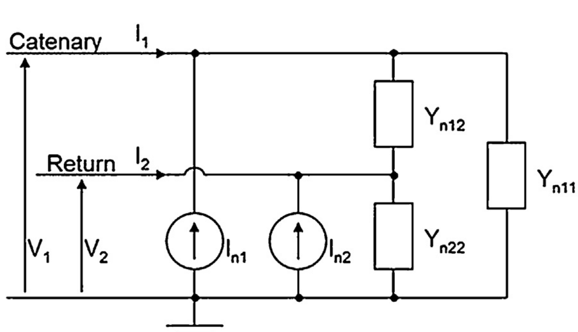

Fig. 2. Traction system Norton equivalent circuit.

- eliminate all internal sources (loads, feeder stations, etc.),
- apply a known current *I* to the conductor "*i*" for all frequencies of interest,
- short-circuit all other conductors to earth,
- calculate voltage V_i and currents in all other conductors for all frequencies.

In this particular example case, the first step is to short the conductor 2 (return) to ground and inject a known current into the conductor 1 (catenary). This is followed with shorting the conductor 1 (catenary) to ground and injecting a known current into the conductor 2 (return).

From these it is possible to write:

$$I_1 = V_1 \times Y_{n11} + V_1 \times Y_{n12} \rightarrow Y_{n11} + Y_{n12} = \frac{I_1}{V_1} \tag{3}$$

$$I_2 = -V_1 \times Y_{n12} \rightarrow Y_{n12} = -\frac{I_2}{V_1} \tag{4}$$

$$I_2 = V_2 \times Y_{n22} + V_2 \times Y_{n12} \rightarrow Y_{n12} + Y_{n22} = \frac{I_2}{V_2} \tag{5}$$

$$I_1 = -V_2 \times Y_{n12} \rightarrow Y_{n12} = -\frac{I_1}{V_2} \tag{6}$$

This effectively determines the Norton equivalent admittances. These admittances must be determined for each harmonic frequency, each feeder station and for each of the feeding configurations, such as transformer outage, feeder station outage, etc.

To determine Norton equivalent source currents, a procedure similar to the one below has to be followed:

- all internal sources have to be re-activated,
- all conductors have to be short circuited to earth,
- the position of traction harmonic current generators (trains) must be changed in accordance with the traffic pattern (power demand and train position),
- train harmonic currents are injected at the location of the train and the currents flowing into the feeder station (I_C, I_R and I_G in Fig. 1) are calculated,
- harmonic current contributions from all trains in the sections are aggregated.

The steps above are repeated for each required frequency.

2.2. Frequency dependency of admittance

Dependency of the catenary system parameters on frequency is very important and needs to be accurately represented. Frequency dependency of a typical catenary system resistance and inductance is shown in Fig. 3 [1].

The conductor resistance dependency on frequency is very noticeable and very important. The change in the conductor inductance may not appear to be high, but it does have an effect and it should not be neglected. The dependency of the catenary system parameters on frequency can be approximated using some exponential functions. For the particular case shown in Fig. 3, a good match is obtained using the following approximations:

$$R(h) = \frac{R_1}{2} \times \left(1 + h^{0.735}\right) \tag{7}$$

$$L(h) = L_1 \times h^{-0.05} \tag{8}$$

where *h* is the harmonic order, R_1 and L_1 are the fundamental frequency resistance and inductance, respectively.