ESTABLISHMENT OF LOAD COMPOSITION IN AGGREGATE HARMONIC LOAD MODEL AT LV BUSES BASED ON FIELD MEASUREMENTS

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INTRODUCTION

This paper presents the methodology developed to derive the linear and nonlinear load composition of an aggregate harmonic load model based on harmonic measurements taken at the service entrance feeder. Based on harmonic current spectra of typical nonlinear loads and aggregate harmonic loads obtained through measurement at service entrance, a weighted coefficient representative of the percentage combination of each type of nonlinear load is determined by solving a set of simultaneous equations with complex variables. Subsequently, linear load fraction is determined through SUPERHARM simulation of the modeled aggregate load.

BACKGROUND

Power electronics technology has advanced so extensively that present day electrical loads found in all sectors of consumers of electricity i.e industrial, commercial and residential consists of a significant portion of power electronic/nonlinear loads such as adjustable speed drives, converters, fluorescent lamps, personal computers and television sets. Connected to the same bus with the power electronic/nonlinear loads are the linear loads such as motor loads, heater/conventional ovens and air conditioning. While power electronic loads generate harmonics, the linear loads act as damping elements to harmonics propagation and alter the resonance frequency of the distribution system [1]. As there are usually a large number of power electronics and linear loads of medium and small power range connected to the same bus, it is not practical to model each load individually for a harmonic propagation study. Hence, an aggregate harmonic load model representative of the aggregate sum of power electronic/nonlinear loads and linear loads are desired. In the case of current source model, an independent harmonic current source is used to represent the power electronic/nonlinear loads and resistive, inductive and capacitive elements are used to represent linear loads.

In developing aggregate harmonic load model, it is crucial that both the linear and nonlinear loads percentage composition be reasonably accurate so that frequency response curves and voltage distortion levels at distribution buses obtained through simulation are in close agreement with those of real distribution network. Published papers on aggregate harmonic load model typically refer to specific groups of nonlinear loads [2-5] and have not considered aggregate harmonic loads made up of linear and a variety of nonlinear loads with medium and small power range such as those classified based on customers activities.

This paper presents a methodology to determine the fraction composition of linear and nonlinear loads through harmonic measurements taken at low voltage (LV) bus of the aggregate harmonic loads classified based on customer types/activities.

GENERIC LOAD REPRESENTATION AT LV BUSES

Load Representation

A generic comprehensive load representation at LV buses for harmonic studies is shown in Fig. 1. Computation of the model parameters are explained and elaborated in reference [1] :

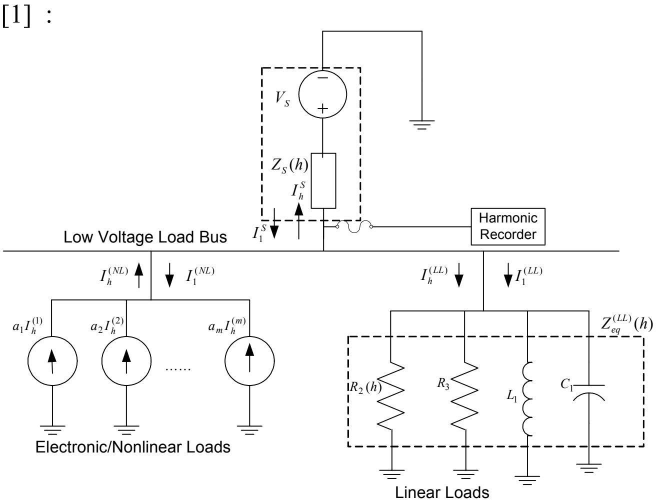

Fig. 1. General load representation for harmonic studies

Circuit Analysis of The Model

The nonlinear load composition at the LV bus typically consists of magnetic ballast discharge lamps (DL), compact fluorescent lamps (CFL), television sets (TV), converters (CONV), computers (PC) and adjustable speed drives (ASD) depending on the class of consumers. The net total harmonic current $I_h^{(NL)}$ is the vector sum of the harmonic current generated by the individual nonlinear load connected to the bus. With reference to Fig. 1, for a 1 p.u fundamental current of the individual nonlinear load, the harmonic current generated based on its fractional active power a_i of the total nonlinear load can be written as $a_i \bar{I}_h^{(i)}$.

Hence, the net total harmonic current generated by the nonlinear loads is,

$$\bar{I}_h^{(NL)} = a_1 \bar{I}_h^{(1)} + a_2 \bar{I}_h^{(2)} + \ldots + a_i \bar{I}_h^{(i)} + \ldots + a_m \bar{I}_h^{(m)} \quad (1)$$

where $a_1, a_2, \ldots a_m$ are weighted coefficients representing the respective individual nonlinear load fraction active power of the total nonlinear load at the LV bus, and $\sum_1^m a_i = 1.0$, $0 < a_i \leq 1.0$

Also, let K_E represents the nonlinear loads fraction of the active power of the total plant load. Assuming that the fundamental current is approximately equal to load rms current, one can write:

$$\bar{I}_1^{(NL)} = K_E \bar{I}_1^S \quad (2)$$

As $\left|\bar{Z}_{eq}^{(LL)}(h)\right| >> \left|\bar{Z}_h^S\right|$, it can be further approximated that,

$$\bar{I}_h^{(NL)} = \bar{I}_h^S \quad (3)$$

where $\bar{I}_1^{(NL)}$ and $\bar{I}_h^{(NL)}$ is total fundamental and harmonic current generated by the nonlinear loads respectively, $\bar{I}_1^S$ and $\bar{I}_h^S$ is the fundamental and harmonic current at the source (service entrance) branch respectively, $\bar{Z}_{eq}^{(LL)}(h)$ is the equivalent impedance of linear loads, $\bar{Z}_s(h)$ is the equivalent source impedance.

Substituting (3) into (1) and writing in matrix form to indicate each harmonic current (up to the 11th) we have,

$$\begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix} = \begin{bmatrix} \bar{I}_3^{(1)} & \bar{I}_3^{(2)} & \bar{I}_3^{(3)} & \bar{I}_3^{(4)} & \bar{I}_3^{(5)} \\ \bar{I}_5^{(1)} & \bar{I}_5^{(2)} & \bar{I}_5^{(3)} & \bar{I}_5^{(4)} & \bar{I}_5^{(5)} \\ \bar{I}_7^{(1)} & \bar{I}_7^{(2)} & \bar{I}_7^{(3)} & \bar{I}_7^{(4)} & \bar{I}_7^{(5)} \\ \bar{I}_9^{(1)} & \bar{I}_9^{(2)} & \bar{I}_9^{(3)} & \bar{I}_9^{(4)} & \bar{I}_9^{(5)} \\ \bar{I}_{11}^{(1)} & \bar{I}_{11}^{(2)} & \bar{I}_{11}^{(3)} & \bar{I}_{11}^{(4)} & \bar{I}_{11}^{(5)} \end{bmatrix}^{-1} \begin{bmatrix} \bar{I}_3^S \\ \bar{I}_5^S \\ \bar{I}_7^S \\ \bar{I}_9^S \\ \bar{I}_{11}^S \end{bmatrix} \quad (4)$$

It should be noted that (4) has been formulated with the assumption that there are five distinctly dominant individual or groups of individual nonlinear loads fed from the particular low voltage bus. With this assumption, a 5X5 matrix is set up, hence limiting the harmonic to be considered to the 11th. This is justified by the fact that field measurements indicated that individual harmonic distortion for harmonic order larger the 11th is relatively small and can be ignored.

Note that all quantities on the right hand side of (4) are obtained from harmonic field measurements.

HARMONIC MEASUREMENTS AT LV BUSES

Ideally, in congruence with the establishment of parameters of the aggregate harmonic load model shown in Fig. 1, separate sets of current measurements should be obtained for the branch that feeds the nonlinear loads and the branch that feeds linear loads in addition to voltage measurement at the common low voltage load bus. However, in practice, only one set of current measurements is taken at the service entrance feeder, as linear and nonlinear loads are not grouped separately and supplied by different cables.

Therefore, the fraction of induction motors and other linear loads, $(1 - K_E)$, together with the fraction of individual/group of nonlinear loads will have to be derived based on measured power and individual harmonic current distortion at the service entrance and harmonic current spectra of individual/group of nonlinear loads.

Sample of results indicating current total harmonic distortion (THD_I) measured at the service entrance are shown in Fig 2. It can be observed that THD_I varies randomly with a trend component that is dependent on time of the day. For simplicity, the trend component can be divided into daytime (9.00 hrs – 18.00 hrs) and nighttime (18.00 hrs – 24.00 hrs). Histogram of the THD_I during daytime and nighttime is approximately a normal distribution.

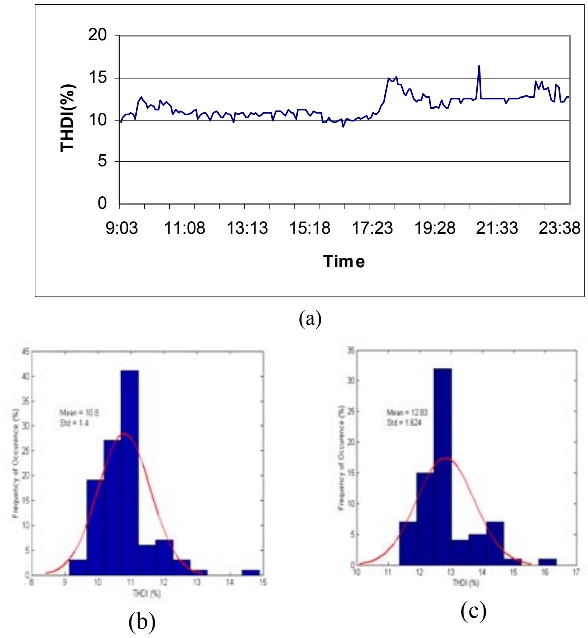

Fig. 2. Bank aggregate harmonic load, (a) THD_I variation with respect to time, (b) THD_I histogram during daytime period, (c) THD_I histogram during nighttime period

DERIVATION OF LOAD COMPOSITION

A simulation model as shown in Fig. 3, using probabilistic values of a_i obtained by solving (4) is used to determine the effective harmonic current spectrum at the aggregate nonlinear load branch.

Characteristic curves indicating variation of THD_I with respect to K_E, are obtained through SUPERHARM simulation using model shown in Fig. 4. Aggregate nonlinear load is represented by a single harmonic current source with the effective harmonic current spectrum derived based on Fig. 3. Linear loads are assumed to be made up of 10% resistive load and 90% induction motor load modeled in

SUPERHARM based on standard locked rotor KVA/HP ranges provided in NEMA MG-1-1993 [6].

Fundamental current at the source branch (I_1^S) is fixed and set equal to field measured values. Values of K_E are then varied from 1 to 0.1 resulting in corresponding variation in THD_I at the source branch (service entrance). The influence of K_E variation on THD_I at the service entrance is illustrated in Fig. 5

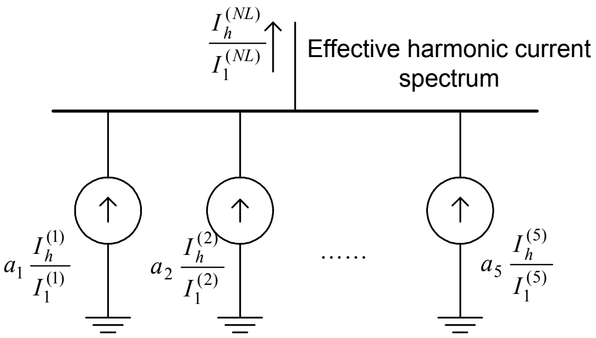

Fig. 3. Simulation Model of Nonlinear Loads

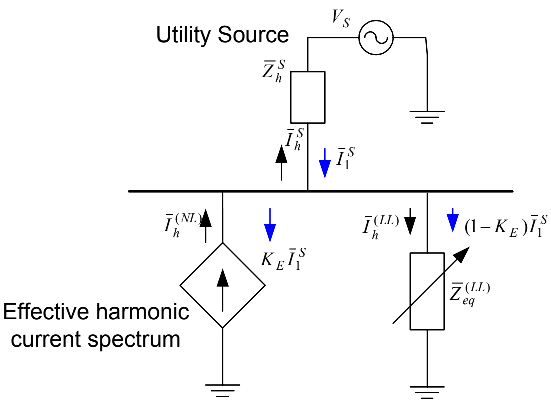

Fig. 4. SUPERHARM Simulation Model

ILLUSTRATION OF THE METHODOLOGY

Harmonic measurement results of individual harmonic distortion at the service entrance (source) and for the respective individual nonlinear loads shown in Table 1 and 2 are used as illustration. It is assumed that all the three classes of consumers have nonlinear loads that can be categorized into five categories as indicated in Table 2.

Coefficients a_i are obtained by solving (4) using the data provided in Tables 1 and 2. These coefficients (shown in Table 3) are subsequently used to calculate (in custom made MATLAB subroutine based on the single line diagram illustrated in Fig. 3.) effective harmonic current spectrum.

Measured values of THD_I at the service entrance are then used to trace the corresponding fraction of nonlinear loads (in total aggregate load at the bus) operating during the day load and night load period for different types of consumers, as indicated in Fig. 5.

The analysis performed showed that for all the three classes of aggregate loads magnetic ballast discharge lamps made up about 30-60% of the total nonlinear loads. The ratio of linear to nonlinear loads varies between different classes of aggregate loads. For example, the bank aggregate load has a ratio of 50:50, the hospital a ratio of 54:46 and the hotel a ratio of 85:15. High proportion of nonlinear loads is found in bank installations mainly due to discharge lamps, six pulse converters and computers. Linear/nonlinear load composition is also influenced by energy usage as indicated by the bank aggregate load which shows a reduction in linear loads during the night as most air-conditioners are switched off. The hospital and hotel aggregate loads linear loads remain about the same throughout the day and night due to the nature of their business needs. The results can be taken as an added value feature to harmonic measurements taken at LV buses as it provides insight into the types and proportion of linear and nonlinear loads found in aggregate loads.

TABLE 1 - Measured harmonic current distortion at the service entrance

h	$\bar{I}_h^S / \bar{I}_1^S$					
	Day			Night		
	Bank	Hosp.	Hotel	Bank	Hosp	Hotel
3	3.0%	3.4%	1.6%	5.0%	3.9%	1.3%
5	5.1%	1.3%	1.3%	10.0%	1.6%	2.0%
7	8.1%	1.8%	0.9%	3.2%	1.6%	1.0%
9	1.3%	1.1%	1.0%	0.3%	1.2%	0.9%
11	2.1%	0.4%	1.0%	5.1%	0.3%	0.8%
THD_I	10.3%	4.2%	2.65%	12.7%	4.7%	2.9%

TABLE 2 - Measured harmonic current spectra and THD_I of individual nonlinear loads

h	$\bar{I}_h^{(i)} / \bar{I}_1^{(i)}$				
	T 1 (e.g., 6-pulse Converter)	T2 (e.g., P.C) *	T 3 (e.g., Compact Fluorescent Lamp) *	T 4 (e.g., Discharge Lamp)	T5 (e.g., TV) *
3	1.9%	65%	90%	15.0%	84%
5	4.3%	23%	72%	8.9%	68%
7	11.0%	21%	51%	3.0%	53%
9	1.0%	27%	23%	1.7%	36%
11	4.5%	13%	15%	1.2%	22%
THD_I	13%	78%	129%	18%	122%

*Diversity factor=0.8 applied [3]

TABLE 3 - Derived nonlinear load composition

Installation / Time of Day		T1 (a_1)	T 2 (a_2)	T 3 (a_3)	T 4 (a_4)	T 5 (a_5)
Bank	Day	0.117	0.144	0.115	0.521	0.103
	Night	0.086	0.152	0.112	0.544	0.106
Hosp.	Day	0.326	0.121	0.074	0.463	0.016
	Night	0.221	0.146	0.033	0.568	0.032
Hotel	Day	0.354	0.163	0.065	0.324	0.094
	Night	0.289	0.152	0.057	0.403	0.099

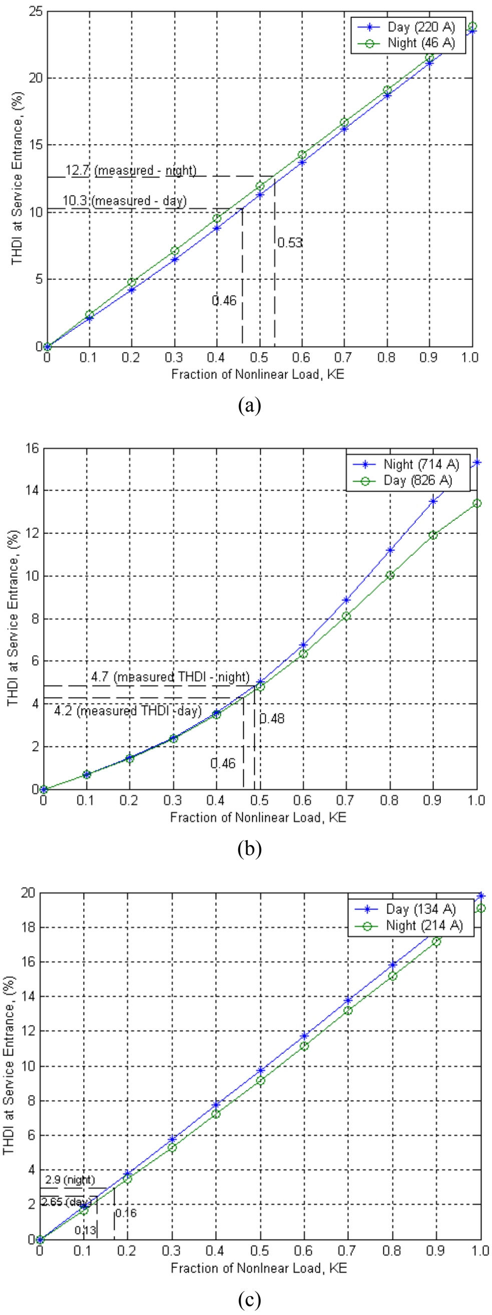

Fig. 5. Characteristic curves of nonlinear load fraction K_E, against THD_I, (a) bank aggregate load, (b) hospital aggregate load, (c) hotel aggregate load

CONCLUSIONS

A methodology to derive approximate percentage composition of linear load and nonlinear loads found in aggregate harmonic loads of different classes of customers is presented. Results of this study concur with findings based on a rough inspection of loads found at the respective customer sites.

As most utilities do not have information about customers load composition, the results are important inputs to aggregate harmonic load modeling which is particularly useful for distribution network harmonic simulation studies. With sufficient amount of harmonic measurements, the methodology presented can be used to further develop harmonic current spectra of typical aggregate loads found in distribution systems.

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REFERENCES

[1] Task Force on Harmonics Modeling and Simulation, 2003, "Impact of Aggregate Linear Load Modeling on Harmonic Analysis: A Comparison of Common Practice and Analytical Models," *IEEE Transactions on Power Delivery*, vol. 18, pp. 625 - 630.

[2] A. Mansoor, W. M. Grady, P. T. Staats, R. S. Thallam, M. T. Doyle, and M. J. Samotyj, 1995, "Predicting the Net Harmonic Currents Produced by Large Numbers of Distributed Single Phase Loads," *IEEE Transactions on Power Delivery*, vol. 10, pp. 2001 - 2005.

[3] A. Mansoor, W. M. Grady, A. H. Chowdhury, and M. J. Samotyj, 1995, "An Investigation of Harmonics Attenuation and Diversity Among Distributed Single Phase Power Electronic Loads," *IEEE Transactions on Power Delivery*, vol. 10, pp. 467 - 473.

[4] J.A. Orr, A. E. Emanuel, and K. W. Oberg, 1982, "Current Harmonics Generated by a Cluster of Electric Vehicle Battery Chargers," *IEEE Transactions on Power Apparatus and Systems*, vol. 101, pp. 691 - 700.

[5] J. M. Crucq, A. Robert, and B. Laborelec, 1989, "Statistical Approach For Harmonics Measurements and Calculations," presented at CIRED.

[6] Electrotek Concepts, 2000, *Users Guide SuperHarm*. Knoxville, Tennessee: Electrotek Concepts.