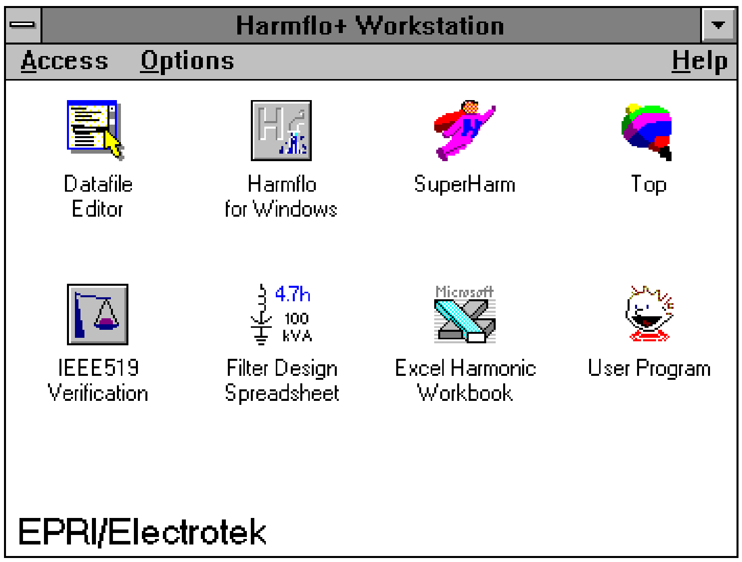
HarmFlo+ Tech Notes



for users of the EPRI/Electrotek HarmFlo+ Workstation

Issue # 94-2 ***October, 1994*** ***Editor: Thomas Grebe***

in this issue:

Letter from the Editor:

This is the second issue of *HarmFlo+ Tech Notes*. The technical newsletter provided to members of the HarmFlo User's Group. The initial plan for the newsletter is a quarterly technical publication highlighting contributions from members of the User's Group. This newsletter is published using Microsoft Word for Windows. If you wish to contribute an article, please contact me for appropriate text and figure formats. Contributions in the following areas are welcome:

- Technical articles
- Modifications / enhancements to the code
- Case studies / unique simulations
- Research projects
- SuperHarm / HARMFLO data preparation / model development
- Include / library files developed for distribution on the BBS
- Letters to the editor / User's Group
- Technical paper abstracts
- Questions for members of the User's Group

I believe that the exchange of technical information is one of the most important functions of the HarmFlo User's Group and this newsletter, in conjunction with The Resonant, will help to serve the needs of the members. As always, I'm open for suggestions regarding this publication and the User's Group in general.

Thanks for your support

For more information concerning the newsletter or to submit a contribution please contact:

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Modeling - Nonlinear Loads

Developing Models to Study the Effect of Numerous Small Nonlinear Loads

Any power system includes large numbers of nonlinear devices which act as small harmonic sources. These devices include electronic equipment such as computers and televisions, fluorescent lighting of all kinds, and small motor drives; as well as the saturation harmonics present from transformers. The penetration of these devices is becoming so wide that it is difficult to find linear loads in some locations. The harmonic currents injected by these small sources cause harmonic voltages to be present on any system. In installations of large converter equipment, these harmonics have been referred to as the “background” harmonic which are measured with the converter off-line. In other systems, there is no single large harmonic source, and the multitude of small nonlinear loads provide all of the harmonic excitation. The presence of these harmonic sources can overload filters designed to operated with an adjustable speed drive or other converter installation, and can excite resonances which otherwise would be dormant. Using SuperHarm to estimate the cumulative effect of the sources, however, is not a simple task. Even with measurement data on hand, it may not be easy to convert the data into useable models.

Modeling these nonlinear loads is quote difficult. Obviously, it is not feasible to model each device in detail. IT is not even feasible to know what devices are installed on the system in most cases, let alone which of these devices are functioning at any given time. At first glance, these facts appear to make the modeling job impossible.

These same characteristics, however, are true for the fundamental frequency requirements of the load - the power and the var needs over the course of time. Methods of predicting load profiles and estimating peak demands have been developed and are both accurate and widely used. These methods are based on empirical knowledge of the past behavior of the specific load in question as well as the knowledge of load behavior in general. It is possible that the harmonic performance of these customers can be modeled by similar techniques.

Many customers can be expected to exhibit similar characteristics. This will be increasingly true for similar types of customers - residential, commercial, etc. While it may not be feasible to define the harmonic performance of a “Typical” customer, it is reasonable to study the characteristics of groups of these loads.

Harmonic currents injected generated by a group of loads will add based on the magnitudes and phase angles of the individual currents. Harmonic cancellation occurs when the harmonic currents generated by adjacent nonlinear loads occur at difference phase angles. Measurements of a group of representative nonlinear loads has suggested that the lower order harmonics of single phase devices will tend to have less cancellation than the higher order harmonics. Figure 1 illustrates this effect for a group of electronic loads {1}/ These angle characteristics, couples with the generally lower magnitudes of the higher harmonic currents, will cause the lower order harmonics to be dominant when the harmonic excitation is due to many small sources. Also, the cancellation will be less when only a few nonlinear loads are being grouped together, so the highest harmonic current levels (expressed in percent of fundamental current) can be expected near the loads, with the percentage levels dropping as the observation point moves from branch circuit to panelboard to the main supply point. This reduction can be seen in the data of Table 1, for third harmonic measurements in a representative commercial building. These measurements show a wide range of third harmonic currents flowing near the load - 4 of 14 measurement points where the fundamental current was under 20 amps had third harmonic levels greater than 20%. Additional cancellation will be seen when the measurements involve larger groups of load, as shown by the measurements at points where the fundamental current flow is greater than 100 amps. These measurements show both lower levels and a reduced range.

The primary distribution system will include a large number of customers, and further cancellation and averaging can be expected. For practical load models, groups of customers will need to be lumped together. In order to be combined effectively, customers should be electrically close and should be of similar load type. Actually measuring the performance for a load group of this type is difficult unless the load group exists at the end of a feeder or on a feeder tap, beyond any capacitor banks. Measurements on load groups at the end of feeders can be loads in place. At present, there is only limited knowledge concerning the harmonic contribution of groups of loads. Current literature suggest that typical residential or commercial groups of amount 1 MW load will most often generate fifth harmonic currents in the range of 1% to 5% of the fundamental current, for example. For a given system, this range can be reduces by targeted measurements to provide models for the harmonic study. In other word, measurements of the background harmonic level taken with known system conditions can be used to estimate the harmonic content of the load. A particular example of this type of study is reported in Reference 2.

The success of any empirical model rests on the accumulation of a wide range of data, and it would be good to develop a database of measurements. In order to be useful for the database, the measurements should include fundamental and harmonic magnitudes for both current and voltage. The harmonic phase angles are useful when they are available. The type of load group should be identified. There can be no primary capacitance beyond the point of measurement, and there should be a reasonable expectation that the customers have no significant capacitance on their systems. We are currently collecting data for such a database, and we encourage any readers having this type of data to communicate it to us at one of the addresses listed above. With the increased knowledge of harmonic current levels which can be constructed. These models can be readily incorporated into SuperHarm, and will provide increased information on the harmonic levels which can be expected on a system.

Table 1 - Third Harmonic Current Levels at Various Points in a Commercial Building

	Fundamental Current Range			
Harmonic Level, % of fundamental	0-20A	20-50A	50-100A	>100A
0-2%	2	1	1	
2-4%		1		
4-6%	1		3	4
6-8%	1	3		2
8-10%	2	2	1	1
10-12%		3	1	1
12-14%	1			
14-16%	1	2		
16-18%	1			
18-20%	1			
>20%	4			

Fundamental Current Range				
Total # at level	14	12	6	8

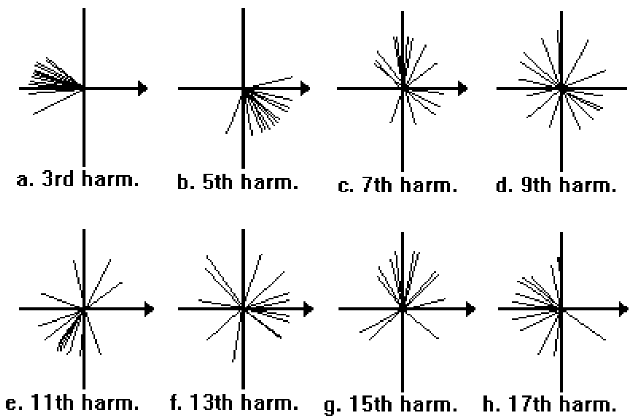

Figure 1 - Harmonic Phase Angles for a Representative Group of Electronic Loads

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Transformer Selection

Selection of Transformers for Commercial Buildings

Introduction

The need to consider the impact of harmonic currents in commercial building systems has arisen due to an increased usage of electrical equipment that draw nonsinusoidal current from the ac line. These nonlinear devices now typically comprise more than half, and in some cases as much as 90% of total building load.

When a transformer supplies nonlinear load current, the heating effect is greater than when the transformer supplies the same RMS value of linear current. Harmonic-induced transformer heating is of particular concern in commercial building because:

- Dry transformers predominate. Frequency-dependent losses are severe in this type of transformer.
- Delta - grounded wye transformers serving single-phase electronic power supplies suffer additional duty due to circulating triplen (3, 9, 15, ...) harmonic currents in the delta winding.

A transformer subjected to harmonic load currents should have a K-factor rating higher than the K-factor of the load it supplies. If the transformer is not K-factor rated, its maximum load kVA should be limited in accordance with ANSI/IEEE Standard C57.110.

Recent articles and papers have pointed out that it is preferable to use a K-factor rated transformer, rather than derating a general purpose transformer, because:

- K-factor transformers are designed for harmonic loading. Skin effect losses are reduced through the use of insulated stranding in the secondary windings. Larger cores are used to reduce the possibility of the transformer saturating due to high peaks on the distorted bus voltage waveform.

- A derated transformer may be overloaded anyway, because its nameplate kVA does not reflect its actual capability.

  These advantages must be weighed against the higher first cost of K-factor transformers.

K-Factor Rated Transformers

K-factor is defined in UL standards 1561 (low voltage) and 1562 (medium voltage) by an equation similar to:

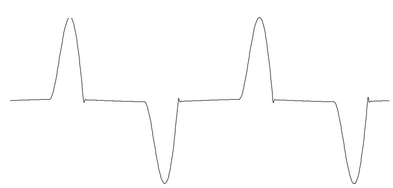
$$K = \frac{\sum_{h=1}^{h_{max}} \left(h\, f_h\right)^2}{\sum_{h=1}^{h_{max}} f_h^{\,2}} \tag{1}$$

where f_h is the RMS current at harmonic number h, per unit of the fundamental current. The UL standards express harmonic current per unit of the RMS load current. Equation (1) is more convenient because most harmonic measurement instruments report f_h..

Transformers Serving Electronic Power Supplies

A K-factor calculation for a typical circuit dedicated to single-phase electronic power supplies, such as personal computers, printers, and copiers, is shown below:

h	f_h	$f_h^{\,2}$	$(h\, f_h)^2$
1	1.000	1.0000	1.0000
3	0.658	0.4330	3.8967
5	0.436	0.1901	4.7524
7	0.203	0.0412	2.0192
9	0.070	0.0049	0.3969
11	0.006	0.0000	0.0044
13	0.026	0.0007	0.1142
15	0.030	0.0009	0.2025
17	0.018	0.0003	0.0936
19	0.009	0.0001	0.0292
21	0.010	0.0001	0.0441
23	0.011	0.0001	0.0640
25	0.006	0.0000	0.0225
	Σ	1.671	12.64



$$K = \frac{\sum_{h=1}^{h_{max}} \left(hI_h\right)^2}{\sum_{h=1}^{h_{max}} I_h^{\,2}} = \frac{12.64}{1.671} = 7.56$$

Figure 1. K-factor calculation

Determining K-factor for such a circuit when measurements are not available (e.g., new facilities) is not simply a matter of summing the load currents. That is, if the circuit consists of N identical loads, it is not correct to assume that the total current at each harmonic is approximately N times the current for a single load. Equipment component tolerances and different system impedances seen at the various receptacle locations along the circuit cause shifting of the phase angle spectra among the loads. The angle shifts, while small, result in significant cancellation in the higher order harmonics. Thus, although the K-factor of individual electronic loads may approach 30, the K-factor for a circuit devoted to these types of loads will rarely, if ever, exceed 9. K-9 transformers are not available from most manufacturers, so K-13 is usually specified. A K-4 rating may be acceptable for a transformer serving a mix of electronic and linear loads.

Transformers Serving Other Types of Loads

Occasionally, transformers dedicated to fluorescent lighting are encountered. K-factors of fluorescent lighting circuits are not as severe as those of circuits serving electronic power supplies. A K-4 transformer should always be sufficient for a fluorescent lighting application.

Adjustable speed drives (ASDs) of the type used in commercial buildings have a very high K-factor, but a transformer serving this type of load may not require a high K-factor rating. The amount of harmonic current injected into the ac system by an ASD is strongly influenced by the impedance of the system seen at the drive. If the transformer significantly increases this impedance, then harmonic injection decreases, and with it, K-factor. The per unit impedance of a transformer serving a number of small ASDs is very small on the MVA base of a single drive. In this case, there is little harmonic suppression, and the K-factor at the transformer can be 30 or even higher. (The manufacturer should be consulted if the magnitude of any single harmonic above the 10^{th} exceeds the fundamental magnitude divided by the harmonic number.)

On the other hand, the impedance of a transformer dedicated to a single drive is significant. Failing to account for this impedance will result in specifying a K-factor rating that is much higher than necessary. As an example, Figure 2 shows the harmonic injection before and after an isolation transformer was added to a 25 HP ASD. Although the initial K-factor was 58.6, a K-13 transformer was found to be adequate.

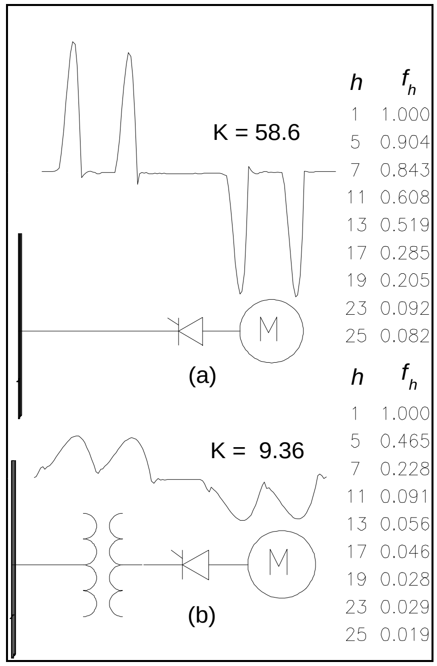


Figure 2. ASD K-factor with (b) and without (a) isolation transformer

Derating General Purpose Transformers

ANSI/IEEE C57.110 applies to general purpose transformers that are subjected to a load current with total harmonic distortion greater than 5%. The object of the standard is to determine the value of nonlinear current which results in transformer heating equal to that produced when the transformer is supplying rated linear load. Heating is due to total load loss, P_{LL}, which is composed of I^2R loss and stray loss. Stray loss, in turn, can be divided into:

- P_{EC} - winding stray loss, due to eddy-currents in the winding strands, and circulating currents between winding strands or parallel winding circuits.

- P_{OSL} - eddy-current loss in the core, core-clamps, tank and other structural parts.

Harmonics in the load current increase I^2R loss due to increased RMS current, but their effect on stray loss is more significant. P_{EC} is assumed to vary with the square of frequency, while P_{OSL} is less frequency-sensitive [2]. C57.110 assumes that all stray loss is due to winding loss, which conservatively overstates its frequency dependence.

Method of Determining Transformer Capability

The maximum RMS transformer load current with a given harmonic content, per unit of the rated linear load current, is derived as follows:

1. I^2R loss with nonlinear load, per unit of rated linear I^2R loss is:

$$\frac{R\,I_{RMS}^{\;2}}{R\,I_{1-R}^{\;2}} = \frac{R\sum_{h=1}^{h_{\max}} I_h^{\;2}}{R\,I_{1-R}^{\;2}} = \sum_{h=1}^{h_{\max}} I_h(pu)^2 \qquad (2)$$

2. Winding loss with nonlinear load, per unit of rated linear I^2R loss is:

$$P_{EC}(pu) = \frac{c\sum_{h=1}^{h_{\max}}\left[h\,I_h\right]^2}{R\,I_{1-R}^{\;2}} = \frac{c}{R}\sum_{h=1}^{h_{\max}}\left[h\,I_h(pu)\right]^2 \qquad (3)$$

Constant of proportionality c is found by evaluating winding loss under rated conditions:

$$\begin{aligned} P_{EC-R} &= c\,I_{1-R}^{\;2} \Rightarrow c = \frac{R\,P_{EC-R}}{R\,I_{1-R}^{\;2}} = R\,P_{EC-R}(pu) \\ &\Rightarrow P_{EC}(pu) = P_{EC-R}(pu)\sum_{h=1}^{h_{\max}}\left[h\,I_h(pu)\right]^2 \end{aligned} \qquad (4)$$

3. The load loss is the sum of the I^2R and winding losses:

$$P_{LL}(pu) = \sum_{h=1}^{h_{\max}} I_h(pu)^2 + P_{EC-R}(pu)\sum_{h=1}^{h_{\max}}\left[h\,I_h(pu)\right]^2 \qquad (5)$$

4. Re-expressing harmonic currents from per unit of the rated linear load current to per unit of the fundamental component of nonlinear load current yields:

$$f_h \equiv \frac{I_h}{I_1} \Rightarrow I_h(pu) = \frac{I_1 f_h}{I_{1-R}} \Rightarrow P_{LL} =$$
$$\left[\frac{I_1}{I_{1-R}}\right]^2 \left[\sum_{h=1}^{h_{max}} f_h{}^2 + P_{EC-R}(pu) \sum_{h=1}^{h_{max}} \left[h\, f_h\right]^2\right]$$
$$= \left[\frac{I_1{}^2 \sum_{h=1}^{h_{max}} f_h{}^2}{I_{1-R}{}^2}\right] \cdot \left[1 + \frac{\sum_{h=1}^{h_{max}} \left[h\, f_h\right]^2}{\sum_{h=1}^{h_{max}} f_h{}^2} P_{EC-R}(pu)\right] \tag{6}$$
$$= \left[\frac{I_{RMS}}{I_{1-R}}\right]^2 \cdot \left[1 + K \cdot P_{EC-R}(pu)\right]$$
$$= I_{RMS}(pu)^2 \cdot \left[1 + K \cdot P_{EC-R}(pu)\right]$$

5. RMS load current reaches the maximum allowed when load loss equals its rated value:

$$P_{LL}(pu) = P_{LL-R}(pu)$$
$$\Rightarrow I_{RMS-Max}(pu)^2 \cdot \left[1 + K \cdot P_{EC-R}(pu)\right] = 1 + P_{EC-R}(pu) \tag{7}$$
$$\Rightarrow I_{RMS-Max}(pu) = \sqrt{\frac{1 + P_{EC-R}(pu)}{1 + K \cdot P_{EC-R}(pu)}}$$

In addition to limiting total loss with harmonic load applied to the rated loss, C57.110 is also intended to limit local loss in the region of highest eddy current loss density (the "hot spot") to its value with rated linear load applied. The local loss limit is more restrictive, so P_{EC-R} *(pu)* in (7) is replaced with *Max* P_{EC-R} *(pu)* - the per unit eddy current loss density at the hot spot. *Max* P_{EC-R} *(pu)* can only be obtained through complex (e.g., finite element) analysis of the transformer, and is rarely available for the sizes of transformers found in commercial buildings.

C57.110 provides a procedure for approximating *Max* P_{EC-R} *(pu)* through the following (very conservative) assumptions:

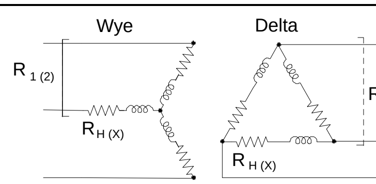
- The hot spot is at the ends of the secondary (inner) winding. The maximum eddy current loss density is four times the average value for the secondary winding.
- The secondary winding accounts for 60% of the total eddy current loss (70% if the turns ratio *TR* is greater than 4, and rated secondary current I_{2-R} is greater than 1 kA).

$$Max\ P_{EC-R}(pu) = \frac{4b\ P_{EC-R}}{p\,R_X\,I_{X-R}{}^2} = \frac{4b\left[P_{LL-R} - p\,I_{2-R}{}^2\left(R_1 + \dfrac{R_2}{TR^2}\right)\right]}{p\,R_2\,I_{2-R}{}^2} \qquad (8)$$

where p is 1.5 for 3-phase transformers, or 1 for single-phase; b is 60% or 70%, as described above; and R_1 and R_2 are the *terminal-to-terminal* DC resistances of the primary and secondary windings, respectively. Thus:

$$I_{RMS-Max}(pu) = \sqrt{\frac{1 + Max\ P_{EC-R}(pu)}{1 + K \cdot Max\ P_{EC-R}(pu)}} \qquad (9)$$

(8) and (9) are the working equations for the derating calculation. A common mistake in applying (8) is using *winding* resistances for R_1 and R_2. Equations for converting winding resistances to terminal-to-terminal resistances are shown Figure 3. (Note that data sheets for three-phase transformers may list resistance for the three windings connected in series.)



$$Wye:\ R_{1(2)} = 2 \cdot R_{H(X)}$$

$$Delta:\ R_{1(2)} = \frac{2}{3} R_{H(X)}$$

Figure 3. Winding resistance vs. terminal-to-terminal resistance.

$I_{RMS-Max}$ *(pu)* is plotted against load K-factor in Figure 4 using loss values typical of transformers 1 MVA and below [3]. The wide range in $I_{RMS-Max}$ *(pu)* for dry transformers indicates that the derating calculation is very sensitive to variations in the input data. Derating calculations based on "typical" loss data are not very meaningful.

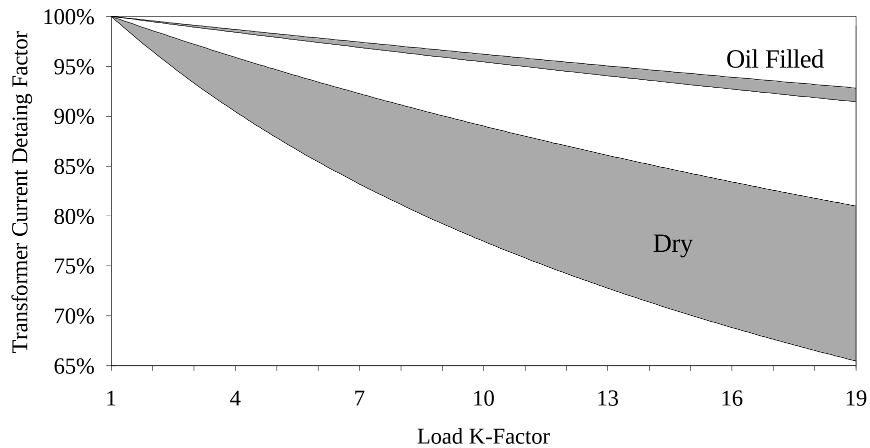


Figure 4. Transformer capability vs. load K-factor for typical range of Max P_{EC-R} (pu).

The CBEMA Derating Calculation

In 1988, the Computer and Business Equipment Manufacturers Association (CBEMA) recommended derating dry-type transformers supplying electronic loads in inverse proportion to the crest factor of the load:

$$I_{RMS-Max}(pu) = \frac{\sqrt{2}}{CF} \qquad (10)$$

where *CF* is the peak value of the load current per unit of its RMS value. While useful as a rule of thumb, the CBEMA method should *not* be used as the basis for establishing the capability of a specific transformer. It is often not conservative enough when applied to transformers in commercial buildings [4].

References

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[3] D. E. Rice, "Adjustable Speed Drive and Power Rectifier Harmonics: Their Effect on Power Systems Components," IEEE Paper No. PCIC-84-52, 1984.
[4] J. Moravek, "Effect of Harmonics on Transformer kVA Rating," Electrical Design and Installation, Vol. 2, No. 7, pp. 17-19, October 1991.

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HarmFlo+ Worksheet Support

Overview