A PRACTICAL EVALUATION OF DISTRIBUTION NETWORK LOSSES DUE TO HARMONICS

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ABSTRACT

Current and voltage harmonics in distribution networks result, among other things, in additional losses on network components. In this paper, a easily implementable, "rule of thumb" approach is presented for the evaluation of losses due to harmonics on the main components of a distribution network, that is the MV and LV lines and the power (HV/MV) and distribution (MV/LV) transformers. Harmonic losses are evaluated as percentages of the respective fundamental frequency losses, available from loss studies and relevant statistics kept by the utilities. Objective of the methodology presented is not to derive an accurate evaluation of harmonics losses on specific components or parts of the network, but rather to provide a fast assessment of the additional energy losses caused by the harmonics over the whole network.

INTRODUCTION

A simplified method is presented for the evaluation of energy losses in distribution networks due to harmonics. The primary objective is to estimate the order of magnitude of these losses, with respect to the fundamental frequency losses, which is the basis for deciding upon remedial action.

Accurate calculation of harmonic losses is a quite complicated task, even for discrete and specific components, let alone for the overall distribution network. Evaluation methodologies available require a significant amount of input data, hardly available in real life situations for extended distribution networks.

In this paper a simplified approach is adopted to evaluate harmonic losses on the main components of the distribution network, i.e. MV and LV lines, power (HV/MV) and distribution (MV/LV) transformers. Less important elements, in terms of their contribution to the overall losses, such as capacitor banks and voltage regulators, are not taken into account. The same applies for the additional losses incurred in the loads due to the harmonic distortion of the network voltage, as well as to increased non-technical losses, due to inaccuracies of the energy meters.

The evaluation is based on a series of simplifying, safe-side assumptions, leading possibly to an over-estimation of the actual harmonic losses on the network. Basic data required for applying the methodology include the allocation of the fundamental frequency energy losses of the network among the various components and the expected harmonic distortion levels of currents and voltages in the network. Outcome of the evaluation are the additional harmonic losses on the various components, expressed as a percentage of the fundamental frequency losses. The evaluation is performed using data for the mainland MV and LV distribution network of Greece.

POWER LOSSES ON NETWORK COMPONENTS

MV lines

Power losses due to harmonic currents on a MV line are given by superposition of the individual losses generated by each harmonic current, of order n:

$$P_n = 3I_n^2 R_n$$

where the ohmic resistance R_n depends on the harmonic frequency, nf_1. To simplify the calculation a rough approximation of the total harmonic power losses, P_h, is given by:

$$P_h = \sum_n 3I_n^2 R_n \approx 3I_h^2 R_h$$

where $I_h = \sqrt{\sum_n I_n^2}$ is the total rms harmonic current and R_h an equivalent harmonic resistance of the line.

The rms value I_h of the harmonic current is related to its fundamental component and the total harmonic distortion coefficient (THD_I) through the following relation:

$$THD_I = \frac{I_h}{I_1} \Rightarrow I_h = THD_I \cdot I_1$$

As a result, the relation between harmonic losses and the power losses due to the fundamental frequency component of the current becomes:

$$P_h \approx THD_I^2 \left(\frac{R_h}{R_1}\right) P_1 \qquad (1)$$

A simplified approximation of the resistive component of the impedance of a line, which accounts for the skin effect at increased harmonic frequencies, is:

$$R_n \approx R_1 \sqrt{n}$$

where n is the harmonic order and R_1 the line resistance at the fundamental frequency.

The equivalent harmonic resistance R_h of the line depends not only on the variation of its resistance with frequency, but also on the levels of the individual harmonic current components. Harmonic measurements [1] show that the MV feeder current distortion is predominantly of the 5th and 7th order. Therefore, a reasonable approximation would be:

$$R_h \approx R_7 \Rightarrow R_h \approx \sqrt{7} \cdot R_1 = 2.65 \cdot R_1$$

which is clearly on the safe side, since the dominant harmonic current component is the 5th order. Further, for small cross-section cables the aforementioned approximation may be quite pessimistic (indicative values are given in [2]).

Using a THD_I value of 7% for the "average" MV line, the resulting harmonic losses would become:

$$P_h \approx 0.07^2 \cdot 2.65 \cdot P_1 \Rightarrow P_h \approx 1.30\% \cdot P_1$$

LV lines

In the case of LV lines, except for the losses on the phase conductors, P_{hL}, there are significant additional losses, P_{hN}, on the neutral conductor, as well:

$$P_h = P_{hL} + P_{hN}$$

For the phase conductors, following the rationale developed for the MV lines and considering a THD_I value of 11% as representative, it is deduced:

$$P_{hL} \approx 0.11^2 \cdot 2.65 \cdot P_1 = 3.20\% \cdot P_1$$

The neutral conductor, besides the fundamental frequency current due to load asymmetry, carries also the zero sequence current harmonics, i.e. odd harmonics of $3kf_1$ frequency (3rd, 9th, 15th, etc.), the 3rd harmonic components, due to single-phase non-linear loads, being the dominant ones. From the analysis of available measurements [1], a safe-side assumption for the zero-sequence harmonic content of the current is that it constitutes approximately 50% of the overall harmonic current distortion. Hence:

$$THD_{I0} \approx 0.5 \cdot THD_I$$

Since the current in the neutral comprises the zero sequence currents of all three phases, I_N=3I_0, it turns out that:

$$I_{hN} \approx 3 \cdot THD_{I0} \cdot I_1 \Rightarrow I_{hN} \approx 3 \cdot 0.5 \cdot 0.11 \cdot I_1 = 0.165 \cdot I_1$$

The resistance of the neutral generally differs from that of the phase conductors for various reasons (different cross sections, operating temperatures, earth return paths in networks with multi-grounded neutrals). A value adopted as typical for the LV distribution line types used in the Greek network is the following, at fundamental frequency:

$$R_{1N} \approx 1.25 \cdot R_1$$

To adopt an equivalent harmonic resistance R_{hN} for the neutral, it has to be considered that the predominant harmonic orders are not the 5th and 7th, as for the phase conductors, but mostly the 3rd and to a much smaller percentage the 9th. Therefore it is assumed that:

$$R_{hN} \approx 2R_{1N} \Rightarrow R_{hN} \approx 2 \cdot 1.25 \cdot R_1 = 2.5 \cdot R_1$$

Based on this reasoning, the power losses due to harmonic currents flowing on the neutral conductor are related to the fundamental frequency losses of the line (calculated under the assumption of symmetrical load) via the following relation:

$$P_{hN} \approx 3\left(\frac{R_{1N}}{R_1}\right)\left(\frac{R_{hN}}{R_{1N}}\right)\left(\frac{THD_{I0}}{THD_I}\right)^2 THD_I^2 P_1 \qquad (2)$$

Based on the aforementioned assumptions for line resistance and THD_I values, it is obtained:

$$P_{hN} \approx 3 \cdot 1.25 \cdot 2 \cdot (0.5)^2 \cdot (0.11)^2 \cdot P_1 \Rightarrow P_{hN} \approx 2.27\% \cdot P_1$$

Hence, the total harmonic losses on a LV line become:

$$P_h = P_{hL} + P_{hN} \approx (3.20\% + 2.27\%) \cdot P_1 = 5.47\% \cdot P_1$$

Transformers

The harmonic losses P_h of a transformer due to the harmonic distortion of the current and the voltage are approximated by the following relation [2,3]:

$$P_h = 3\sum_n I_n^2 R_n + P_{Fe} \sum_n \left(\frac{V_n}{V_1}\right)^m \frac{1}{n^{2.6}} \qquad (3)$$

where I_n and V_n are the nth order harmonic components of the current and the voltage

R_n is the equivalent copper loss resistance of the transformer at the nth order

P_{Fe} are the fundamental frequency iron losses and

m is an exponent with an assumed value m=2

For the variation with frequency of the harmonic resistance R_n of the transformer, the following relation is used [4]:

$$R_n = R_1(c_0 + c_1 n^b + c_2 n^2) \qquad (4)$$

where values for the parameters are provided in Table 1.

Using eq. (4), the following values are obtained for R_n, at the 5th and 7th harmonic orders:

Distribution transformers: $R_5 \approx 3.0R_1$ and $R_7 \approx 4.7R_1$

Power transformers: $R_5 \approx 4.4R_1$ and $R_7 \approx 7.6R_1$

As for the lines, a single value is adopted for the harmonic resistance, to simplify the calculation. For this purpose, the 7th order is selected as a safe-side assumption, although this may be pessimistic for MV/LV distribution transformers, where significant 3rd order harmonics flow in the transformer windings.

The same is done for voltage harmonics. Since their contribution to the overall losses is negligible, the following unfavourable approximation is used in eq. (3):

$$\frac{1}{n^{2.6}} \approx \frac{1}{3^{2.6}} \approx 0.05$$

which however has no significant effect on the results.

	c_0	c_1	c_2	b
Distribution transformers	0.85-0.90	0.05-0.08	0.05-0.08	0.9-1.4
Power transformers	0.75-0.80	0.10-0.13	0.10-0.13	0.9-1.4
	Provided that $c_0+c_1+c_2=1$			

Table 1. Typical values for the coefficients of eq. (4), [4].

Based on these simplifications, the total harmonic losses of a transformer are related to the fundamental frequency copper and iron losses by the following equation:

$$P_h \approx \left(\frac{R_h}{R_1}\right) THD_I^2 P_{Cu} + \left(\frac{1}{h_v^{2.6}}\right)\left(THD_V^2\right)^{m/2} P_{Fe} \quad (5)$$

where $R_h \approx R_7$, h_v=3 and m=2, as already explained.

Based on measurements [1], representative *THD* factor values for the currents and voltages of network transformers are the following:

Distribution transformers: $THD_I \approx 11\%$ and $THD_V \approx 5\%$
Power transformers: $THD_I \approx 7\%$ and $THD_V \approx 4\%$

Substituting to eq. (**), yields for distribution (MV/LV) transformers:

$$P_h \approx 4.7 \cdot 0.11^2 \cdot P_{Cu} + 0.05 \cdot 0.05^2 \cdot P_{Fe} \approx 0.0572 P_{Cu} + 0.001 \cdot P_{Fe}$$

and for power (HV/MV) transformers:

$$P_h \approx 7.6 \cdot 0.07^2 \cdot P_{Cu} + 0.05 \cdot 0.04^2 \cdot P_{Fe} \approx 0.0372 P_{Cu} + 0.001 \cdot P_{Fe}$$

Core loss coefficients in these relations have been incremented to 0.001 (0.1%) from the actual 0.000125 and 0.00008 calculated values.

ENERGY LOSSES IN THE NETWORK

Approximate calculation

The analysis presented in the previous section correlates harmonic power losses with the fundamental frequency ones. At fundamental frequency, the loss factor is used to calculate energy losses from power losses. To derive an equivalent loss factor for harmonics, knowledge of their time variability is required. This difficulty is overcome assuming that the harmonic loss factor is equal to the fundamental frequency one. Then, the relation between harmonic and fundamental frequency power losses becomes also the relation between the respective energy losses.

Application of this simplified approach leads to the results presented in Table 1. In the first column, the fundamental frequency energy losses on the main components of the network are shown, expressed as a percentage of the total incoming energy to the network (measured at the HV terminals of the infeed HV/MV transformers), [5]. The next two columns, titled “Approximate Calculation”, provide estimates of the harmonic energy losses, as a percentage of the respective fundamental frequency ones and of the total incoming energy to the network. The sum of these latter percentages provides the increment of the total losses in the network due to the presence of harmonics. Hence, the energy losses in the overall distribution network appear to increase by 0.18% (from 6.55% to 6.73%), if harmonics are taken into account. Performing a sensitivity analysis for the various assumptions involved in this calculation (THD, harmonic impedances etc.) always leads to loss increments varying between 0.1% and 0.2%.

Detailed calculation

Energy losses on an element of the network over a period T (usually 1 year = 8760 h) are:

$$E_A = \int_0^T P_A(t)dt$$

where the instantaneous power losses $P_A(t)$ are either copper losses, associated with current and resistance, or core losses, which depend on the applied voltage.

Copper losses on 3-phase elements are given by:

$$P_A(t) = 3RI^2(t)$$

where the value of resistance R depends on the frequency. Hence, the fundamental frequency and the harmonic energy losses are given by:

$$E_{A1} = \int_0^T P_{A1}(t)dt = 3R_1 \int_0^T I_1^2(t)dt$$

$$E_{Ah} = \sum_k \left[\int_0^T P_{Ak}(t)dt\right] = 3\sum_k \left[R_k \int_0^T I_k^2(t)dt\right]$$

where the summation takes place for all harmonic orders. Taking the ratio of each part of these equations leads to

$$\frac{E_{Ah}}{E_{A1}} = \sum_k \left[r_k \frac{\int_0^T I_k^2(t)dt}{\int_0^T I_1^2(t)dt} \right]$$

where $r_k = R_k / R_1$ is the ratio of the harmonic to the fundamental frequency resistance of the network element. If an equivalent harmonic resistance R_h is introduced, the above relation is simplified:

$$\frac{E_{Ah}}{E_{A1}} \approx r_h \frac{\sum_k \left[\int_0^T I_k^2(t)dt\right]}{\int_0^T I_1^2(t)dt} = r_h \frac{\int_0^T \sum_k \left[I_k^2(t)\right]dt}{\int_0^T I_1^2(t)dt} = r_h \frac{\int_0^T I_h^2(t)dt}{\int_0^T I_1^2(t)dt} \quad (6)$$

It can be easily shown that the ratio of current integrals in eq. (6) is directly related to the harmonic and fundamental frequency loss coefficients, F_A and F_{Ah}:

$$\frac{F_{Ah}}{F_{A1}} \approx \frac{1}{THD_I^2} \frac{\int_0^T I_h^2(t)dt}{\int_0^T I_1^2(t)dt} \quad (7)$$

For LV lines, in particular, energy losses on the neutral, E_{AhN}, are required as well. It can be easily shown that:

$$\frac{E_{AhN}}{E_{A1}} \approx 3r_{hN} \frac{\int_0^T I_{h0}^2(t)dt}{\int_0^T I_1^2(t)dt} \quad (8)$$

		Fundamental Frequency Losses, E_{A1} (% of total incoming energy, E_I), [5]	Additional Losses, E_{Ah}, due to Harmonics			
			Approximate calculation		Detailed calculation	
			% of E_{A1}	% of E_I	% of E_{A1}	% of E_I
LV lines		1.90%	5.47%	0.1039%	6.00%	0.1140%
MV/LV transformers	Copper	0.55%	5.72%	0.0315%	4.02%	0.0221%
	Core	0.92%	0.10%	0.0009%	0.10%	0.0009%
	Total	1.47%		0.0324%		0.0230%
MV lines		2.70%	1.30%	0.0350%	1.72%	0.0464%
HV/MV transformers	Copper	0.21%	3.72%	0.0078%	4.94%	0.0104%
	Core	0.27%	0.10%	0.0003%	0.10%	0.0003%
	Total	0.48%		0.0081%		0.0106%
TOTAL		**6.55%**		**0.1794%**		**0.1941%**

Table 2. Calculation of energy losses due to harmonics.

where I_{h0} is the rms value of the zero-sequence harmonics and

$$r_{hN} = \frac{R_{hN}}{R_1} = \left(\frac{R_{1N}}{R_1}\right)\left(\frac{R_{hN}}{R_{1N}}\right) \tag{9}$$

The resistance ratios r_h and r_{hN} are calculated as discussed in the previous section, for the calculation of harmonic power losses on lines and transformers.

Hence, in order to correlate fundamental and harmonic energy losses, the ratios of the time integrals of fundamental and harmonic frequency currents are needed. These ratios were evaluated using available harmonic measurements [1], leading to the typical values of the following table. Zero-sequence harmonics are relevant only in the LV network.

	LV network	MV network
$\int_0^T I_h^2(t)dt \Big/ \int_0^T I_1^2(t)dt$	0.0085	0.0065
$\int_0^T I_{h0}^2(t)dt \Big/ \int_0^T I_1^2(t)dt$	0.0050	–

To estimate transformer core harmonic energy losses, a similar approach may be followed, whereby integrals of voltages would appear, instead of currents. However, since these losses contribute negligibly to the overall harmonic losses (Table 2), it may be simplifyingly assumed that transformers operate continuously under constant harmonic voltage distortion conditions. Then, the relation of harmonic energy losses to the fundamental frequency ones is the same as for power losses, calculated in the previous section.

Calculation results following this procedure are presented in the last two columns of Table 2. The resulting increment of the total energy losses of the distribution network due to the harmonics is 0.194%, a value close to the 0.18% percentage of the simplified calculation. This very small increase in network losses is mainly due to the LV lines, followed by the MV lines and the MV/LV transformers.

Hence, applying this more refined calculation procedure, leads again to a secondary and rather unimportant effect of harmonics on the overall losses of the network.

CONCLUSIONS

A simplified methodology has been presented for the evaluation of additional losses caused by harmonics in distribution networks. The application of the method to the Greek distribution network demonstrates an increment of 0.15-0.2% of the overall network losses, for the level of harmonic distortion currently encountered in the network.

Such an increase is definitely not significant, since it lies within the limit of accuracy of the fundamental frequency losses calculation and their variation from year to year. Further, it is of the same order of magnitude as the various non-technical losses, which inevitably exist.

Hence, any attempt to reduce harmonic distortion levels in the network, pursuing the reduction of energy losses, is rather questionable, from an economic point of view. The gain is even less significant if it is taken into account that complete elimination of harmonics in the network is clearly unfeasible.

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