DETERMINATION OF HARMONIC POLLUTION SOURCES IN DISTRIBUTION NETWORKS THROUGH SIMPLE MEASUREMENTS

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ABSTRACT

This paper is focused to address the problem of interactions between supply distortion and load distortion. The problem is composed of two parts. The first part is involved to detect how each load in a power system network behaves under the presence of harmonics. The second part is devoted to develop a suitable quantitative measure for the sharing of the harmonic distortion produced by individual loads. Finally, the two parts are used to make the engineer be able to quantify the waveform distortion caused by a single customer (non-linear load) when there are several customers (linear and non-linear loads) sharing the same feeding distribution network (and separate the contributions of waveform distortion between customer side and supply side). An estimated degree of non-linearity factor (N.L.F) for every non-linear load is introduced and evaluated. This factor will be useful in arriving at a fair estimation of the customer cost share of the quality source impact. The proposed technique involves simple measurements of the distorted current and voltage waveforms caused by different types of linear and non-linear loads fed at a bus bar of common coupling. These measurements were made in carefully chosen sites and representing different classes of loads at the 11-kV Alexandria electrical distribution system.

Keywords: Harmonics, Distortion Networks, Industrial Loads, Power Quality

INTRODUCTION

Over the past several years, the automation of industrial processes has increased the use of various sources of harmonic distortion such as rectifiers, inverters, adjustment speed drives, and several other types of converters. Other sources of harmonics include power system components and conventional loads with non-linear operation characteristics (e.g television appliances, gas discharge and fluorescent lamps, computers and other electronic equipment), or fast varying demands for active and reactive power (e.g. arc furnaces and welding machines). The harmonic contents of these non-sinusoidal load currents may couple with other distorting loads sharing the same feeding point or other distorting loads located on another feeding point energized by the same transformer. The produced harmonic currents (or voltages) propagate throughout the system which gives rise to troubles and serious problems in the power system network. References 1 to 3 contain a sampling of the literature, which describe these harmonics, their causes and impacts on the electrical power system.

Because we are dealing with a distribution network including different types of loads and variety of common couplings, the contribution of waveform distortions between supply side and load side and also the interactions among the system network

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load waveforms are of growing interest. Harmonics generated by a distorting load located in a certain distribution network may affect other load equipment located on another distribution network energized by the same bus bar. There will be some loads which do not generate harmonics but they may be sensitive to any harmonics produced by another distorting load sharing the same feeding point.

At the customer side, electrical energy is demanded within standard limits of power quality [4], because the modern design approaches of electrical equipment design are becoming more sophisticated and usually more sensitive to the distortion of voltage and current waveforms. Thus, separating customer and supply sides harmonics distortion will be useful in finding quick and reliable solution to the customer complains and in settling his responsibility share in the cost of the waveform distortion through penalties, rate structure, etc [5-6].

Separating the interactions of waveform distortion was firstly discussed in Reference 7. This research work introduced a useful approach to determine the origin of harmonics and isolate the interactions of waveform distortion between load side and supply side. The principle which has been used in the proposed method is based on tracing and measuring the harmonic powers at the load points. The authors succeeded in establishing a calculated formula for the harmonic powers, which is supposed to be in both directions. The positive harmonic power convention is considered to flow from the supply side to the customer side, while the negative harmonic power convention is considered to flow from the customer side to the supply side. Thus, as the harmonic powers are of two directions, they can be easily separated so as to isolate the interactions between supply distortion and customer distortion. Although the proposed technique is logically accepted, it does not match the reality. The direction of the harmonic power does not have any definite indication about its origin. We might say $20\angle 60^\circ$ (or $17.3+j\ 10$) of harmonic power flowing from (A) to (B) or $20 \angle 60+180^\circ$ (or $-17.3 - j\ 10$) of harmonic power flowing from (B) to (A), it is mainly dependent on the load behavior.

This paper presents a method for determining the origin of the harmonic distortion and estimating the cost of waveform distortion to the customer who is responsible of it. Thus, isolating the contribution to waveform distortion between the customer side and the supply side becomes feasible. The developed approach is based on finding the interrelationship between the distorted voltage waveform, the distorted current waveform, and the R and L load parameters. How any load behaves under the influence of harmonics is our aim and there is nothing that can describe the load behavior (linear or non-linear) perfectly rather than its parameters. An estimated non-linearity factor (N.L.F) will be introduced to determine the sharing of the distortion level for the individual distorting loads connected at the same feeding distribution network.

RELATIONSHIP BETWEEN VOLTAGE AND CURRENT DISTORTIONS

Basically, harmonic distortion originates with non-linear devices connected to the power systems. A non-linear device is a component in which, the voltage is not proportionally related to the current. To understand this phenomenon consider two types of v and i waveforms characteristics, where one is linear (non-distorting load) and the other is non - linear (distorting load) as shown in Figure 1.

Investigation of Figure 1 shows that, a sinusoidal voltage applied to a linear load yields a sinusoidal current waveform. On the other hand, distorted current waveform will result if a non-linear element exists. Likewise, if we inject a sinusoidal current through a non-linear impedance, the voltage across that element would be distorted. Thus, non-linear loads indicate distorted voltage or/and distorted current waveforms but the opposite is not true. A load having a distorted current or voltage waveform is not a definite indication that it will be a source of harmonics (non-linear load). So, looking at the distorted voltage and current waveforms is not sufficient to pronounce the source of harmonics. It is mainly dependent on the nature of the load impedance (linear or non-linear). Now, it is more convenient to find parameters that can sense the load characteristics. Generally, there is nothing that can describe the load behavior rather than its parameters (R and L). These parameters are the link that relates the load voltage and current waveforms.

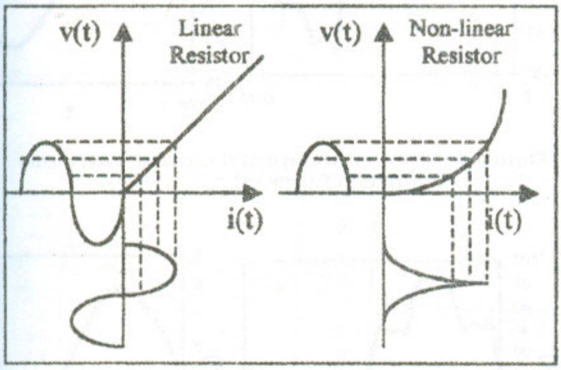

Figure 1 v and i waveforms characteristics

THE PROPOSED METHOD

As mentioned before, it is not possible to separate the contributions of waveform distortions or to identify the source of harmonics by merely looking at the distorted voltage and current waveforms. When considering the origin of harmonics, the primary think is monitoring the behavior and the nature of the load parameters (R and L variations). If these values behave linearly, representing the same ratio of the current and the voltage values at any instant, it means that the load under study is linear (non-distorting load) even though the supply voltage is already distorted. On the other hand, if the load parameters (R and L) represent non-linear instantaneous variations, this indicates a source of harmonics even though the supply voltage is free of harmonics. Thus, the first step for tracing the problem solution is to find a simple way that can be used to monitor the load pattern under the influence of harmonics.

The instantaneous voltage value v(t) and the instantaneous current value i(t) in RL circuit are related as:

$$v(t) = R(t)\, i(t) + \frac{d}{dt}(L(t) i(t))$$

Suppose that, the voltage and the current values are given in a waveform patterns as shown in Figure 2

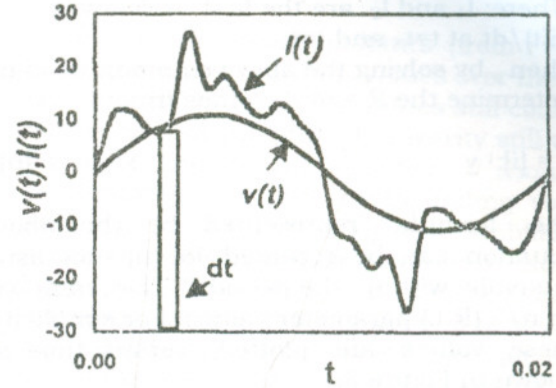

Figure 2 Distorted voltage and current waveforms

For an incremental time (Δt, the R and L values can be considered as constant parameters and Equation 1 can be rewritten as:

$$v(t) = R\, i(t) + \frac{di(t)}{dt} \qquad (2)$$

If v(t) indicates an instantaneous voltage value for a distorted voltage waveform, for certain load, and i(t) indicates an instantaneous current value for the corresponding distorted current waveform, then the (R and L) parameters indicate the load pattern under influence of harmonics. For two successive instants (t_1 and t_2), Equation 2 can be written as :

$$v(t_1) = R\, i(t_1) + \frac{L(i(t_1 + \frac{\Delta t}{2} - i(t_1 - \frac{\Delta t}{2})}{\Delta t} \qquad (3)$$

$$v(t_2) = R\, i(t_2) + \frac{L(i(t_2 + \frac{\Delta t}{2} - i(t_2 - \frac{\Delta t}{2})}{\Delta t} \qquad (4)$$

Equations 3 and 4 can be written in a matrix form as:

$$\begin{bmatrix} v(t_1) \\ v(t_2) \end{bmatrix} = \begin{bmatrix} i(t_1) & I_1 \\ i(t_2) & I_2 \end{bmatrix} \begin{bmatrix} R \\ L \end{bmatrix}$$

or $\underline{v} = [i]\,\underline{Z}$ (5)

Where: I_1 and I_2 are the first derivatives $di(t)/dt$ at $t=t_1$ and $t=t_2$.
Then , by solving the above equation we can determine the R and L values from:

$$\underline{Z} = [i]^{-1}\,\underline{v} \qquad (6)$$

The formula represented by the above equation can be repeated for (n) successive intervals within the period T. The result will be n/2 (R,L) parameter values. For simplicity, these values are plotted versus time as shown in Figure 3.

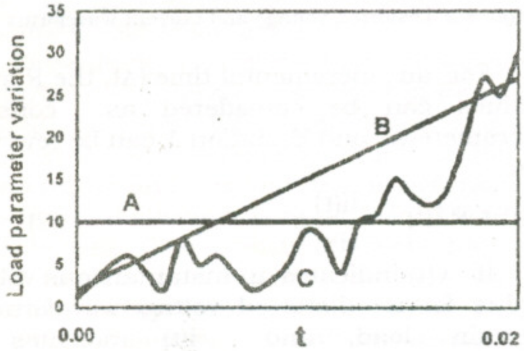

Figure 3 Load parameters variations

If the instantaneous (R and L) parameters represent linear variation or have constant values during the waveform period (pattern A or B), this indicates that the load under study is linear (non-distorting load). On the other hand, if the instantaneous (R and L) parameter values represent non-linear variations (pattern C), this indicates that the load is a source of harmonic.

DEGREE OF NON-LINEARITY

The mathematical approach developed in the previous section has been applied to measured voltage v(t) and current i(t) waveforms of different load types and , due to limited paper size, only samples of these measurements are given in Figures 4 to 6.

The calculated load parameters are shown in Figures 7 to 9.

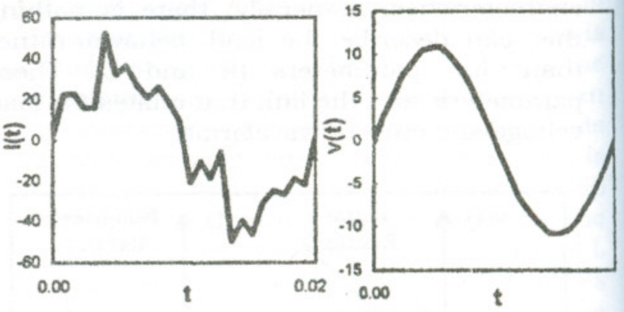

Figure 4 Distorted voltage and current waveforms (induction furnaces)

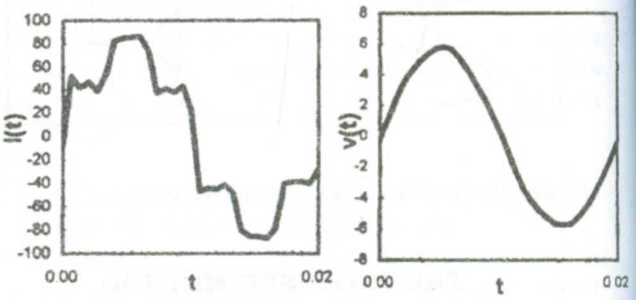

Figure 5 Distorted voltage and current waveforms (Six-pulse rectifiers)

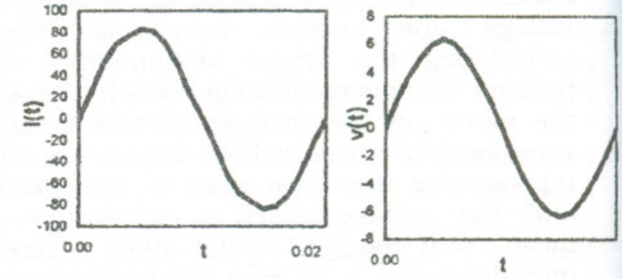

Figure 6 Distorted voltage and current waveforms (induction motors)

The analytical study of the obtained results concludes that there is no real load which can operate with exactly linear, or constant pattern. They always vary to some degree, where some loads representing higher non-linearity than others. The conclusive result coincides with that obtained in Reference 7. Thus, a quantitative measure for the degree of non-linearity of a customer load pattern will be effective in isolating the portion of the distortion caused by such an industrial load.

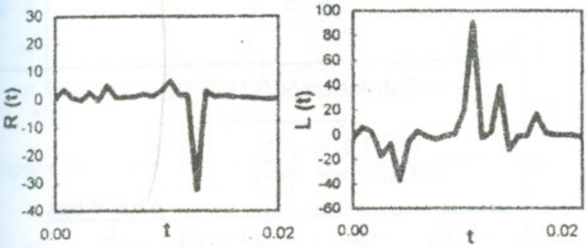

Figure 7 Load parameters (R and L) variations of Figure 4

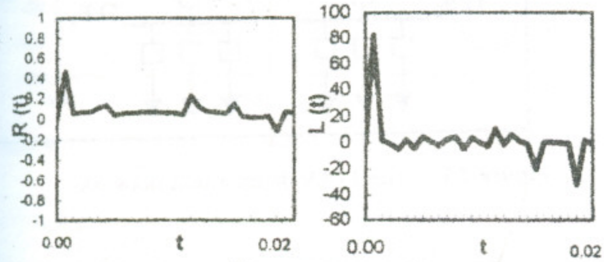

Figure 8 Load parameters (R and L) variations of Figure 5

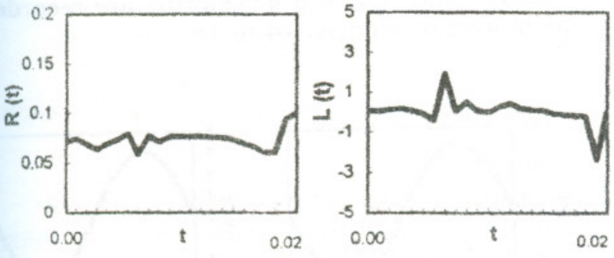

Figure 9 Load parameters (R and L) variations of Figure 6

By definition, non-linearity is a measured quantity that can be used to quantify how a distorted waveform is far from sinusoidal. Evaluation of the degree of non-linearity is based on comparing two waveforms. One of them is the actual distorted waveform which can describes the load itself, while the other waveform can also describe the load behavior but, provided that the load is linear. If the load pattern R and L is assumed linear, then the corresponding voltage waveform can be calculated from the following equation:

$$v_{calculated} = R\, i(t) + L\, \frac{di(t)}{dt} \tag{7}$$

Where:

$i(t)$: measured distorted load current at instant (t).

$v_{calculated}$: calculated voltage at instant (t).

For n successive instants (from $t = t_1$ to $t=t_n$), there will be i_1 to i_n values over the load period, but the (R and L) values still constant where the assumption of linearity still valid. For each instant (t), Equation 7 should be recalculated and the corresponding voltage values from $v(t_1)$ to $v(t_n)$ will establish the simulated linear voltage waveform. Now we have two waveforms, the actual distorted waveform which reflects the real behavior of the distorting load and the calculated waveform which indicates the load behavior provided that, the load is linear. The instantaneous relative difference between the two waveforms can be considered as a good estimate for the instantaneous degree of non linearity at that instant. This difference is expressed by the equation:

$$S(t) = \frac{v_1(t) - v_2(t)}{v_1(t)} \tag{8}$$

Where, v_1 and v_2 are the voltage values at instant (t) of the distorted waveform and the calculated linear waveform. For $t=t_1$ to $t=t_n$, over the load cycle, Equation 8 should be repeated and for each time a new difference S(t) should be calculated.

The mathematical calculation procedure is then applied to the measured distorted voltage and current waveforms of Figures 4 to 6. For each load type, during the load cycle, non-linearity variations are plotted and the non-linearity factor is calculated. These results are shown in Figures 10 to12 and summarized in Table 1.

Table 1 N.L.F for different types of load patterns of Figures 7-9

Load type	N.L.F
Induction furnaces	15.6
Six pulse rectifiers	5.2
Induction motors	0.27

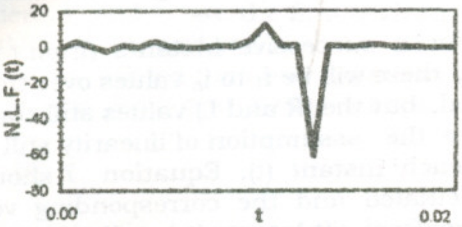

Figure 10 Non-linearity variation of Figure 4

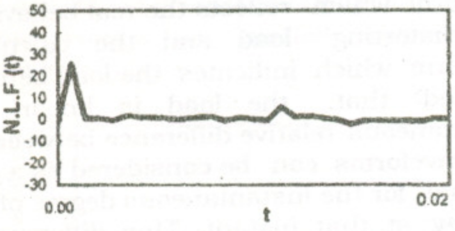

Figure 11 Non-linearity variation of Figure 4

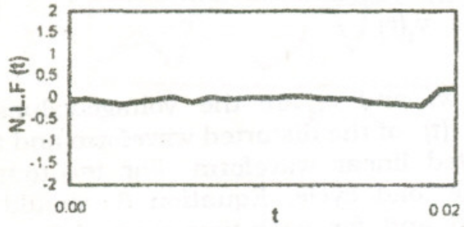

Figure 12 Non-linearity variation of Figure 6

CASE STUDY

The proposed method is applied to different sites in the 11 kV of Alexandria Distribution Network. Due to limited space only a case study of one site (RAS AL-SODA 66/11 kV substation) is illustrated, as shown by the single line diagram of Figure 13. In this network, a common bus bar is feeding five 11 kV-primary feeders. Each feeder is used to supply residential, commercial and industrial loads of different types. The common bus voltage is distorted and the system loads are sharing the distortion level. Some of these loads are fed directly from the common bus bar while the other loads are fed through the 11 kV distribution points $D.P_1$ and $D.P_2$.

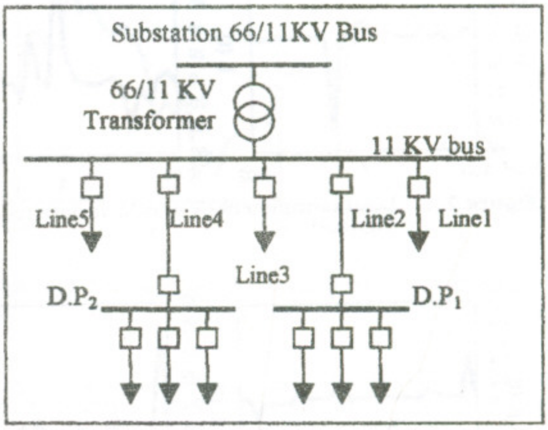

Figure 13 The 11 kV distribution network

Real measurements are made at the load points using an advanced energy analyzer instrument. For each load, the distorted voltage and current waveforms are recorded as shown in Figures 14 to 18.

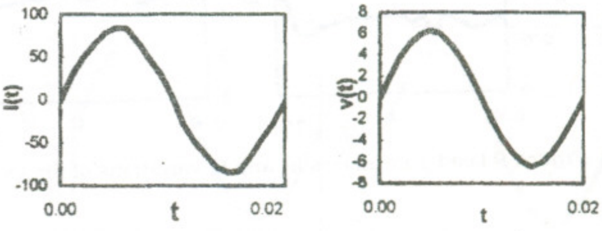

Figure 14 Distorted voltage and current waveforms (Line # 1)

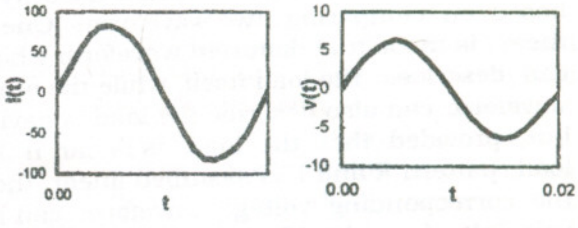

Figure 15 Distorted voltage and current waveforms (Line # 2)

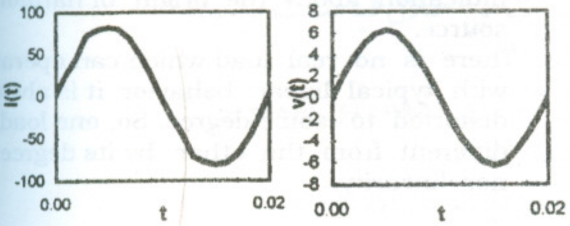

Figure 16 Distorted voltage and current waveforms (Line # 3)

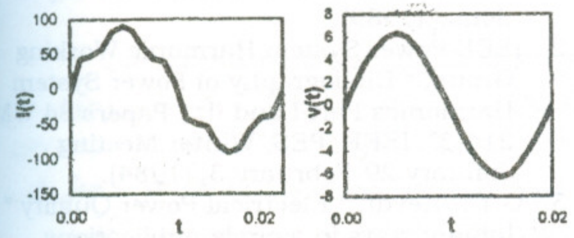

Figure 17 Distorted voltage and current waveforms Line # 4)

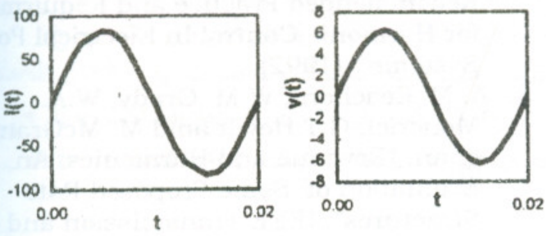

Figure 18 Distorted voltage and current waveforms (Line # 5)

The recorded data are analyzed to quantify the share of waveform distortions caused by the individual distorting loads and thus determining the dominant line that may be considered as the main (worst) source of harmonics. The results are summarized in Table 2 and the graphs are plotted in Figures 19 to 23.

Table 2 Loads non-linearity factors

Line #	N.L.F
1	0.54
2	0.09
3	0.83
4	1.20
5	0.22

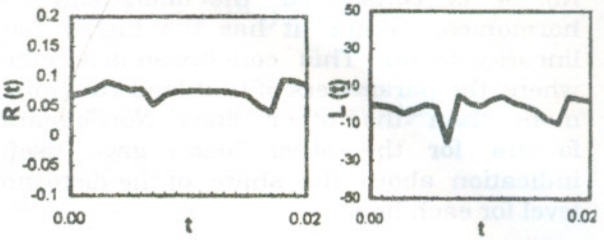

Figure 19 Load parameters R and L variations Line # (1)

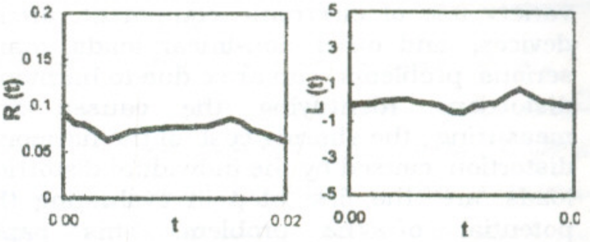

Figure 20 Load parameters R and L variations Line # (2)

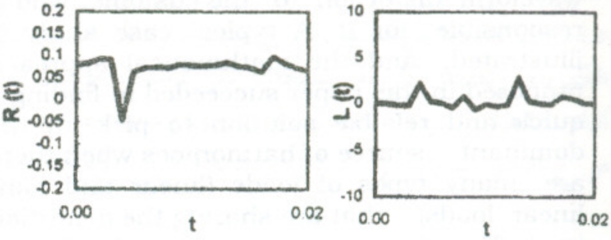

Figure 21 Load parameters R and L variations Line # (3)

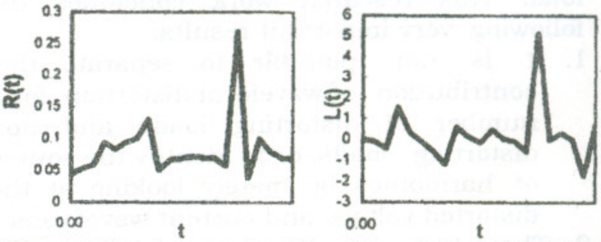

Figure 22 Load parameters R and L variations Line # (4)

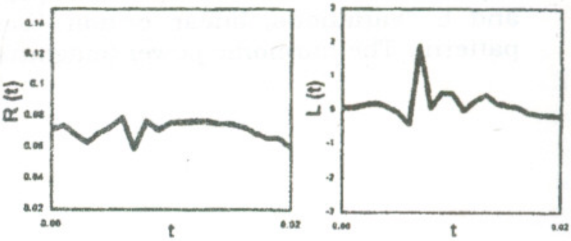

Figure 23 Load parameters R and L variations Line # (5)

The analytical study reveals that , line No. 4 is considered the main source of harmonics, where it has the higher non-linearity factor. This conclusion is accepted where the parameters of that load vary much more than the other lines. Non-linearity factors for the other loads gave useful indication about the share of the distortion level for each line.

CONCLUSION

In today's power systems with their variety use of electronic equipment, arcing devices, and other non-linear loads, many serious problems can arise due to harmonic distortion. Identifying the causes and measuring the sharing cost of the harmonic distortion caused by the individual distorting loads are the first step in evaluating the potential of the problem. This paper presented a method for determining the origin of harmonis and estimating the cost of waveform distortion to the customer who is responsible for it. A typical case study is illustrated, and the mathmatical approach proposed in this paper succeeded in finding a quick and relaible solution to pick up the dominant source of harmoniocs when there are many types of loads (linear and non-linear loads) that are sharing the distortion level. The sharing cost of distortion for the individual loads is well established by determining the non-linearity factor for each load. This research work concludes the following very important results:

1. It is not possible to separate the contribution of waveform distortion, for a number of distorting loads and non distorting loads, or to identify the source of harmonics by merely looking at the distorted voltage and current waveforms.
2. The harmonic distortion is mainly dependent on the load pattern (the R and L variations, linear or non -linear pattern). The harmonic power (magnitude and direction) doesn't have any definite indication about the origin of harmonic source.
3. There is no real load which can operate with typical linear behavior, it is always distorted to some degree. So, one load is different from the other by its degree of non-linearity.

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تحديد مصادر تلوث شبكات التوزيع بالتوافقيات من خلال قياسات مبسطة

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ملخص البحث

يركز هذا البحث على حل مسألة التداخل بين التشوهات الناشئة من المصدر الكهربى التشوهات الصادرة الأحمال الكهربية. ويقسم البحث المسألة الى جزأين. حيث يهتم الجزء الأول بالكشف عن كيفية تصرف الأحمال الكهربية فى وجود التوافقيات بينما يختص الجزء الثانى بتقديم قياس كمى مناسب لمساهمة الأحمال المختلفة فى تلويث شبكة التوزيع بالتوافقيات حين يتم تغذيتها من نقطة توزيع مشتركة فى الشبكة. وأخيرا ، يتم استخدام الطريقة المستحدثة لتحديد مسئولية كل حمل لاخطى فى التشوية المقاس عند نقطة التوزيع المشتركة لمجموعة أحمال مختلفة الأنواع وبالتالى فصل التداخل بين مسئولية المصدر الكهربى ومسئولية الأحمال الكهربية المنفردة عن مصدر التشوية المقاس. ومن خلال تحليل نتائج القياسات المختلفة وجد أن الأحمال الكهربية على وجه العموم لاخطية ولكن بدرجات متفاوتة. ويقدم البحث قياس كمى لدرجة اللاخطية لكل حمل على حده عندما يتم تغذيتها من مصدر كهربى مشترك وذلك لتيسير توزيع تكلفة معالجة الآثار المترتبة عنها من قبل شركات توزيع الكهرباء. وتعتمد الطريقة المستحدثة على قياسات مبسطة لتوافقيات مصدر جهد المنبع المشترك وتوافقيات تيار الأحمال المختلفة أثناء التشغيل وبدون الحاجة لفصل أيا منها باستخدام محلل التوافقيات المعروف. ويقدم البحث تطبيق للطريقة المستحدثة على موزع الرأس السوداء (١١ ك.ف) فى شبكة توزيع الإسكندرية والذى يحتوى على ٦ مغذيات رئيسية لأنماط مختلفة من الأحمال.