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Allocated harmonic quantities as the basis for source detection

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Abstract

A considerable body of literature examines assessment, from measurements, of whether it is the network or a customer installation which makes the greater contribution to harmonic distortion at a point of common coupling. However, the customer contribution to harmonic distortion at a point of common coupling depends heavily upon the definition chosen for that contribution. For example, expressing contributions as currents instead of voltages or vice versa may lead to large changes in results. Further, it can be shown that the harmonic voltage at the point of common coupling cannot be expressed independently of the network conditions, meaning that the customer contribution under existing definitions is a function not just of the customer parameters but of the network parameters as well. In the harmonic framework described by the technical report IEC/TR 61000-3-6, adopted as a standard in some jurisdictions, each customer installation is entitled to a harmonic allocation; that is, the right to inject a certain quantity of harmonic distortion into the network. IEC/TR 61000-3-6 suggests procedures for determining the allocated emission levels based on the harmonic voltage planning level at each bus. The problem of harmonic source detection can be recast as a search for customer installations exceeding allocated injection levels. With this approach, the challenge ceases to be comparison of the contributions made by the network and customer sides to observed harmonic distortion. Instead, it is shown that the problem becomes a process of reconciliation of the allocated quantity with field measurements.

Keywords

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Allocated Harmonic Quantities as the Basis for Source Detection

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***Abstract*—A considerable body of literature examines assessment, from measurements, of whether it is the network or a customer installation which makes the greater contribution to harmonic distortion at a point of common coupling. However, the customer contribution to harmonic distortion at a point of common coupling depends heavily upon the definition chosen for that contribution. For example, expressing contributions as currents instead of voltages or vice versa may lead to large changes in results. Further, it can be shown that the harmonic voltage at the point of common coupling cannot be expressed independently of the network conditions, meaning that the customer contribution under existing definitions is a function not just of the customer parameters but of the network parameters as well.**

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***Index Terms*—Power system harmonics, harmonic source detection, harmonic allocation, harmonic compliance assessment.**

I. INTRODUCTION

HARMONIC source detection [1]–[5] has traditionally involved a search for the largest contributor to harmonic voltage or current distortion at the point of common coupling (PCC). The usual assumption is that a single measurement of voltage and a single measurement of current are available, V_{PCC} and I_{PCC} respectively in the simple Thévenin–Norton equivalent circuit given in Fig. 1.

In this paper, an approach to harmonic source detection based upon allocation is presented. Following an examination of dominant source concepts in Section II, the customer contribution to harmonic voltage and current distortion at the PCC is shown in Section III to be unsuitable as a measure of compliance. An alternative approach is proposed, which reconciles allocated harmonic emission levels (Section IV) against an assessment of the Norton–equivalent circuit parameters of the customer from a time series of measurement data (Section V).

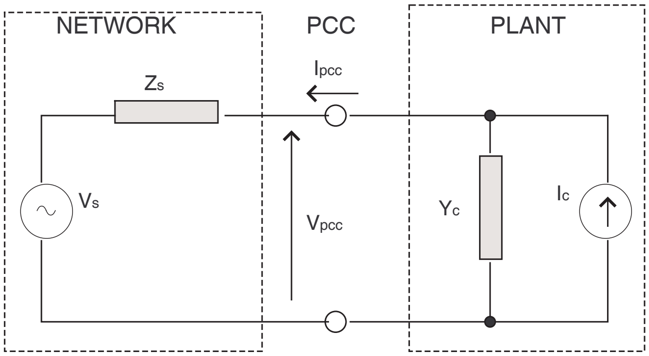

Fig. 1. Representation of network and customer installation at a point of common coupling at a particular harmonic

II. IDENTIFICATION OF DOMINANT HARMONIC SOURCES

The concept of a dominant harmonic source can be considered as an attempt to determine, with respect to the general network–plant interface of Fig. 1, which side of the PCC makes a greater contribution to harmonic distortion at the PCC. Much of the literature addressing dominant harmonic source identification assumes one specific quantity, for example voltage or current, in which dominance is exhibited at the PCC. The problem with such an assumption can be demonstrated with reference to Fig. 2. If one supposes that the dominant source in this case is the source making the greater contribution to harmonic voltage at the PCC, then by any logical measure of contribution chosen, the voltage source will be determined to be the dominant source. By contrast, if the PCC current is the property determining dominance, then the current source will be marked as the dominant source. The argument can therefore be made that in this instance *both* sources are dominant harmonic sources. "Dominance" *per se* has been shown to have no well–defined meaning.

Harmonic power flow has been proposed [6], [7] as a means of determining the direction of a dominant harmonic source. This quantity has been demonstrated [1], [8] to be unsatisfactory. A simple analogy with the flow of power at fundamental frequency indicates that the active power flowing through the PCC will be, in most cases, more dependent upon source phase angle differences than upon the magnitude of those sources. Despite having been used as the basis for instrumentation [7], the direction of harmonic active power

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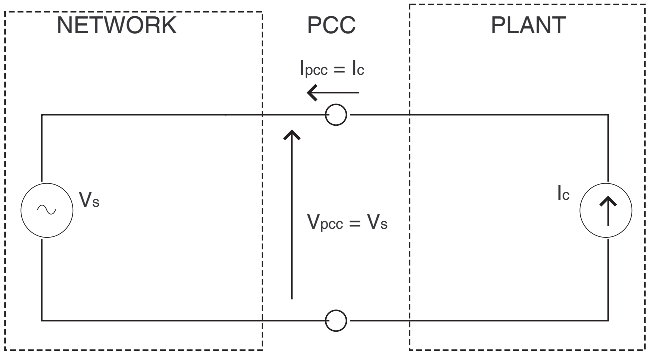

Fig. 2. Voltage and current sources connected

flow is problematic also by virtue of sensitivity to harmonic phase angle measurements. Such measurements are prone to inaccuracy.

Having established that the concept of a dominant harmonic source is shown not to be a well–defined concept, the purpose of dominant harmonic source identification can also be questioned. It might be argued that detection of a dominant harmonic source will make identification of the cause or causes of a harmonic problem apparent. However, harmonic distortion is a combination of source and impedance effects, so identification of only a source may well obscure problematic impedance conditions.

An alternative approach to harmonic source detection is to assess compliance of individual installations against agreed limits. This approach removes the motivation to determine a dominant harmonic source. To compare a measured quantity with a pre–determined limit, an appreciation of the customer contribution to harmonic distortion at the PCC is necessary.

III. INTERPRETATION OF CUSTOMER CONTRIBUTION TO HARMONIC DISTORTION

The concept of customer contribution is here approached from a voltage standpoint, on the basis that IEEE and IEC guides both place the burden of harmonic voltage management onto the utility, and voltages are more readily associated with a location than with a particular installation. Consider the customer contribution to the harmonic voltage at the PCC. By the superposition principle, and assuming that the Thévenin and Norton circuit parameters of Fig. 1 are fixed, the harmonic voltage at the PCC can be expressed as

$$\begin{aligned} V_{PCC} &= \frac{Y_c^{-1}}{Z_s + Y_c^{-1}} \cdot V_s + \frac{Z_s Y_c^{-1}}{Z_s + Y_c^{-1}} \cdot I_c \\ &= \frac{Y_c^{-1}}{Z_s + Y_c^{-1}} \cdot (V_s + Z_s I_c) \end{aligned} \qquad (1)$$

Equation (1) shows that the voltage at the PCC cannot be made independent of the network conditions when the network– and plant–side parameters are independent of each other. A strict customer contribution can only be apportioned when independent contributions to V_{PCC} from the network and customer sides can be identified. If V_{PCC} could be split into a term $V_{PCC,1}$ dominated by only network parameters and a term $V_{PCC,2}$ dominated by only installation parameters then such independent contributions would be clear. However, (1) demonstrates that this is not possible.

Alternatively, a dual equation to (1) can be developed if a customer contribution to current is intended. Again, it is not possible to isolate contributions made by the network and contributions made by the customer to distortion in the harmonic current flowing through the PCC. Therefore, analogous to harmonic voltage, the concept of a customer contribution to the PCC harmonic current is not meaningful.

The demonstration of customer contribution as a meaningless concept is valid in the general case. However, specific conditions exist in which meaning can be attributed to the customer contribution. Making Z_s infinite — that is, forcing an open circuit at a particular harmonic — is one such situation: the entire V_{PCC} can in this case be defined purely by the parameters of the customer side. However, the plant contribution is then ill–defined: to say that no such contribution exists is fallacious, as the situation only exists by virtue of the infinite network impedance. The analogous situation applies when Z_s is finite and instead Y_c is infinite.

It might be tempting to conclude that setting the customer source I_c to zero at a particular harmonic instead would similarly force the customer contribution to zero and the network contribution to the full PCC voltage. However, this conclusion is not appropriate: the harmonic voltage at the PCC remains dependent upon the customer shunt admittance; changing this admittance will change the PCC voltage regardless of conditions in the network.

This section has shown that customer contribution to harmonic voltage or contribution distortion is, in general, a concept which is not well–defined and lacks a theoretical basis. This is true for linear systems in which the principle of superposition can be assumed to apply. Rather than attempt to work around the difficulty, the remainder of this paper focusses upon the alternative approach of verification of compliance with a harmonic allocation.

IV. HARMONIC ALLOCATION

A. Standards

The development of restrictions on harmonic emissions, via allocation of injection rights to individual customers, has been addressed in national and international standards. Two well known harmonic standards are IEEE–519 [9] and IEC/TR 61000–3–6:2008 [10]. The first is applicable to distribution and transmission systems and is relatively simple to apply. Harmonic current is allocated to a customer in different frequency bands depending on the short–circuit ratio at the point of connection of the installation. The second is strictly a technical report rather than a standard reflecting that it is more a set of principles rather than a fully set-out process for determining harmonic allocations. To some extent it is shown how these principles can be applied to distribution systems but the treatment of transmission systems is incomplete. Compared to the IEEE standard, which contains some hidden assumptions, the IEC document can be applied to a wide variety of systems and conditions at the cost of being complicated. The authors have made several studies [11] of the application of the IEC document and it will be the main focus of subsequent discussion, with an emphasis on distribution systems. Some of the difficulties of applying the document to transmission systems are to be found in [11].

B. Planning levels

Using the terminology of [10], it is important that utilities manage their network so that harmonic voltages do not exceed the compatibility levels which depend on the harmonic frequency, decreasing with increasing harmonic order. It is interesting to note that this is in conflict with the IEEE limits which do not change with frequency, noting that there are different limits in both standards for odd and even harmonic orders. To achieve this, utilities need to select internal targets called planning levels. The values are chosen to be slightly smaller than the compatibility levels, giving a safety margin to allow for data uncertainties and approximations used in the harmonic allocation calculation.

C. Principles of harmonic allocation

Utilities have the responsibility to ensure that harmonic voltage levels do not exceed the compatibility levels. At MV (1–35kV), this is achieved by determining an appropriate level of harmonic allocation for each customer. This allocation can be expressed as an harmonic voltage, current, or sometimes VA, but the ultimate aim is to limit the maximum harmonic voltage in the network. We shall use the terms and symbols of [10] as far as possible in discussion although they are not generally familiar. The following allocation principles are recommended in [10]:

1) Customers of equal maximum demand (”agreed power” using the terminology of [10]) are to have equal allocation.
2) The allocation is to increase with maximum demand.
3) The allocation shall be such that the planning level is just met when all customers, both present and future, are taking their full allocation.

In general, the detailed operation of all the loads in a distribution system are unknown. To guide analysis, the following assumptions may be made:

1) Time-varying quantities are represented by their 95% probability values. The aim of harmonic allocation is to ensure that the 95% value of all harmonic voltages in the network do not exceed the appropriate planning level.
2) Where duty cycle and phase variation are not known, it may be assumed that independent harmonic quantities combine with diversity accounted for by the Summation law which is applied to the 95% values. For example, if $U_1, \ldots, U_n$ are the 95% values of independent harmonic voltage contributions, all of the same harmonic order, the 95% value of resultant harmonic voltage is given by

$$U_{tot}{}^{\alpha} = U_1{}^{\alpha} + \ldots + U_n{}^{\alpha} \quad (2)$$

Recommended values of α are given, for example $\alpha = 1.4$ at the fifth harmonic.
3) The upstream system need only be represented by a voltage source at the primary of the supply transformer.

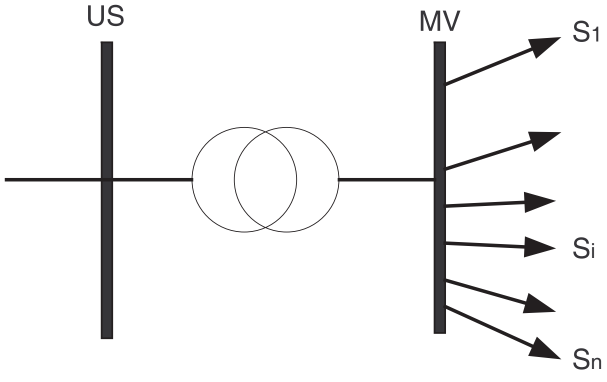

Fig. 3. Example distribution system

The quantity to be allocated depends on the type of system under study. Normal distribution systems, with a variation in fault level from supply to the feeder extremity of about 10:1, are best handled by an allocation of harmonic VA [12]. For short feeder systems, with little variation in fault level, allocation of voltage, current and VA are all equivalent. Harmonic voltage is most suitable for transmission systems [11].

A short feeder distribution system as shown in Fig. 3 is a simple but effective means of showing a distribution harmonic calculation in detail. The following symbols are used in the diagram: US — upstream, MV — medium voltage, S_i — installation under study. It is further assumed that there are no LV loads and that the system supply capacity is given by

$$S_t = S_1 + \ldots + S_i + \ldots + S_n \quad (3)$$

The loads $S_1 \ldots S_n$ include all projected loads even when not yet connected.

It is assumed that, when all loads are taking their full allocation, that the upstream system just reaches its planning level at the h^{th} harmonic, L_{USh}. It is required to maintain the downstream MV bus at or below the MV planning level, L_{MVh}. Accounting for diversity by the summation law, the harmonic voltage available for local MV loads is given by

$$G_{MVh} = (L_{MVh}{}^{\alpha} - L_{USh}{}^{\alpha})^{1/\alpha} \quad (4)$$

If there is no diversity (that is, if $\alpha = 1$), assumption 2) suggests that installation i receives an allocation varying with S_i. It can be shown, when diversity follows (3), that a more appropriate allocation of harmonic voltage is

$$E_{Uhi} = G_{MVh} \left(\frac{S_i}{S_t} \right)^{1/\alpha} \quad (5)$$

V. ASSESSMENT AGAINST ALLOCATED QUANTITY

A. Comparisons Between Allocation and Measurements

Since the customer contribution to harmonic voltage or current contribution cannot satisfactorily be defined, some alternative method of relating the allocated quantity to field measurements is required. Section III showed that the PCC

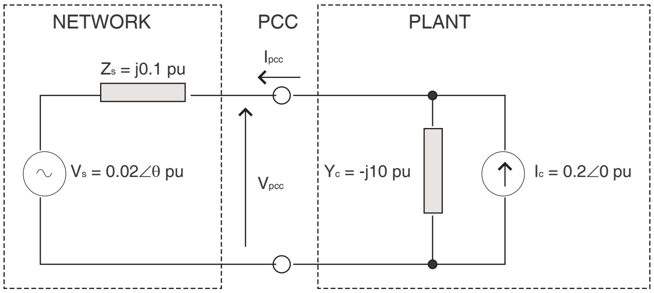

Fig. 4. Simple test case to illustrate failure of direct comparison between measured and allocated currents

Allocation: $E_{Ihi} = 0.1$					
System parameters				**Compliance test**	
I_c	Y_c	Z_s	V_s	$\lvert I_{PCC} \rvert$	**State**
0	$-j10$	$j0.1$	0	$0.1 = E_{Ihi}$	Pass
			$0.2\angle{-90°}$	$0.2 > E_{Ihi}$	Fail

TABLE I
TEST RESULTS DEMONSTRATING THAT NETWORK VOLTAGE SOURCE V_s MAGNITUDE CHANGES CAN ALTER PLANT COMPLIANCE WHEN PLANT DOES NOT CHANGE (ALL VALUES IN pu)

harmonic voltage and current cannot be expressed in terms of a customer–only part and a network–only part. Comparing the measured PCC current magnitude $|I_{PCC}|$ with the allocated current E_{Ihi} for a particular customer is thus not appropriate. As an example, consider the simple test system of Fig. 4. Suppose that the plant has been allocated an h^{th} harmonic current emission level of $E_{Ihi} = 0.1$pu. If the network h^{th} harmonic voltage source V_s were set to zero then the PCC current I_{PCC} would be equal to the allocated current E_{Ihi}, and so the plant would be deemed to comply with the allocation. If, however, the network voltage source were instead 0.02pu, lagging the assessed plant current source I_c by 90 degrees, the PCC current I_{PCC} would increase to 0.2pu, causing the allocated emission level to be exceeded even in the presence of zero voltage — obviously well below the planning level — at the PCC. These results are summarized in Table I, and provide numerical demonstration that a direct comparison between the measured and allocated currents is not appropriate.

B. Correction of Non–Compliance

Let us now suppose that an acceptable test of compliance exists. Principles behind one such test will be developed in Section V-C. Implicit in the existence of a compliance test is an assumption of the ability of a customer to correct a non–compliant installation [13]; inability to take corrective action beyond simple disconnection would remove much of the purpose behind compliance assessment.

One straightforward way of achieving compliance from a non–compliant state is to modify the distorting process. To correct non–compliant fifth and seventh harmonics, for example, a multi–pulsed converter might be one solution considered. In this case, modification to the distorting process is effectively a change in the representative harmonic source associated with the installation.

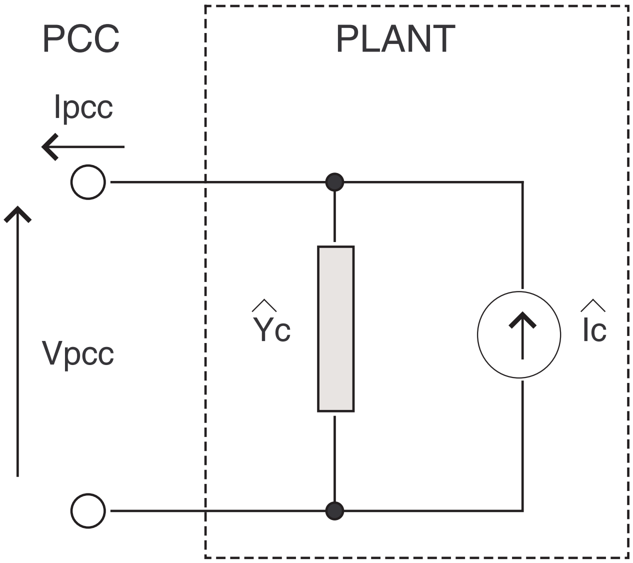

Fig. 5. Norton–equivalent circuit parameters assessed for customer installation from measurement data

A second approach to achieve compliance is modification of the shunt impedance. The typical technique is installation of, or modification to, harmonic filter banks. The design of the compliance test should require [13], for a given non–compliant harmonic, that some filter will exist, able to return the plant to compliance.

These two approaches to compliance amount to restrictions upon the Norton–equivalent parameters of the plant, respectively I_c and Y_c.

C. Constraints on Plant Norton Equivalent Circuit

With the PCC current discarded as a candidate for comparison with the allocated current, currents derived from the Norton–equivalent circuit for the customer installation can be considered. The use of the Norton parameters for compliance assessment assumes that such parameters can be determined from measurements. Although in general it is not possible to identify any of the Norton parameters from measurements of PCC voltage and current, it is possible to identify the Norton parameters on one side of the PCC when that side is fixed and the other varies. A series of measurements of PCC voltage and current can therefore be used to estimate a Norton circuit for the customer, as per Fig. 5, when variations in the network are significantly more substantial than variations on the customer side of the PCC. An example of such a situation is a large, constant industrial plant connected to a transmission network undergoing capacitor switching and generator scheduling changes throughout the course of a day.

When a Norton–equivalent circuit can be identified for the customer plant, the most obvious assessment approach might be to compare the estimated customer harmonic current source $\hat{I}_c$ with the allocated current. However, this comparison is unsuitable as an indicator of compliance. Under this test, changing the harmonic filtering — in effect, the estimated customer shunt admittance $\hat{Y}_c$ — will be unable to move the plant from non–compliance to compliance.

The customer contribution concept hints at a possible alternative test. The current flowing through the PCC attributable to only the estimated Norton current source on the plant side, can be expressed as

$$I_{PCC}^{(c)} = \hat{I}_c \frac{1}{1 + \hat{Y}_c Z_s} \tag{6}$$

As has been noted previously, this current varies with the network impedance and is thus unsuitable as a compliance indicator. However, if the Z_s can be assumed to be either fixed or limited to within a known range, having the value $Z_{s,\mathrm{ref}}$, then this current becomes dependent only upon the customer side of the PCC:

$$I_{PCC}^{(c)} = \hat{I}_c \frac{1}{1 + \hat{Y}_c Z_{s,\mathrm{ref}}} \tag{7}$$

The intention would be to restrict the magnitude of this current to be no greater than the allocated current:

$$\left| I_{PCC}^{(c)} \right| \leq E_{Ihi} \tag{8}$$

This test allows correction of non–compliance through changes to either of the two Norton–equivalent parameters, and does not make customer compliance conditional upon conditions in the network. Key challenges remaining from this proposal are development of suitable ranges of $Z_{s,\mathrm{ref}}$ and application of this method under conditions where noise and other variables make assessment of the Norton parameters difficult.

In our view, it is the utility's responsibility to determine the Norton equivalent circuit constraints corresponding to a particular value of harmonic voltage (5). This requires the utility to have a good understanding of the range of network harmonic impedance at the PCC. It is then the customer's responsibility to comply with the Norton equivalent circuit constraints.

This approach has the sensible consequence that each party is responsible for a quantity or quantities almost directly under its control. This is particularly so with the customer. It is not entirely true for the utility since the harmonic impedance at any point can be affected by the actions of other customers, but only the utility can take up the role for managing the range of network impedance variations and determining and implementing suitable limits on installation practices to control it.

VI. CONCLUSIONS

The concept of a dominant harmonic source has been shown to be not well–defined. Similarly, the concept of a customer contribution to PCC harmonic voltage and current distortion is also not well–defined. These two constraints necessitate an alternative approach to harmonic source detection.

The key objective associated with harmonic source identification is maintenance of harmonic levels within a network below assigned limits. As harmonic source detection is generally only of interest when a harmonic limit is exceeded, detection may be viewed as a search for equipment breaching its allocated emission level. However, allocations may be made in terms of quantities which are not directly measurable. An example of such a quantity is the harmonic voltage which would appear at the PCC if no other harmonic source were to be present. Nevertheless, it is possible to transform an allocated quantity, in combination with additional knowledge of system impedances, into less abstract quantities, such as constraints upon plant Norton–equivalent circuits.

Variations in the harmonic behavior of the network occur as customer loads change, with network equipment such as generating units and shunt capacitors being switched in and out accordingly. For a customer plant which remains largely constant over the course of a day, applicable to some large industrial processes, variations in the harmonic behavior of the network can be exploited to estimate the Norton–equivalent circuit of the plant. The estimated Norton–equivalent circuit of the plant can then be compared with conditions acceptable under the allocation.

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BIOGRAPHIES

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Sarath Perera (M'96) received the B.Sc.(Eng.) degree in power from the University of Moratuwa, Sri Lanka, in 1974, the M.Eng.Sc. degree from the University of New South Wales in 1978, and the Ph.D. degree from the University of Wollongong in 1988. He was a Lecturer for twelve years with the University of Moratuwa. Currently he is an Associate Professor with the University of Wollongong and is the Technical Director of the Integral Energy Power Quality and Reliability Centre. His research interests are in power quality.