1-1-2008

Conditions for the assessment of the harmonic compliance of an installation

Timothy J. Browne
University of Wollongong, tbrowne@uow.edu.au

Sarath Perera
University of Wollongong, sarath@uow.edu.au

Victor J. Gosbell
University of Wollongong, vgosbell@uow.edu.au

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Recommended Citation

Browne, Timothy J.; Perera, Sarath; and Gosbell, Victor J.: Conditions for the assessment of the harmonic compliance of an installation 2008, [6].
<https://ro.uow.edu.au/infopapers/1832>

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Abstract

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Keywords

Conditions, for, assessment, harmonic, compliance, installation

Disciplines

Physical Sciences and Mathematics

Publication Details

T. J. Browne, V. J. Gosbell & S. Perera, "Conditions for the assessment of the harmonic compliance of an installation," in ICHQP 2008: 13th International Conference on Harmonics and Quality of Power, 2008, p. [6].

Conditions for the Assessment of the Harmonic Compliance of an Installation

T. J. Browne, *Member, IEEE*, V. J. Gosbell, *Member, IEEE*, and S. Perera, *Member, IEEE*

Abstract—Methods of allocating harmonic emission limits to customer installations have evolved considerably, as evidenced by the development of harmonic guides such as IEEE-519 and IEC/TR 61000-3-6. However, there is only limited consensus on appropriate techniques validating compliance of installations with those limits. Existing techniques are reviewed and related problems are examined. Conditions which acceptable tests of compliance should meet are proposed.

Index Terms—Harmonic allocation, harmonic assessment, power system harmonics.

I. HARMONIC ALLOCATION AND ASSESSMENT

HARMONIC allocation [1] is the setting of planning and emission levels to maintain harmonic voltages and currents in a network within ranges acceptable to utilities and customers. Guides such as IEC/TR 61000-3-6 [2] — implemented in Australia as a full standard [3] — and IEEE-519 [4] recommend methods for deriving acceptable allocated emission levels. Harmonic compliance assessment, by contrast, relates field measurements to the allocated emission levels, in order to determine whether or not a customer installation is behaving within prescribed conditions. Voltages, currents and powers are all possible candidates for field measurements. For compliance assessment purposes, it is assumed that field measurements are confined to a single site, specifically the point of common coupling.

Under the IEC framework, the allocated h th harmonic emission level for an installation i is set [2] as the current E_{Ihi} . At the transmission level, emission levels are calculated on a system-wide basis, with the assumption that every customer installation injects its full allocated current. The model given in Fig. 1, where individual installations are represented purely as harmonic current sources, is therefore appropriate when calculating the allocated harmonic currents across the network.

One way of conceptualising the measured harmonic current flowing from a customer installation into the utility network is the combination of the effects of

- 1) harmonic current sourced from within the installation, and
- 2) harmonic current, generated on either side of the PCC, absorbed by the installation

upon that measured current. These two effects must be decoupled in order to gain an appreciation of the impact of the installation upon the network, and therefore to assess the

compliance of the installation. The decoupling implies a view of the installation as a Norton model. Such an arrangement is given in Fig. 2. The shunt admittances Y_c included in Fig. 2 but not Fig. 1 represent passive shunt equipment — for example, harmonic filters — forming part of the customer installations. At first glance the compliance assessment problem appears straightforward: for an installation i , compare the harmonic current $|I_{PCCi}|$ flowing from the customer installation through the PCC with the harmonic current E_{Ihi} which was allocated. However, the two quantities reflect different requirements. No case has been made that the allocated harmonic current E_{Ihi} should be equal to the magnitude of the plant-side Norton-equivalent current source I_{ci} for installation i ; that is, in general

$$E_{Ihi} \neq |I_{ci}| \quad (1)$$

The allocated currents E_{Ihi} are calculated on the basis of all customers injecting the allowable distortion simultaneously; when assessing the compliance of an individual installation based on field measurements, no such assumption holds. A suitable method of compliance assessment is therefore required.

II. PURPOSE AND OBJECTIVES OF COMPLIANCE TESTING

To assess compliance of a customer installation, the utility must determine whether some measured quantity, either raw or processed, lies outside a set of acceptable values. A procedure for making this determination requires both that the measured quantity be clearly defined and that the allocation process be able to yield the set of acceptable values.

The need to specifically assess compliance, rather than simply identify the contribution made by an installation to a PCC quantity, was examined by Stapleton and Bones [5]. However, the proposed technique was based on the harmonic power flow direction method, which has since been shown to be flawed [6], [7]. Compliance assessment is therefore by no means a solved problem.

Many authors have investigated methods of separating network- and plant-side contributions to harmonic voltage and current distortion at the PCC. Even if the two contributions could be isolated from each other, no method has been established by which compliance assessment could be carried out from the isolated contributions. Further, from the utility point of view, some sense of the plant-side contribution to PCC distortion is not necessarily strictly relevant; rather, all that is required is a method of determining whether or not the installation is behaving as agreed.

Similarly, the problem of dominant harmonic source identification has been examined extensively in the literature; a

This work was supported by the Australian Research Council and Powerlink Queensland under Linkage Project LP0232383.

T. J. Browne is with Arizona State University (email: tbrowne@ieee.org).
V. J. Gosbell and S. Perera are with the University of Wollongong (e-mail: v.gosbell@uow.edu.au and sarath@uow.edu.au).

Fig. 1. Equivalent circuit for allocation purposes

solution which appears promising has been found [8]. However, this again is of value to the utility only insofar as it can be extrapolated to the immediately useful problem of whether or not an installation is violating its allocation.

III. KEY ASSUMPTIONS UNDERPINNING PREVIOUS COMPLIANCE ASSESSMENT STUDIES

Fig. 3 gives an equivalent circuit in the vicinity of the point of common coupling (PCC) between the network and the customer installation. When considering the compliance of a distorting load, the expression ‘distorting load’ is taken to mean the entire customer installation — that is, both I_c and Y_c in Fig. 3, and not just I_c or the distorting voltage contribution I_c/Y_c [9].

The existing literature on compliance assessment and related topics assumes that harmonic voltage and current measurements are available at the PCC and nowhere else. This

Fig. 2. Equivalent circuit for assessment purposes

Fig. 3. Equivalent circuit of network-plant interface for compliance assessment

assumption is maintained throughout this paper. Instrumentation is assumed to comply with the relevant IEC standard, IEC 61000-4-30:2003 [10].

It is further assumed that recorded measurements can be accepted as sufficiently accurate from which to draw conclusions on compliance. Particularly with harmonic voltage measurements, such an assumption is dubious: voltage transducers appear to be suspect above even the 5th harmonic for EHV measurements and the 10th harmonic at HV [11]; recent advances in capacitive voltage transformers may assist

in alleviating this problem [12]. Both the magnitude and phase angle components of those measurements are assumed to be available [13]. Further, it is assumed [9], [14], [15] that measurements can be made while the customer installation under consideration remains in service.

In the harmonic allocation methodology of [2], [3], nonlinear summation [16], [17] of voltages A_i or currents A_i as

$$A^{\alpha_h} = \sum_i A_i^{\alpha_h} \quad (2)$$

(where α_h is a harmonic-dependent summation exponent in the range 1–2) is required in order to account for the effects of combining statistical 95% quantities in the absence of *a priori* knowledge of phase and time diversity between those quantities. For compliance assessment based upon measurements, instantaneous circuit quantities can be employed and so the loss of information implicit in the use of statistical 95% measures need not be considered. The identified nonlinear summation law for voltages and currents is therefore ignored here. It should be noted that measurements, and therefore the parameters in the equivalent circuit of Fig. 3, are not necessarily constant over time [13].

IV. PROBLEMS CLOSELY RELATED TO COMPLIANCE ASSESSMENT

Four problems related to compliance assessment are examined:

- 1) identification of background voltage;
- 2) determination of the dominant harmonic source;
- 3) separation of customer and supply contributions to harmonic distortion at the PCC; and
- 4) network harmonic impedance assessment.

Each of these has features in common with compliance assessment, while not specifically yielding a compliance test.

Assessment of “background voltage” is a separate problem which has been considered by utilities but remains of limited value for explicit compliance assessment purposes. There is some conjecture as to how best to define background voltage: it could be

- 1) the voltage at the PCC when the customer installation is not connected (equal to the Thévenin-equivalent harmonic voltage source V_s of the network, as per Fig. 3), or
- 2) the voltage at the PCC when the harmonic source in the customer installation is deactivated.

Since the term ‘background’ implies that the installation should have no effect, only option 1 is satisfactory; for option 2, changing harmonic filter switching conditions (for example) would affect the background voltage. This effect can be observed by examining Fig. 3: with the customer source deactivated, the PCC voltage is controlled by the divider action of the two impedances. Changing the customer impedance Z_c by altering harmonic filter switching conditions will change the PCC voltage and consequently — if option 2 is selected — the background voltage. When using option 1, background voltage can be readily assessed prior to commissioning new equipment.

The objective of dominant source identification is to find which side of the PCC contributes more (in some sense) to harmonic distortion at the PCC. This problem is not particularly meaningful [14]: it cannot determine whether or not an installation exceeds an allocated emission level and therefore does not yield immediately useful corrective action. Further, the result of a dominant source identification depends heavily on the measure of harmonic distortion: for example, a situation can arise where the utility side dominates the PCC voltage whereas the plant side dominates the PCC current.

A popular test for identifying a dominant harmonic source is based on finding the direction in which harmonic real power flows [5], [9]; as was noted in Section II, this method has been discredited [6], [7]. An analogy with real power flow at fundamental frequency suggests why the method is unsuitable: the well-known power-angle equation shows that the direction in which power flows through a largely reactive line is controlled primarily by the phase angles, and not the magnitudes, of the voltages on opposite sides of a line. The supposition that harmonic voltage magnitudes should indicate the direction of harmonic power flow across a PCC is therefore inconsistent with the situation at fundamental frequency. Li [8] and Sneddon [18] have postulated that reactive power flow direction may be more suitable. It should be noted that the concept of harmonic power flow remains suitable for other applications; for example, in harmonic state estimation it is a necessary tool. Rather, specifically for assessing the location of major harmonic sources, the direction of harmonic power flow is not overly useful even though instruments have been developed [5]. Additionally, this quantity does not relate to an allocated emission level and is therefore not an optimum solution to the compliance assessment problem.

Techniques involving representation of the customer installation by an equivalent linear circuit have been developed. One such technique [19] examines the extent to which the installation deviates from the behaviour expected of an equivalent resistor-inductor combination; an extension [20] specifically requires that the equivalent circuit draw the same fundamental real and reactive power as the actual installation. Neither case is particularly constructive: capacitance is neglected completely in the equivalent circuit, so even a resistor-capacitor combination would be replaced with a resistor and inductor, potentially leading to identification of severe distortion where none exists. Further, the technique does not identify a specific compliance test.

Other papers also claim to solve the separation problem. Reliance on the sign of an ill-defined impedance quantity [21] is highly susceptible to noise problems, as harmonic impedances can easily cross the real and imaginary axes on the complex plane. The same is true of conditions based on the sign of a power [22], an extension to the approach of [23] which involves separation of the PCC current into “conforming” and “non-conforming” components. The conforming/non-conforming current method is noted by [21] to be essentially a futile exercise, in that the two current components are not orthogonal and therefore cannot be uniquely separated.

Some attention has been directed [15], [24] to assessment of the network harmonic impedance at a bus from measurements

or simulation. Both invasive (requiring equipment switching or full disconnection) and non-invasive methods have been reported. An on-line harmonic impedance assessment device, for assessing the network impedance under a variation in the plant parameters, has been described [25]. The method relies on PCC measurements for only two windows; during each window all parameters are assumed constant. More rigorous means of approaching this identification problem can be developed using least-squares estimation [9].

V. EXISTING ASSESSMENT TECHNIQUES

The harmonic assessment level¹ of a distorting load has been defined by the French utility EdF to be the harmonic voltage which would occur at the PCC in the absence of all other distorting loads [14]; CIGRÉ has recommended this definition also [9]. However, this definition is unsatisfactory for compliance assessment purposes: variation in the *network* impedance Z_s (as per Fig. 3) influences the harmonic assessment level of the plant.

Examination of detail embedded in [9] reveals the need for the definition (in Section III) of ‘distorting load’ as the entire customer installation: whilst the text of [9] suggests that calculation of the harmonic assessment level assumes no other distorting load exists, the equations given include the network impedance Z_s . Since the Z_s and V_s partially represent the combined effects of all remote distorting loads, the text and equations of [9] are not consistent with each other. This inconsistency has propagated to [25], where harmonic assessment levels for the network and plant sides of the PCC are based on two different criteria. Effects of the network impedance are included in harmonic assessment level definitions made by [26]; however, this reference does note the difficulty imposed by such a definition.

An alternative view [14], [27] identifies distorting loads as either “friendly” or “harmful”, depending upon the direction of change observed in the harmonic voltage at the PCC after the distorting load is connected. Since different results could be obtained if (a) the PCC current were to be used for the comparison, or (b) the effect of connection on remote buses were to be considered, this suggestion is not pursued within this paper. A different method proposed [28] apportions voltage distortion between customers based solely on modelling — contradicting the assertion of [5] that assessment should be derived from measurements instead — and relies on assumptions suited to distribution networks. Changes in the equipment parameters do not result in any changes in the responsibility attributed. Principles and assumptions governing this method are not sufficiently clear to be useful, and so no further attention is given.

Yang [14] examines the classification [27] of “harmful” and “friendly” harmonic injection, where discrimination is between differing effects of the installation on the harmonic voltage at the PCC. In that examination it is shown that the distinction between friendly and harmful injections does not provide

any information on contribution of individual installation or network to distortion at the PCC.

Both “invasive” and “non-invasive” tests have been described [9], [14], the distinction being whether or not the customer installation is to be disconnected as part of the test. For the bulk of large industrial installations, disconnection is impractical, especially in the case of potentially large harmonic sources such as aluminium smelters. Under these circumstances, a change in operating condition has been proposed as an alternative [15] for harmonic impedance measurements.

The assessment techniques which Yang presents [14] rely on the EdF definition of the harmonic [injection] level from a distorting load, namely the [harmonic] voltage that would be caused by that load at the PCC if no other distorting load were present. There are several difficulties with this approach. Firstly, the Thévenin or Norton equivalent circuit for the network must take into account all distorting loads on the network; they cannot readily be deactivated. Secondly, the definition is not clear as to whether it is just the harmonic source component or the entire installation which is to be assumed disconnected in the other installations. The CIGRÉ report [9] is also unclear on this point: the text makes one supposition but mathematical derivations choose the alternative.

VI. REQUIREMENTS OF A HARMONIC COMPLIANCE TEST

As was noted in Section V, harmonic compliance testing has received little attention. Before suitable compliance tests can be identified, criteria for separating acceptable tests from the unacceptable are necessary. Four criteria are proposed which should be met by a satisfactory compliance test.

- 1) *Any compliance test adopted ought to relate in some way to the allocated quantity.* Allocated harmonic emission levels are meaningful and useful only if such levels can be linked to a test of compliance. Tests which do not make this connection are not examined as possibilities. Ideally the test would be able to make a direct comparison between instrumented data and a prescribed emission level.
- 2) *An acceptable compliance test requires some independence between the network and customer sides of the PCC: a change in operating conditions only on the network side should not change the customer status from compliant to non-compliant or vice versa.* It is reasonable to expect that any test should allow for time variation in either or both the network and customer installation.
- 3) *The design of the compliance test ought not to preclude corrective action from being taken when an installation is found to fail to comply with its allocation.* That is, a non-compliant installation should be able to take action which enables compliance to be achieved. Without this possibility, the utility would be faced with allowing the non-compliant installation to remain on the network or requiring that it be permanently disconnected; neither is likely to be satisfactory. Corrective action in many instances involves installation of harmonic filters. Without this criterion, harmonic filter installation ceases to serve any harmonic-reducing purpose.

¹Referred to as “emission level” in the literature; the term “assessment level” is substituted to avoid confusion with allocated emission levels.

- 4) *The compliance test should not promote behaviour likely to cause damage to either the network or the customer installation.* The design of the test should not encourage customers to connect equipment which is deemed satisfactory but which leads to excessive harmonic voltages or currents on the network or at the PCC.

Much of the existing literature is based on a single measurement of voltage and a single measurement of current at the PCC. Whilst this criterion might under some circumstances be desirable in a test of compliance assessment, it is not essential. The IEC guide [2] casts allocation in terms of 3-second and 10-minute quantities rather than strictly instantaneous values. Since compliance tests should reflect the circumstances under which the allocation is made, forcing compliance tests to be undertaken on a single instantaneous measurement would impose an unnecessary constraint. Further, the additional measurement burden in logging multiple measurements rather than only one number is likely to be minor relative to the effort involved in setting up the requisite field tests.

VII. CONCLUSIONS

Previous work on harmonic compliance assessment has been reviewed and related to harmonic allocation. Key assumptions necessary for compliance assessment, including definitions of the appropriate equivalent circuits, have been identified and grouped together. These assumptions form the basis for four criteria to be met by any test of harmonic compliance. The criteria require a relation between the allocated and measured quantities, independence between the two sides of the PCC, scope for corrective action, and deterrence of behaviour likely to cause damage.

ACKNOWLEDGMENT

The authors would like to thank the Australian Research Council and Powerlink Queensland for financial support under Linkage Project LP0232383. Paul Windle of Powerlink Queensland has provided valuable technical guidance.

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BIOGRAPHIES

Timothy Browne (S'02, M'07) holds the B.E. (Hons) degree in Electrical Engineering from the University of New South Wales and has completed the Ph.D. degree at the University of Wollongong. He is presently with Arizona State University.

He was with distribution utility EnergyAustralia and is now an adjunct associate with Arizona State University, Tempe.

Vic Gosbell (M'75) obtained his BSc, BE and PhD degrees from the University of Sydney. He has held academic positions at the University of Sydney and the University of Wollongong where he became the foundation Professor of Power Engineering. He is now an Honorary Professorial Fellow and Technical Advisor to the Integral Energy Power Quality and Reliability Centre. He is currently working on harmonic management, power quality monitoring and standards. He is a member of Australian standards and CIGRE sub-committees and is a Fellow of the

Institution of Engineers, Australia.

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.