Voltage Unbalance Emission Assessment in Radial Power Systems

U. Jayatunga, *Student Member, IEEE*, S. Perera, *Member, IEEE*, and P. Ciufo, *Senior Member, IEEE*

***Abstract*—Voltage unbalance (VU) emission assessment is an integral part in the VU-management process where loads are allocated a portion of the unbalance absorption capacity of the power system. The International Electrotechnical Commission Report IEC/TR 61000-3-13:2008 prescribes a VU emission allocation methodology establishing the fact that the VU can arise at the point of common connection (PCC) due to upstream network unbalance and load unbalance. Although this is the case for emission allocation, approaches for post connection emission assessment do not exist except for cases where the load is the only contributor to the VU at the PCC. Such assessment methods require separation of the post connection VU emission level into its constituent parts. In developing suitable methodologies for this purpose, the pre and postconnection data requirements need to be given due consideration to ensure that such data can be easily established. This paper presents systematic, theoretical bases which can be used to assess the individual VU emission contributions made by the upstream source, asymmetrical line, and the load for a radial power system. The methodology covers different load configurations including induction motors. Assessments obtained by employing the theoretical bases on the study system were verified by using unbalanced load-flow analysis in MATLAB and using DIgSILENT PowerFactory software.**

***Index Terms*—Current unbalance, load asymmetry, power quality (PQ), system inherent asymmetry, voltage unbalance (VU), VU emission allocation, VU emission assessment.**

I. Introduction

VOLTAGE-UNBALANCE management in power systems requires approaches to allocate and assess VU emission levels in a systematic manner. In this regard, the IEC Technical report IEC/TR 61000-3-13:2008 [1] provides guiding principles to system operators and owners to determine the connection requirements of unbalanced installations to medium-voltage (MV), high-voltage (HV), and extra-high-voltage (EHV) public power systems. The philosophy of this report is similar to those of the counterpart IEC recommendations for harmonics (IEC 61000-3-6) [2] and flicker (IEC 61000-3-7) [3] allocation. Coordination of VU emission levels between different voltage levels of the power system is prescribed based on planning limits as reference values. The global emission allowance is then derived through a general summation law considering upstream emission contribution through transfer coefficients. The "k_{uE} factor" approach is used to account for the unbalance that arises at the point of common connection (PCC) caused by upstream supply system asymmetry, when apportioning the global emission allowance to unbalanced installations. A range of values for the "k_{uE} factor" is given in [1] from which a suitable value can be selected for a system with some qualitatively characteristics.

Most of the available literature on voltage unbalance [4], [5] discusses its causes and effects and present related standards, definitions, and mitigation techniques. The asssessment of VU emission at the PCC with the help of the sequence energies is discussed in [6] and prediction of VU emission given by loads through unbalanced fundamental power is presented in [7]. None of the aforementioned work discusses or give methodologies that can be used to separate the individual emission contributions made by different sources of unbalance.

The work presented in [8] provides insights in relation to the approaches and concepts given in [1], including new methodologies to evaluate global VU emission due to load and line asymmetries. Although the unbalance arises due to unbalanced installations and inherent system asymmetries, determination of the level of contributions to the total VU emission at the point of evaluation (POE) is not a straightforward procedure due to the complex interactions that can take place between numerous sources, particularly in an interconnected network environment [9], [10]. The contribution of individual emission levels to the overall VU measured at the POE is often required with only knowledge of the pre- and postconnection voltage and current measurements in combination with some relatively easy-to-establish parameters.

In this regard, some preliminary work exists on VU emission assessment in the C4.109 report [11] produced by the CIGRE/CIRED Joint Working Group on emission assessment techniques. The same work summarized in [12] presents the 'k_{uE} factor' in a more generalized manner. However, this formulation does not consider the load type dependency or sensitivity of the "k_{uE} factor" to other system conditions. Thus, the proposed study makes a sufficiently rigorous and comprehensive fresh approach for compliance assessment providing further improvements to IEC work on VU management.

This paper presents deterministic approaches for the evaluation of individual VU emission contributions made by different sources of unbalance at the POE for a radial power system. The theoretical basis is developed to quantify the individual contributions made by upstream source unbalance, load asymmetry, and line asymmetry at the POE for different load configurations.

Manuscript received November 15, 2011; revised February 20, 2012; accepted April 11, 2012. Date of publication June 01, 2012; date of current version June 20, 2012. Paper no. TPWRD-00978-2011.

The authors are with the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, Wollongong 2522, Australia, and also with the Endeavour Energy Power Quality and Reliability Centre, NSW 2522, Australia (e-mail: ppc@uow.edu.au).

Digital Object Identifier 10.1109/TPWRD.2012.2196294

The mathematical models are verified using three-phase unbalanced load-flow programs.

This paper is organized as follows: the general concepts associated with VU emission are described in Section II. The proposed mathematical modeling for the separation of different VU emission contributors is presented in Section III and verification of the proposed methodology, together with test system specifications, is included in Section IV. Conclusions are given in Section V.

II. General Concepts of VU Emission [11]

According to IEC/TR 61000-3-13:2008 [1], the unbalance emission caused by an installation is the magnitude of the VU factor ($\mathrm{VUF} = |(U_2/U_1)|$) where the installation under consideration gives rise to the POE. In many practical situations, the zero-sequence unbalance is generally ignored, considering its insignificance compared to negative-sequence unbalance from an equipment impact perspective and/or because of three-wire situations.

The sequence voltages at the POE can be described as a function of the sequence currents drawn by the connected installation and the upstream network (e.g., transmission line) sequence impedance matrix $[Z_{012,t}]$. Thus, the negative-sequence voltage at the POE (U_2) can be expressed as

$$U_2 = U_{2,\mathrm{oc}} - (Z_{20,t}I_0 + Z_{21,t}I_1 + Z_{22,t}I_2) \tag{1}$$

where $U_{2,\mathrm{oc}}$ is the open-circuit negative-sequence voltage which can be obtained from preconnection voltage measurement ($U_{2,\mathrm{preconnection}}$) at the POE. U_2 can be obtained from the postconnection voltage ($U_{2,\mathrm{postconnection}}$) at the POE. The following comments are applicable to the three impedance voltage drop terms in (1):

- $Z_{20,t}$ is relatively small and $I_0 = 0$ in many situations and, hence, $Z_{20,t}I_0$ can be ignored;
- $Z_{21,t}I_1$ is the negative-sequence voltage that arises as a result of the asymmetrical upstream network itself and can be defined as the system inherent unbalance ($U_{2,i(\mathrm{line})}$); this term can be of significance since I_1 is usually large; $Z_{21,t}$ exists only if the upstream network is asymmetrical;
- $Z_{22,t}I_2$ can be of significance if there is an unbalance current due to load unbalance (assuming that there are no contributions to I_2 from upstream unbalance and asymmetrical upstream impedances); therefore, this term is the negative-sequence voltage which arises as a result of load unbalance and is defined as the load unbalance emission ($U_{2,i(\mathrm{load})}$).

Hence, ignoring the term $Z_{20,t}I_0, U_2$ can be re-expressed as shown in (2):

$$U_2 = U_{2,\mathrm{oc}} - (Z_{21,t}I_1 + Z_{22,t}I_2) = U_{2,\mathrm{oc}} + U_{2,i} \tag{2}$$

where $U_{2,i}$ is the VU emission resulting from the connection of installation which consists of the asymmetrical load and line contributions.

The approach given in the CIGRE/CIRED report on emission assessment techniques [11] is to evaluate unbalance emission levels based on preconnection and postconnection measurements at the POE. Having suitable measurement results with phase-angle information (pre and postconnection), the total emission $U_{2,i}$ can naturally be established as given by

$$U_{2,i} = U_{2,\mathrm{postconnection}} - U_{2,\mathrm{preconnection}}. \tag{3}$$

Accordingly, the emission level that arises as a result of a particular installation can lead to an increase or a decrease of the resulting unbalance level at the POE. At the postconnection of the installation, if the net unbalance level decreases, no emission assessment has to be carried out in relation to the particular installation. Conversely, if the net unbalance increases, the fraction of the emission level which the installation is responsible for ($U_{2,i(\mathrm{load})}$) has to be evaluated.

So the challenge lies in the decomposition of U_2 to determine the individual contributions made by different sources of unbalance in the network (i.e., background unbalance voltage, asymmetrical supply network impedances, and the installation in question) for which a comprehensive methodology or methodologies do not exist.

In the straightforward case where the VU at the POE arises only as a result of installation asymmetry, $U_{2,i(\mathrm{load})}$ can be established using the well-known result employing the quantities of current unbalance factor (CUF, that is, the ratio of negative-sequence to positive-sequence current), load VA loading level (S_i), and the short-circuit capacity (S_{sc}) as given by

$$\left|\frac{U_{2,i(\mathrm{load})}}{U_1}\right| = \frac{S_i}{S_{\mathrm{sc}}}|\mathrm{CUF}|. \tag{4}$$

Further with (4), the VU emission that arises at the POE due to an asymmetrical upstream network (or line) asymmetry ($U_{2,i(\mathrm{line})}$) can be estimated using

$$\frac{U_{2,i(\mathrm{line})}}{U_1} = \frac{S_i}{S_{\mathrm{sc}}}\left|\frac{Z_{12}}{Z_1}\right| \tag{5}$$

where Z_{12} is the positive-sequence negative-sequence coupling impedance of the upstream network, and Z_1 is the positive-sequence impedance of the upstream network.

The specific results given by (4) and (5) can be used individually to determine the contributions to the VU at the POE made by an installation or the network. However, they are not sufficiently comprehensive to be used with pre and postconnection measurements to separate the VU at the POE into constituent components. Further, the impact of the upstream source unbalance[1] on the POE is not accounted for by these results. Hence, it can be noted that a holistic approach and fresh formulations are required to separate the VU measurements at the POE into its constituent components, which forms the thrust of this paper. The specific results given by (4) and (5) can be shown to be intrinsically built into the mathematical formulations that will be presented in this paper.

III. Evaluation of Individual Unbalance Emission Contributions at the POE: Theoretical Bases

A deterministic approach is proposed which forms the bases for evaluation of the individual contributions made by the installation asymmetry, upstream network asymmetry, and the up-

[1] Can be considered as a Thévenin equivalent unbalance voltage.