INTERNATIONAL SURVEY OF UNBALANCE LEVELS IN LV, MV, HV, AND EHV POWER SYSTEMS: CIGRE/CIRED JWG C4.103 RESULTS

Robert KOCH
Eskom – South Africa
robert.koch@eskom.co.za

Germain BEAULIEU
Hydro Quebec – Canada
beaulieu.germain@hydro.qc.ca

Luc BERTHET
EDF – France
luc.berthet@edf.fr

Mark HALPIN
Auburn University
halpin@eng.auburn.edu

Paper presented on behalf of CIGRE/CIRED JWG C4.103[1]

ABSTRACT

Technical considerations are reported that informed the recommendations made by CIGRE/CIRED Joint Working Group C4.103 on a methodology for developing (negative sequence) unbalance emission limits for installations connected to MV, HV, and EHV power systems. Measured survey data provided by international distribution and transmission companies on levels of unbalance measured in their systems is reported on. Technical considerations identified in the analysis of the data are also discussed, i.e. system-generated unbalance and misconceptions about the levels of unbalance that can arise due to "short lines,", and the impacts of unbalance attenuation from HV to MV or from MV to LV due to motor loads. This information is used also to recommend indicative planning levels.

INTRODUCTION

One of the deliverables of CIGRE/CIRED JWG C4.103 was to develop recommendations on how emission limits can be calculated for unbalanced installations connected to EHV, HV, and MV systems (only negative sequence unbalance is considered). These recommendations form the basis of a new IEC Technical Report (IEC 61000-3-13) under development by IEC 77A/WG8. This report is based on the philosophy applied in related IEC Technical Reports 61000-3-6 (Harmonics) and 61000-3-7 (Flicker) [1],[2]. A key aspect of these technical reports is the use of planning levels at the various voltage levels as a basis for determining emission levels for customer installations.

One of the activities undertaken by the JWG was to analyse measured unbalance data that was submitted by various international transmission and distribution companies. The analysis of this data led to additional questions such as the propagation of unbalance in networks and the impact of this propagation on unbalance emission calculation methods.

SURVEY RESULTS

A request was made by the working group for data from national surveys on levels of unbalance in transmission and distribution systems. The final count of measured sites with data generally compatible with IEC 61000-4-30 measurement methods was 168 EHV, 940 HV, 497 MV, and 222 LV sites. The results are shown in figures 1 to 4. The index used in the analysis of the data for each site was the 95% weekly 10-minute value. (Note that extreme values in the measurement sets should be considered with caution, because the measured levels of unbalance in networks exclusively supplying loads such as single phase AC traction loads may not be representative of general network performance.

From this data, it was concluded that the levels of unbalance tend (for 95% of sites) to be less than: 1% at EHV; 2% at HV and MV; and 1,4% at LV.. These levels may be compared with the voltage characteristics (1,5% at EHV, and 2% at HV and MV) recommended by JWG C4.07 [3]. It may be noted that the "system indices" recommended in [3] are based on a "high percentage of sites" e.g. 90%, 95%, or 99% of sites. The conclusions in this paper on levels of unbalance are based on 95% of sites at each voltage level.

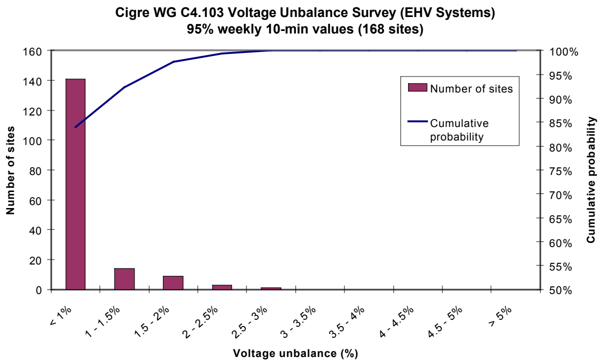

Figure 1. Measured unbalance levels at 168 EHV sites

1 Cigré/Cired Joint Working Group C4.103 consists of : G. Beaulieu (Convenor), P. Goossens (secretary), R. Koch, M. Halpin, L. Berthet, A. Baitch, M. McGranaghan, M. Lahtinen, J. Sinclair, J. Schonek, V. Gosbell, G. Bartak, H. Rochereau, M. Bollen, G. Borloo, H. Bronzeado, M.B.S. Diaz, G. OhEidhin, Z. Emin, S. Georghe, O. Gonbeau, U. Grape, Y. Hirata, J.L. G-Iglesias, K. Heidenreich, L. Fickert, P. Maigler, S. Malgarotti, C. Namhun, C. Unger, G. Valtorta, A. Zobaa.

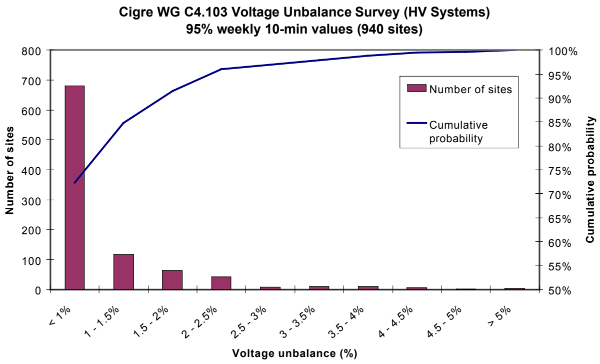

Figure 2. Measured unbalance levels at 940 HV sites.

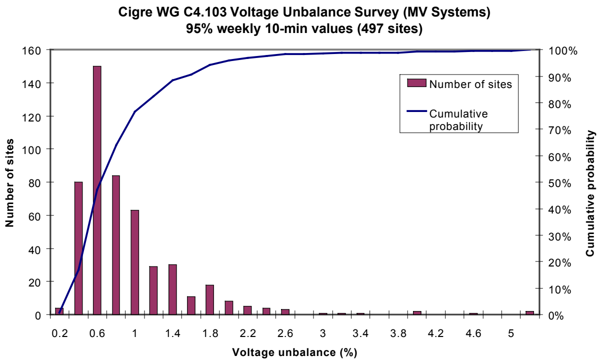

Figure 3. Measured unbalance levels at 497 MV sites.

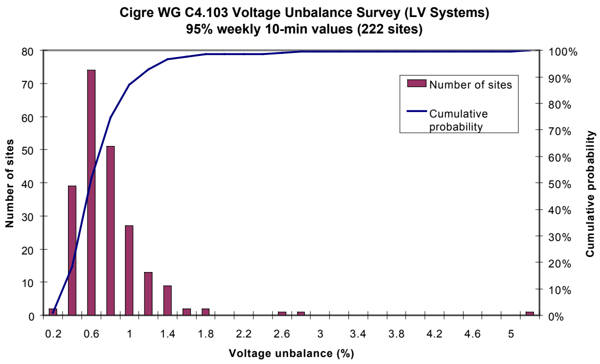

Figure 4. Measured unbalance levels at 222 LV sites.

Some considerations arise when analysing the survey data: • In some cases, measurements were undertaken for a week, while in other cases the instruments are permanently installed. As the maximum 95% weekly value is reported for each permanent installation, the likelihood of measuring higher values at these sites is higher than in the case of the weekly survey method (considering seasonal variations). Survey data should ideally span a full year..

• Abnormal network conditions that may have given rise to high levels of voltage unbalance were not specifically reported. Ideally only "normal" network conditions should be considered (note that "normal" may include contingencies for which the system is designed). In a similar sense, cases where improvements were subsequently made based on the "high" levels of unbalance were not specifically identified.

• Few surveys detailed the types of loads connected (e.g. single-phase traction). Better analysis of results would be possible if load types were identified in the survey.

• Where capacitive voltage transformers (CVTs) are used (typically at EHV and HV), differences in the capacitive elements of the three phases may give rise to incorrect measurements. Ideally the accuracy of the transducers used to measure the levels of unbalance should be known.

• Few surveys could provide corresponding EHV, HV, MV, and LV measurement data. This limited use of the data to assess the propagation of unbalance in the power system (in particular to understand the apparent lower levels of unbalance at LV discussed later in this paper).

• Limited information was available on the level of transposition of transmission or distribution lines. Transposition can play an important role in the unbalance characteristics of the network, as discussed in this paper.

THE EFFECT OF MOTORS

The lower negative sequence impedance (in relation to the positive sequence impedance) of a three-phase motor or generator, results in proportionally higher negative sequence currents. This phenomenon gives rise, at points electrically closer to the terminals of the motor, to a reduction of upstream negative sequence voltages. Consider a negative sequence voltage source at an upstream busbar. The smaller the negative sequence impedance of a motor connected downstream of this source via a transformer with a given impedance (the same as the positive sequence impedance of the transformer), the smaller the negative sequence voltage will be at the motor terminals (and also at points upstream of the motor - depending on the system impedances). This phenomenon may be considered by introducing a transfer coefficient in the calculation of the global unbalance available at a given site. The transfer coefficient from MV to LV may either be measured or may be approximated by:

$$T_{MV-LV} = \frac{1}{\left| 1 + k_m \left(\frac{k_s - 1}{k_{sc} + 1} \right) \right|} \quad (1)$$

where: k_{sc} is the ratio between the short circuit level at the LV busbar (in kVA) and the total LV load (in kVA) connected at this busbar; k_m is the ratio between the rated motor load (in kVA) and the total load (in kVA) connected at the LV busbar; and k_s is the ratio between the positive and negative sequence impedance of the motors (which can in many cases be approximated by the ratio between the starting current and full load current of the motor).

The impact of this approximated transfer coefficient on unbalance levels (i.e. the reduction of unbalance from MV to LV) is shown in figure 5. What is apparent is that the reduction in upstream unbalance levels can be between 5% and 50% depending on the system and load characteristics.

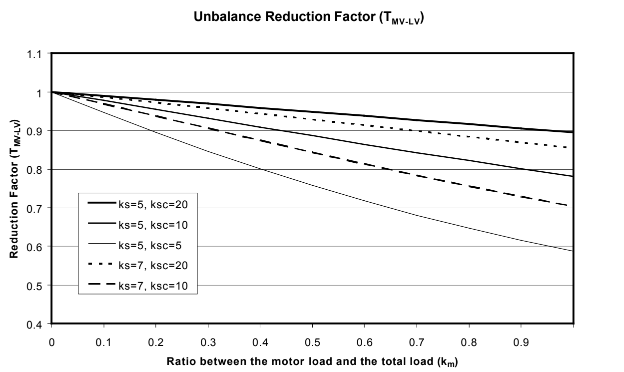

Figure 5. Unbalance reduction factor from MV to LV for various combinations of: motor loading, motor positive and negative sequence impedances, and short-circuit powers v.s. total load power (see Equation 1).

An interesting example for a mining operation is shown in figure 6, where HV unbalance levels become significant due to an *abnormal* system condition which results in the load being supplied radially by long un-transposed EHV and HV lines. The unbalance on the MV system can be seen to vary according to (mainly motor) loading on these networks – as illustrated by comparing days 2 and 4. The measurements after day 10 reflect the *normal* system condition where HV levels of unbalance are low and the apparently high transfer factor is due to unbalance generated at MV.

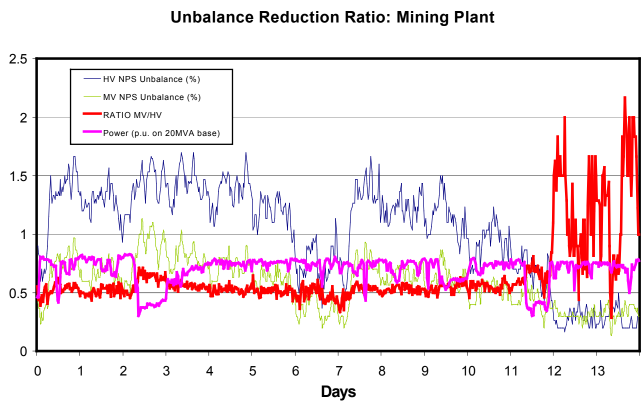

Figure 6. Example of unbalance ratio measurement for a remote mine with largely motor loading.

The implication is that higher unbalance emission limits for individual 3-phase loads can be allowed in cases where the transfer factor is known to be less than unity.

TRANSPOSITION

Another consideration in the calculation of emission limits is the unbalance generated by un-transposed lines. The general view is that this affects mainly long lines. However, cases of heavily loaded HV lines of approximately 20km in length have been shown to give rise to voltage unbalance levels of 1%. Similarly, some overhead MV lines configurations can cause significant voltage unbalance. Figure 7 shows the voltage unbalance (V_2/V_1 %) for an overhead line (quasi-horizontal conductor configuration) in relation to the product of the line current and the line length (kA·km). In the case of an un-transposed 10 kV line, the voltage unbalance can reach 1% for a line current of 100A and a distance of 17 km (i.e.1,7 kA·km). At LV, many reports on voltage unbalance state that load unbalance is the only important parameter to consider. While this is generally true for LV cables or twisted conductors, it should be recognized that in some cases the voltage unbalance due to LV lines might not be negligible. Figure 8 illustrates the case of an overhead LV feeder (open-wire configuration) where the voltage unbalance (V_2/V_1 %) reaches 0,5% on a 500V feeder carrying 400A over 100m (i.e. 40 kA·m).

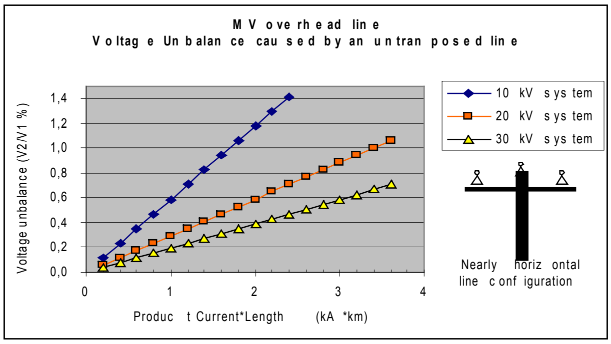

Figure 7. MV overhead line unbalance.

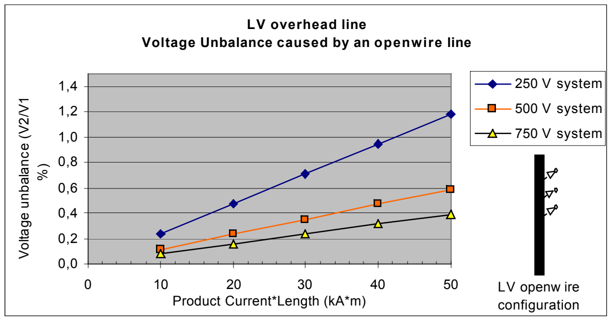

Figure 8. LV overhead line unbalance.

The JWG recommendations address such system-generated unbalance by introducing a factor (k_{uE}) in the calculation of emission limits for an installation at MV, HV and EHV, i.e.:

$$E_{ui} = \sqrt[\alpha]{k_{uE}} \cdot G_{uMV+LV} \sqrt[\alpha]{\frac{S_i}{S_t}} \qquad (2)$$

where: E_{ui} is the voltage unbalance emission limit for the installation *i* directly supplied at MV (%); k_{uE} is the fraction of the global contribution to voltage unbalance that can be allocated for emissions from unbalanced installations in the considered system; G_{uMV+LV} is the acceptable global contribution to the voltage unbalance in the MV system of the MV system inherent asymmetries and of the unbalanced installations supplied at MV and LV; $S_i = P_i / \cos\varphi_i$ is the agreed power of the installation *i* (or the MVA rating of the installation); S_t is the total supply capacity of the considered system including provision for future load growth; and α is a summation law exponent (discussed later in this paper).

It is recommended that k_{uE} be determined by the system owner or operator depending on the system characteristics. The coefficient k_{uE} should be set as to allow an equitable share of emissions between the unbalanced installations and the various inherent sources of unbalance present in the power system. Indicative values for k_{uE} are given in table 1.

Table 1. Indicative range of values of k_{uE}.

System characteristics	k_{uE}
• Highly meshed system with generation locally connected near load centers. • Transmission lines fully transposed, otherwise lines are very short (few km). • Distribution systems supplying high density load area with short lines or cables.	0,8-0,9
• Mix of meshed system with some radial lines either fully or partly transposed. • Mix of local and remote generation with some long lines. • Distribution systems supplying a mix of high density and suburban area with relatively short lines (<10 km)	0,6-0,8
• Long transmission lines generally transposed, generation mostly remote. • Generally radial sub-transmission lines partly transposed or un-transposed. • Distribution systems supplying a mix of medium and low density load area with relatively long lines (>20 km). • 3φ motors account for only a small part of the peak load (eg. 10%).	0,5-0,6

SUMMATION LAW EXPONENT (α)

Unbalance due to a large number of varying loads is generally random and independent. A summation law exponent α is used to approximate the summation of a set of random unbalance vectors of magnitude u_{2i}, i.e.:

$$u_2 = \sqrt[\alpha]{\sum_i u_{2i}^{\alpha}} \quad (3)$$

Unbalance caused by many three-phase customer installations may not necessarily be random in time, but may be assumed for the purpose of allocating emission limits to be randomly connected between the phases of the system. (The report does not address the allocation of unbalance emission limits to single-phase installations, as connections to the system network should be managed by the system operator). In cases where large unbalanced installations dominate in some part of a system (e.g. large traction loads), their impact should be assessed by taking into consideration the physical connection and the load characteristics.

INDICATIVE PLANNING LEVELS

Planning levels should allow coordination of voltage unbalance emissions between different voltage levels so that the compatibility level of 2% is not exceeded at LV. Only indicative values can be recommended (see Table 2) as planning levels will differ from case to case, depending on the system structure and circumstances. Table 2 is based on assumptions of a 2% compatibility level at LV, an equal share of unbalance allowed across the voltage levels, a transfer factor of 0,9 (MV to LV) and 0,95 (HV to MV), and a summation coefficient of 1,4 (see [1] and [2]).

Table 2. Indicative planning levels – unbalance.

Voltage level	Planning Level - L_{u2} (%)
MV	1,8
HV	1,4
EHV	0,8

CONCLUSIONS

Measured data was collected for 1827 EHV, HV, MV, and LV sites. From this data it was concluded that the levels of unbalance tend (for 95% of sites) to be less than: 1% at EHV; 2% at HV and MV; and 1,4% at LV. Based on this data and the technical discussion in this paper, indicative planning levels have been recommended.

Technical considerations were identified which can improve the analysis of future survey data. A new joint working group (JWG C4.105) has been established to develop general methods for benchmarking power quality data.

REFERENCES

[1] G. Beaulieu, R. Koch, M. Halpin, L. Berthet, P. Goossens, 2007, "Developing Limits For Controlling Disturbances Produced By Large Installations Connected To Power Systems", *Cigré Symposium, Zagreb.*

[2] G. Beaulieu, R. Koch, M. Halpin, L. Berthet, 2007, "Recommended Methods of Determining Power Quality Emission Limits for Installations Connected to EHV, HV, MV and LV Power Systems ", *CIRED 2007, Vienna, Austria.*

[3] CIGRE/CIRED JWG C4.07, 2004, *Power Quality Indices and Objectives,* Cigré Technical Broshure TB261, Paris, France.

Acknowledgments

The authors acknowledge the excellent contributions of members of JWG C4.103, and Mr Hennie Mostert for contributing field measurements of motor unbalance effects.