VOLTAGE REFERENCE SELECTION: WHO'S CONCERNED ABOUT?

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***Abstract* – This paper discusses the importance of the correct voltage reference point selection for measurements under present day operation conditions. The growing use of electronic converters and controllable loads in modern power systems led to the increasing presence of current and voltage harmonics. Some of them present zero sequence characteristics and circulate in the neutral conductor of the otherwise balanced 3-phase system. The determination of a virtual reference point, as proposed in the literature, is analyzed both from power transfer and power quality points of view. It is concluded that they are conflictant and a tradeoff decision has to be made in order to provide the maximum power to the loads, while attending power quality recommendations.**

***Keywords* – Voltage reference, Non-linear loads, Neutral current, Power quality, Power measurement.**

I. INTRODUCTION

The worldwide search for a generalized power theory, applicable for power systems under non-sinusoidal and unbalanced conditions, has largely been motivated by the introduction of power electronic converters, reactive compensators and active filters in the last twenty years. A vast literature on new power theories has been published and despite the enormous efforts already spent, there is still no complete agreement on several important power definitions. Most important experts are involved with the problem, and almost all aspects of this basic and apparently simple matter have being focused recently by Depenbrock [1,2,3], Emanuel [4], Willems [5,6].

In the last ten years, concerns about electromagnetic compatibility (EMC) and, more specifically, power quality (PQ), added new issues to the problem. Nowadays the main questions to be answered may be summarized as: which are the power components that should be supplied by the power system, which should be compensated close to the disturbing sources and which are the tolerable limits of the uncompensated components?

We recognize that these problems involve a clear comprehension and knowledge about electrical power definitions, decomposition and measurement, electro-magnetic interference identification, compensation and filtering technologies, protective requirements, responsibility identification, economical aspects and normalization needs [7,8]. The extensive scope of the subject may thus explain the difficulty of finding a throughout satisfactory response to the above questions.

Thus the main focus of this paper is the very basic problem of choosing the voltage reference in order to emphasize that under non-sinusoidal and unbalanced conditions, the selection of the voltage reference point dramatically affects the content of the resulting power components as well as the power quality measurements.

It will be shown that in order to cope with these problems a crucial decision has to be made about the choice of voltage reference, in order to obtain the correct information, e.g. for revenue purposes or power quality improvements. The first one obviously attends the utility's (classical) point of view, while the second, essentially the costumers' (modern) point of view. This conflict can no more be relegated in the general case of non-sinusoidal and unbalanced conditions, because long-term cumulative effects point to the second option (the costumers' point of view) as being the most effective and economic option to accomplish the final objectives (i.e., supplying high quality electric power, at competitive prices).

II. THE IMPORTANCE OF THE VOLTAGE REFERENTIAL

A. The past environment: invariant linear systems

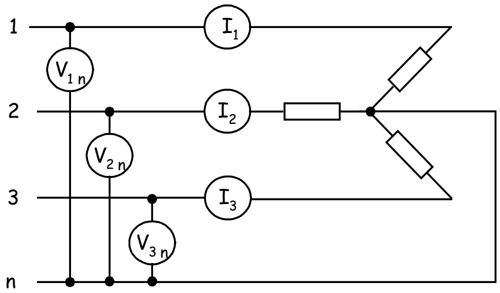
Since the beginning of electric energy usage, the basic circuit rules expressed by Kirchoff's current law $\left(\sum i_{node}=0\right)$ and voltage law $\left(\sum v_{loop}=0\right)$ have successfully been applied for calculation of electric quantities in DC and AC power systems. Their generality is valid even for non-linear and time variant components. Nevertheless the classic power systems analysis has been built on the more restrict linear and time invariant circuit theory. The time is coming to extend power systems theory and include also non-linear and time variant component analyses. Lets initially review some classical basic concepts.

From a single component terminals (*a-b*) point of view, the relevant electric information is associated with the "across/through" variables: the voltage across the component (v_{ab}) and the current through the component (i_{ab}) and, of course, the functional relation between them $f(v_{ab}, i_{ab})$. While *current through* presumes continuity ($i_{ain} = i_{ab} = i_{bout}$), *voltage across* presumes a difference between two voltages referenced to a common reference point x ($v_{ab} = v_{ax} - v_{bx}$), which cancels and can therefore be any point, even external to the circuit.

Steinmetz and Blondel, faced this problem a hundred years ago and showed that the power transmitted through a $m+1$ conductor AC power system could be measured with m phase measuring device, by selecting the $(m+1)^{th}$ conductor (current return path) as the voltage reference (neutral). Fortescue showed that the direct sum of the m line currents or the m phase-to-neutral voltages sum up to zero in balanced systems, if excited by sinusoidal and symmetrical voltages. Under unsymmetrical conditions those summations represent the total zero sequence or homopolar currents and voltages.

Today's most common practices have been disseminated from this classical knowledge, concerning the electrical measurements in three-phase systems using phase-to-phase or phase-to-neutral quantities. The connection of the measuring devices has been determined by the network topology (star or delta), the presence or not of the return conductor and the final purpose of the measured data.

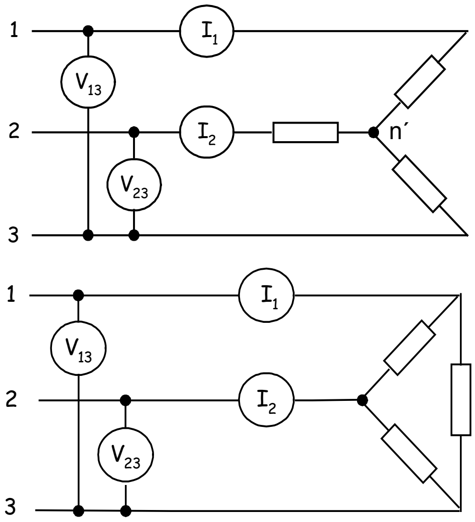
According to Fig. 1a, the reference on the return ($m+1$) conductor enables the detection of zero sequence voltage (V_0) and current (I_0) by summing up the m voltages and currents. In the lack of the return conductor, Fig.1b, the zero sequence path is interrupted, thus enabling to select any of the m conductors as the reference. Besides avoiding zero sequence current circulation, this case also filters out the zero sequence voltage, since the phase-to-phase voltages always sum up to zero.



$$i_1 + i_2 + i_3 = i_n = 3i_0$$

$$v_{1n} + v_{2n} + v_{3n} = 3v_0$$

a) Reference on the return conductor



$$i_1 + i_2 = -i_3$$

$$v_{13} + v_{32} = -v_{21}$$

b) Reference on phase 3.

Figure 1 – Usual reference selection for 4 and 3 wire systems.

It should be stressed that in the star connection without return conductor, the voltages to the load common point (n′) depend on the load components. Thus under-voltages or over-voltages can take place at the load installation due to the lack of the return conductor. From the customers point of view this characterizes a power quality problem.

Even so, three-phase systems without return conductor have been the natural choice for power transmission, mainly for economic advantages, since zero sequence currents (or powers) have not been an important issue most of the time. They had only to be considered in transient ground faults protection and atmospheric discharge circuits dimensioning.

The return conductor is usually present at low voltage distribution feeders, in order to supply unbalanced (single and double-phase) loads. In those cases, zero sequence components may arise under normal and sustained operating conditions. As indicated in Fig. 1a, in this case the return conductor is used as the reference for phase–to-neutral voltage measurements. Phase-to-phase voltages can be derived from the phase-to-neutral magnitude and angle measurements.

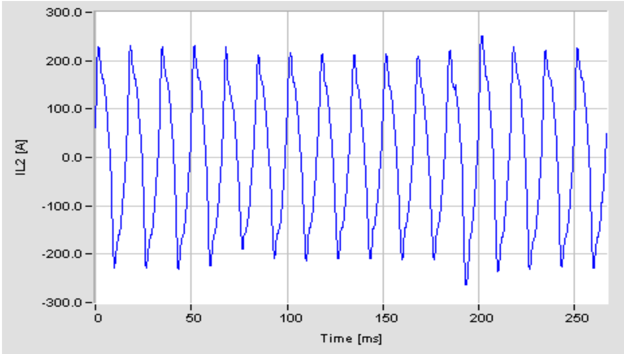
The return current obviously causes voltage drop along the path, thus affecting the phase-to-neutral voltage measurements, according to the instrument location (nearby the consumer's installation or at the beginning of the distribution system). In order to minimize the return current at the distribution transformer and consequently reduce the impact on the reference location along the return conductor, utilities try, as much as possible, to balance the single-phase loads, by redistributing them conveniently among the three phases.

B. The present environment: variant nonlinear systems

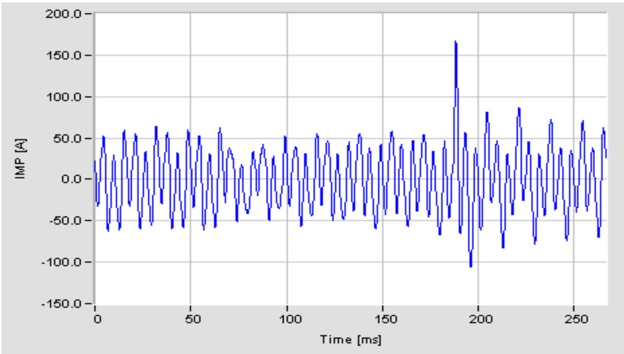
What changed? The first important changes in this scenario aroused with the increasing presence of nonlinear electronic power converters and controllers feeding industrial motor drives, informatics load clusters and electronic household loads. The second important change relies on the increasing presence of digital instrumentation for power system data processing. Both technologies are complementary and provide fast and precise information for rapid control actions at almost any voltage and current levels. The fast power electronic devices unfortunately constitute the most frequent non-linear and time-variant devices acting on the power system, braking down the classical assumption of linearity and time invariance of power systems. Problems resulting in such operating conditions may be well illustrated by observing the shape of typical phase and neutral currents measured at a three-phase distribution transformer secondary, feeding commercial and residential loads, as shown in Fig. 2.

It is noticeable that the prevailing neutral current is of 3rd harmonic and varies from 5A to 40A during the day, which is about 25% of the maximum phase current. This current is resultant from combined effect of several commercial and domestic non-linear loads (informatics equipment, TV sets, fluorescent and compact lamps, etc.), which hardly can be eliminated or compensated by shunt passive filters [9], and which is responsible for several disturbing effects such as motor torque oscillations, increased power losses insulation stresses, measurement errors, protection malfunctions, etc.

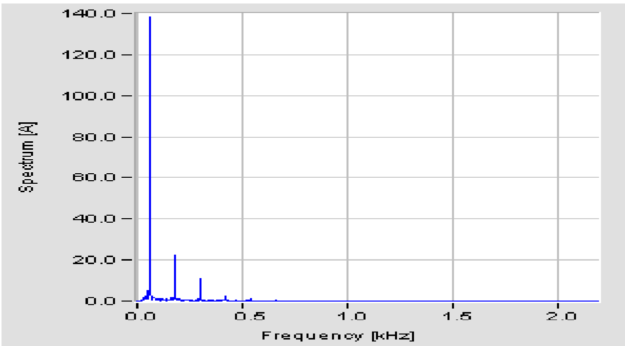
Thus the discussions about a general power theory for multi-phase systems, under non-sinusoidal and unbalanced conditions should begin by answering the questions about the voltage reference point selection, since the neutral conductor is no more an unloaded path.



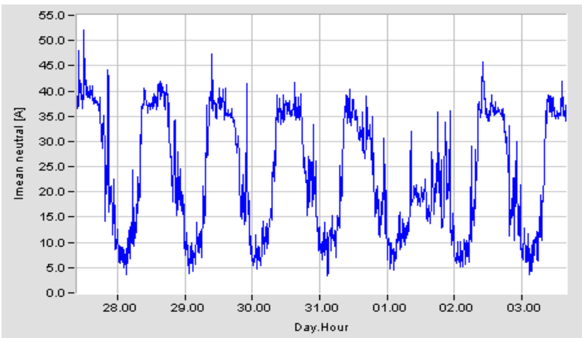
a) Measured secondary phase current.



b) Measured secondary neutral current.



c) Spectrum of the current.



d) Seven days rms neutral current evolution.

Figure 2 - A 75KVA, 13.8/0.22kV three-phase transformer currents for typical urban loads.

III. VOLTAGE REFERENCE SELECTION IN POWER SYSTEMS

In this section additional analyses are made in order to enlighten the related problems. Firstly the case with a return conductor will be analyzed and then the case without it.

A. Power system with return conductor

Lets consider a balanced *m+1* conductor AC power system, with the *(m+1)*th conductor functioning as the return path and also as the voltages common (neutral) reference. As we know from Fortescue, if a balanced linear load is fed by a symmetrical set of sinusoidal voltages, the *m* balanced line currents sum up to zero return current (Kirchoff´s current law for *m* balanced phases). It is easy to conclude that in this case the *m* phases loop voltages also sum to zero, since no voltage drop is caused on the return conductor (Kirchoff´s voltage law for *m* phase-to-neutral loops). Figure 3 illustrates this situation.

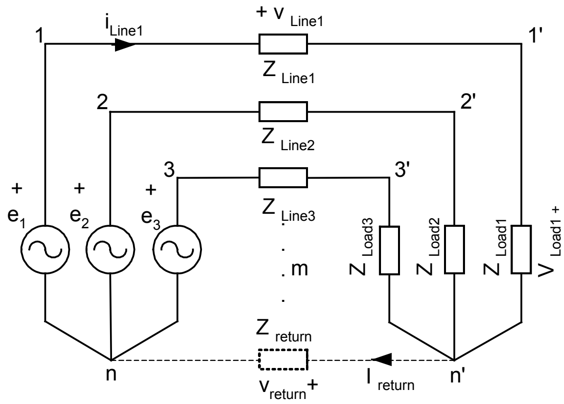


Figure 3 - A balanced *m+1* conductor system.

The voltage law for the kth loop renders:

$$e_k = v_{linek} + v_{loadk} + v_{return}\,, \qquad k=1,2\ldots m \quad (1)$$

or, in terms of the line currents:

$$e_k = z_{linek}\, i_{linek} + z_{loadk}\, i_{loadk} + v_{return}\,. \qquad k=1,2\ldots m \quad (2)$$

Since the system is balanced, all line and load impedances are equal, and the star connection imposes $i_{linek} = i_{loadk}$, thus we can rewrite (2) as:

$$e_k = (z_{line} + z_{load}).i_k + v_{return} \qquad k=1,2\ldots m \quad (3)$$

Summing all *m* source voltages renders:

$$\sum_{k=1}^{m} e_k = (z_{line} + z_{load})\sum_{k=1}^{m} i_k + m.v_{return} \qquad (4)$$

and, since $\quad v_{return} = z_{return}\cdot\sum_{k=1}^{m} i_k\,, \qquad (5)$

we get also

$$\begin{aligned}\sum_{k=1}^{m} e_k &= (z_{line} + z_{load})\sum_{k=1}^{m} i_k + m.z_{return}\cdot\sum_{k=1}^{m} i_k \\ &= [z_{line} + z_{load} + m.z_{return}]\sum_{k=1}^{m} i_k\end{aligned} \qquad (6)$$

According to Fortescue, the summation of all phase voltages or currents renders the homopolar (zero) components, thus:

$$\sum_{k=1}^{m} e_k = m.e_0 , \tag{7}$$

$$\sum_{k=1}^{m} i_k = m.i_0 . \tag{8}$$

Substituting (7) and (8) into (6) we get the zero sequence voltage loop equation (9):

$$\begin{aligned} e_0 &= (z_{line} + z_{load}) i_0 + m.z_{return}.i_0 \\ &= [z_{line} + z_{load} + m.z_{return}]\, i_0 \end{aligned} . \tag{9}$$

Three important conclusions can be drawn from (9):

a) if the m source voltages sum up to zero(e_0=0), then the m currents in the balanced network also sum zero (i_0=0);

b) if e0 ≠ 0, then zretunn should be as small as possible because of the (m) multiplying factor;

c) if i0 ≠ 0, the homopolar (zero sequence) voltage drop may be negligible on zline but may be not on zload and zreturn.

Note that these conclusions are valid even in the presence of negative sequence, which, as the positive sequence, doesn't impose current on the returning path. In the presence of zero sequence components, the neutral impedance plays an important role on the return path voltage drop and choosing a thinner return conductor may be a wrong technical decision. It should also be stressed that the return voltage drop, certainly influences the power calculation based on local voltage measurements.

B. System without the return conductor

According to Kirchoff´s current law, if the return conductor is not present, the current sum over the *m* conductors must be zero. Thus eq. (4) reduces to:

$$\sum_{k=1}^{m} e_k = m.v_{return} . \tag{10}$$

It should be stressed that v_{return} represents no more a voltage drop imposed by a return current (there is no return path). It represents the voltage difference between the common star points of the source and the load. Considering (7) we conclude also that:

$$e_0 = v_{return} . \tag{11}$$

So, for a balanced network, if the source zero sequence voltage (e_0) is nil, then v_{return} is also zero, *even without the return connection*. This explains why the fluctuating star point of a balanced load is at the same voltage potential of the source common star point. That is also the reason why in the past the return conductor could be omitted, without loosing the overall voltage reference along the power system.

The foregoing considerations were made to reinforce that nowadays, in the presence of zero sequence harmonic components, the situation is completely different.

C. Effect of zero sequence harmonics

As we know, all triple order equal harmonics are of zero sequence (homopolar) nature, and force current circulation through the return conductor, thus imposing zero sequence voltage drop along the network according to (12):

$$e_{h0} = [z_{hline} + z_{hload} + m.z_{hreturn}]\, i_{h0} \quad h=3,6,9... \tag{12}$$

Equation (12) is similar to equation (9), but refers to all triple order harmonics present in the non-linear system. All conclusions drawn from (9) also apply to equation (12). Additionally, it shows that even moderate harmonic currents can give rise to large zero sequence harmonic voltages, since inductive impedances increase with the harmonic order.

In this case v_{return} constitutes only part of the total zero sequence voltage If there is no return conductor, these harmonics impose the total zero sequence voltage (v_0) on the load star point (*n´*).

If there is no return conductor, the total zero sequence voltage e_{h0} will appear between the source star point (*n*) and load star point (*n'*).

The basic differences between the conditions that lead to equation (9) and (12) are as follows:

i) the presence of e_0 or i_0 clearly represents a abnormal operating condition. This can be caused by unsymmetrical source voltages, unequal network impedances or unbalanced connected loads. The solutions to those problems obviously rely on fault elimination and the balancing of the lines and the loads;

ii) the presence of e_{h0} or i_{h0} points to the presence of nonlinear components in the system. This may be caused by nonlinear loads or by nonlinear control devices. Electronic power converters are the most common examples of nonlinear components encountered in residential, commercial and industrial loads. Nevertheless modern power system present FACTS devices and alternative power generation which also account for harmonic degradation in the system. The solution to the harmonic effects in this case requires active filtering capacity. This depends on a still expensive technology.

D. The Virtual Reference Point

It is well known that the 3-phase delta connection does not present zero sequence components in the line voltages nor line currents. This is a direct consequence of Kirchoff´s voltage and current laws for the 3-phase delta connection, respectively:

$$v_{12} + v_{23} + v_{32} = (v_{10} - v_{20} + v_{20} - v_{30} + v_{30} - v_{20}) \equiv 0 \tag{13}$$

$$i_1 + i_2 + i_3 \equiv 0 \tag{14}$$

The voltage index *0* in (13) represents the common voltage reference point. The absolute potential of this point is irrelevant, since only the voltage differences are imposed to the 3-phase system. The fact that the line voltages sum up to zero, guarantees that no common mode voltage (zero sequence components) is present in these voltages. For the same reason there cannot circulate any zero sequence current, since there is no return conductor.

We conclude that the delta connection automatically filters out the zero sequence components. Under unbalanced conditions only negative components may arise. Even in this case equations (13) and (14) apply.

A very challenging problem is to find the common voltage reference point (*0*), which represents the equivalent star connection, under balanced and unbalanced conditions.

Depenbrock focused that problem from the power transfer point of view, assuming *m+1* equal conductor impedances [2]. He concluded that the so called *virtual reference point* corresponds to the "common connection point of equal (non zero) resistances connected between all *m+1* conductors of the source-load system". Under this condition he proved that the resulting phase-to-reference voltages always summed up to zero (do not contain any zero sequence components). He also proved that the power transfer based on the product of the collective voltage V_Σ and collective current I_Σ corresponds to the total power exchange between the source and loads under balanced or unbalanced, sinusoidal or distorted conditions.

Emanuel chaired an IEEE WG, which elaborated the Standard 1459 [7] adopting another approach to the problem. They calculate equivalent phase voltages (*Ve*) and currents (*Ie*) representing the equivalent balanced system under the assumption of equal transmission losses. In this case, the equivalent voltages are calculated using phase-to-neutral and phase-to-phase measured voltages and line currents. According to this method a different impedance of the return conductor (neutral) may be assumed, which may be an advantage over the former Depenbrock´s method. However, no physical meaning of the common reference of the equivalent voltages is offered. Simulation tests confirm that both methods render very precise values for the total active power transfer from source to load, with almost the same apparent power, even at unbalanced and distorted conditions.

Willems also has contributed significantly to this topic showing how to generalize Depenbrock´s virtual star point concept for the general case of different impedances of the m+1 conductors, while preserving Emanuel´s assumption of constant transmission losses [5]. As a result, equivalent voltages and currents were obtained, but his most important conclusion is that the voltage reference selection is dependent of the definition of the equivalent current. This is not obvious because Kirchoffs current law implies redundancy (return current is the sum of all line currents). Since the scalar product of the current vector renders the equivalent square mean value of all conductor currents, they are not redundant. So the definition of equivalent current affects the voltage reference selection in order to provide the correct power transfer values.

E. Impact of the reference selection on measurements

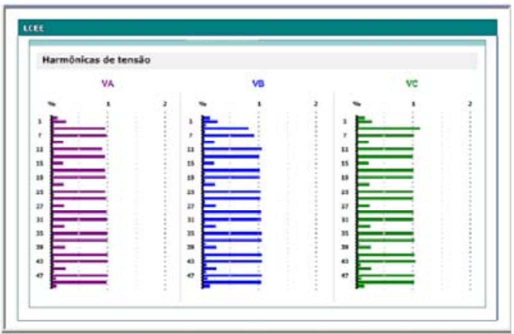
From the foregoing we found that if the return path current exists, then the system has to supply zero sequence power ($p_0=v_0.i_0$). This may be caused 1) by unbalanced (linear) loads at the fundamental frequency or 2) by zero sequence harmonics (non-linear loads) or 3) a combination of both. The first case is usually managed by balancing the loads among the phases, but the second case demands for much more expensive harmonic compensators or filters.

Since dynamic compensation or active filtering of undesired voltage or current components is one of the outstanding capabilities of power electronic devices, it is natural that people seeks for mathematical and physical support to a general power theory, capable of combining the power electronics flexibility with the precision of digital signal processing in order to solve present and future problems in power systems.

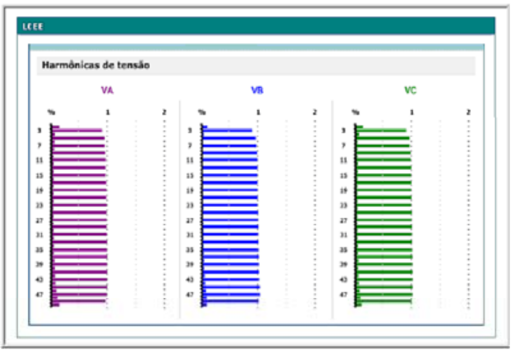
The above discussion about voltage reference provided new insights to treat unbalanced and distorted voltages and currents in multiphase systems in order to determine the necessary compensation needs for maximum power transfer.

Nevertheless this may not be sufficient to guarantee adequate power quality conditions neither for the consumer nor for the supplier. For example, Depenbrock´s approach assumes that currents are proportional to voltages, (Fryse´s invariant resistance concept), thus clearly allowing the presence of harmonics in power systems. Moreover, since the virtual reference point filters out the zero sequence components, the phase-to-virtual reference point voltages automatically filter triple harmonics of the measurements. Using the neutral (return) conductor as the reference, the zero component voltage upon to the loads is correctly measured.

Figure 4 shows an example of problem associated with the wrong choice of voltage reference. The very simple experiment consists of measuring the harmonic content of the phase voltages in a 3-phase, 4-wire supply system. An arbitrary voltage source has been programmed to provide a balanced fundamental combined with a number of harmonics up to order 50, all equally adjusted to 1% amplitude.



a) Measurement result with floating reference point.



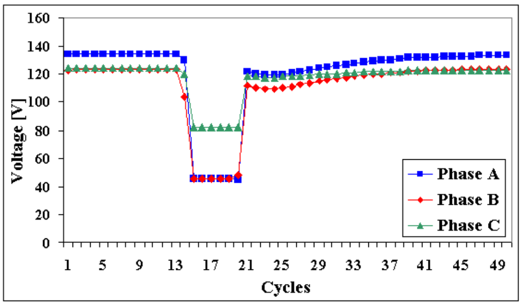
b) Measurement result with reference point on the neutral.

Figure 4 - Harmonic content observed using different voltage references.

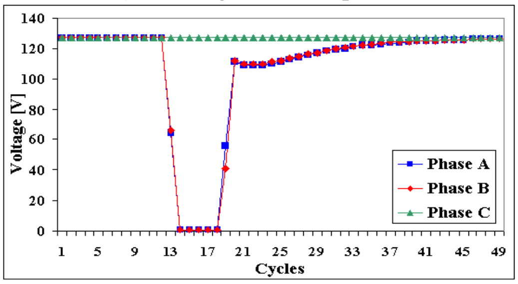
Since the measuring instrument had three differential input channels the first measurement used the floating star point connection to measure the three phase voltages and the second measurement used the voltage referenced to the neutral conductor. The results are shown in Figure 4 a) and b) respectively.

In the first case all zero sequence harmonics (multiples of 3) appeared as almost zero. In the second case, all harmonics, which had been programmed in the voltage source, have been quantified correctly.

The floating common reference corresponds to Depenbrock´s method without measuring the M+1 (neutral) voltage to the virtual reference point, which contains the zero sequence information. In the second case, zero sequence voltage drops were imposed on the phase-to-neutral voltages due to the return path connection. In this case only the voltage drop on the feeder (line and return conductors) haven't been measured, but this is only part of the total zero sequence voltage, according to (9) and (12).



a) Floating reference point.



b) Reference on the neutral.

Figure 5 – Unbalanced Sag Measurement using different voltage references.

Another example is shown in Fig. 5, corresponding to the measurement of a unbalanced voltage sag. In the first case (a), the 3-phase input voltage channels were connected together, forming a floating reference point. In (b) the common point was connected to the neutral. Consequently in the first case the measurement does not include zero sequence components. A much more realistic measurement is obtained in the second case, at least from the costumers point of view.

IV. CONCLUSIONS

It was discussed how the voltage reference point selection can affect the calculation of the power transferred from source to load or power quality measurements in multi-phase systems. Depending on the equivalent current definition and the conductor resistances, different voltage reference points have to be selected in order to obtain the effective power transfer. The equivalent phase-to-reference voltages obtained this way, although rendering the correct power transfer, do not represent real voltage measures for power quality monitoring purposes. They can even lead to misinterpretation if measures were obtained by implementing the virtual reference point, mainly due to the zero sum property of those voltages (zero sequence filter).

Thus, in order to capture the real operating condition at the loads, the best choice is to put the voltage reference on the local common point (neutral conductor). The essence of the present paper's message is: *in the present environment, of distorted and unbalanced operating conditions, the power measuring and power quality monitoring devices should be connected according to the costumers connection form, to be able to perceive the electromagnetic phenomena, which the per phase loads are exposed to.*

Otherwise wrong conclusions may be drawn about the loads effective power consumption, harmonic emission or absorption, compensation devices effectiveness, etc. This is in contrast to the traditional procedure, which focused mainly the utilities point of view when deciding about the connection form of measuring equipment and protective devices settings (eg. by measuring line-to-line voltages instead of phase-to-neutral) based on the presumption that the system is balanced under normal conditions.

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