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The Compensation in Three-Phase Four-Conductor Systems: A Dynamic Approach

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Abstract: Scientifically correct power definitions and sound compensation strategies for three-conductor systems are known since many years, commercial products are available. Nowdays, many low-power power electronic devices together cause undesirable operating conditions in four-conductor systems, making an extension of the scope of definitions and compensation sreategies mandatory. Depending on the theoretical basis used, the extension from three-conductor definitions to four-conductor definitions is not always straightforward. Based on the straightforward approach given by Fryze, Buchholz and Depenbrock, known as the FBD method, this study gives guidance on how to avoid traps and common mistakes. Aims of compensation, mathematics for easy treatment and resulting consequences as well as solutions based on active and passive compensators are discussed.

Key words: Compensation, power system, hyper space vector, neutral conductor, three-phase

INTRODUCTION

Modern power theory started with the work of Fryze (1932) and Buchholz (1950) being extended to the so-called FBD method by Depenbrock (1962) published in English language in 1993. No restriction concerning the number of conductors is contained in this theory.

Independently, Akagi *et al*. (1983) published a theory of instantaneous power, specially designed for three-conductor circuits. This theory leads to the same results as the FBD method, but uses orthogonal components for the calculations, reducing the number of quantities employed in calculations from 3 to 2 and increasing graphic understanding.

Fast switching converters made compensators possible which could be controlled based on these power theories. Controlled operation utilising high switching frequencies is in many respects superior to known passive compensation by inductors and capacitors, even if these are not fixed but switched slowly. Many research projects where conducted searching optimal compensation methods for three-conductor circuits, most of them based on the instantaneous power theory. Since some years problems with neutral conductor currents of four-conductor circuits come more and more into focus, making an extension of known theories necessary. This is recognised by standardisation bodies incorporating definitions for nonsinusoidal voltages and currents and for circuits with more than three conductors into updated versions of existing standards (DIN, 1994, 2002; IEEE, 2000).

The implications of these definitions are normally not recognised when extending the three-conductor instantaneous power theory (Akagi *et al*., 1983) to the four-conductor case, leading to non optimal theories and compensation results (Depenbrock *et al*., 2002).

This study points out some common mistakes when dealing with the compensation of four-conductor circuits and gives guidance how to avoid them. This guidance covers the theoretical treatment, the aims of compensation and the demands concerning the compensator following from those aims.

ZERO-SUM QUANTITIES

Such physical quantities of an N-conductor circuit are called zero-sum quantities, which always sum up to zero. For example, the sum of all N currents is zero due to Kirchhoff's current law, Fig. 1.

$$\sum_{v=1}^{N} i_v(t) = 0 \qquad (1)$$

The usual-but in no way mandatory-way to associate the conductors L_1, L_2, L_3 and N of a normal

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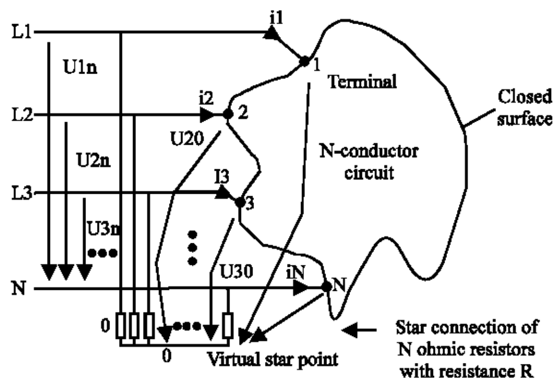

Fig. 1: Multi-conductor circuit

four-conductor circuit to the terminals of the multi-conductor circuit is also given in Fig. 1. In the same way as the instantaneous power of a N-conductor circuit as a whole is characterised by only one value, the set of instantaneous voltages also should be characterised by one value. This value is the collective (or multi-conductor) value (Depenbrack, 1993, 2002). It is marked by the use of the subscript Σ.

$$i_{\Sigma}(t)=\sqrt{\sum_{v=1}^{N} t^{2}_{v}(t)};u_{\Sigma}(t)=\sqrt{\sum_{v=1}^{N} u^{2}_{v0}(t)} \qquad (2)$$

Zero-sum quantities of currents and voltages can effectively be combined to vectors, allowing easier mathematical treatment:

$$i=[i_1\; i_2 \dots i_N]^T;\quad u=[u_{10}\; u_{20} \dots i_{N0}]^T \qquad (3)$$

The collective quantities are identical to the norms of these vectors.

While there is no choice how to determine the currents of a terminal, to determine voltages always requires the choice of a reference potential (subscript r). Often, the conductor with the highest number, e.g., N = 4, is selected as reference and associated with the neutral conductor. In this case the sum of the voltages is normally not zero, the collective value of voltages $u_\Sigma(t)$ depends on the chosen reference, if other than zero-sum quantities are used for its determination.

Collective quantities (2) become minimal if zero-sum quantities are used in the definition. The associated voltage reference is given by the virtual star point 0 seen in Fig. 1. Kirchhoff's current law guarantees that the sum of currents flowing through the N equal ohmic resistors is always zero. The voltages from the N conductors to the virtual star point are given by the respective currents,

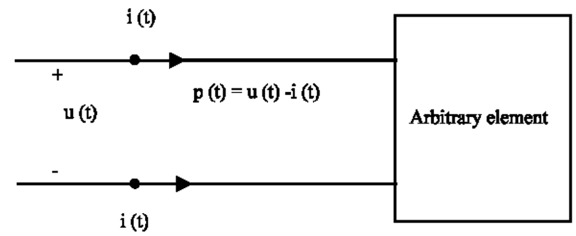

Fig. 2: Power at one-port element

each multiplied with the same resistance R, transferring the property of the currents to the voltages.

In practice it is not necessary to realize such a virtual star point, the associated voltages may well be calculated from only (N-1) voltages against, e.g., conductor N:

$$\begin{aligned}&\sum_{v=1}^{N} u_{v0}=\sum_{v=1}^{N}(u_{vr}+u_{r0})=\sum_{v=1}^{N}u_{vr}+Nu_{r0}=0\\&u_{r0}=-\frac{1}{N}\sum_{v=1}^{N}u_{vr}\xrightarrow[u_{NN}=0]{r=N}u_{N0}=-\frac{1}{N}\sum_{v=1}^{N-1}u_{vN}\end{aligned} \qquad (4)$$

The voltage u_{N0} is the common mode content of the N voltages measured against the selected reference.

A link exists between common mode content and zero-sequence component of voltages in the case of four-conductor circuits:

$$\begin{aligned}u_{III}(t)&=\frac{1}{\sqrt{3}}\left(u_{1N}(t)+u_{2N}(t)+u_{3N}(t)\right)\\&=-\frac{4}{\sqrt{3}}u_{N0}(t)\end{aligned} \qquad (5)$$

Strictly, the zero-sequence component can only be defined under sinusoidal conditions, (5) is the extension to nonsinusoidal use.

Instantaneous power: The basic power definition is for one-port elements, it can be found in Fig. 2. At least (N-1) one-port elements are necessary to represent the load and determine the collective power p_Σ of an N-conductor circuit (6) Fig. 3.

$$p_{\Sigma}(t)=\sum_{v=1}^{N-1}p_{vN}=\sum_{v=1}^{N-1}u_{vN}\,i_v \qquad (6)$$

In this case the current flowing in conductor N mathematically does not contribute to power, it is implicitly taken into account by the other currents. Each single term p_{Vn} in (6) depends on the chosen reference conductor and generally has no physical meaning, only the sum p_Σ is invariant.

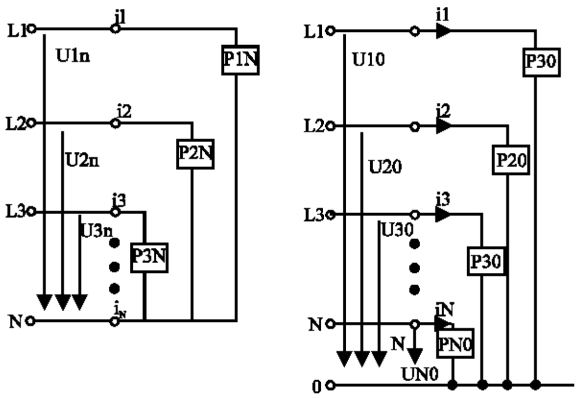

Fig. 3: One-part elements for load representation

Interpretation and representation of instantaneous power becomes much easier, if zero-sum quantities are used for the calculation. In this case N two-port elements represent the load, right side of Fig. 3, leading to

$$p_{\Sigma}(t) = \sum_{v=1}^{N} p_{v0} = \sum_{v=1}^{N} u_{v0} i_v \qquad (7)$$

With this definition, each term p_{V0} can be interpreted as the contribution of conductor v to collective power p_{Σ}.

TRANSFORMATIONS FOR POWER SYSTEMS

Transformations may reduce calculation effort and enhance graphic understanding. However, using transformed quantities must not change the results obtained in comparison to those given above for direct use of original zero-sum quantities. Transformations are used in norm-invariant or reference component invariant form, here the norm-invariant version is presented.

Three conductor circuits: For three-conductor circuits often the α-β-transformation, also known as d-q-transformation, is applied to the original quantities q1r, q2r and q3r, leading to the transformed quantities q_α and q_β

$$\begin{bmatrix} q_\alpha \\ q_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} q1r \\ q2r \\ q3r \end{bmatrix} \qquad (8)$$

α- and β-component may be combined to the complex space vector $\underline{q} = q_\alpha + jq_\beta$. This transformation automatically removes any three-conductor common mode content (4).

The inverse transformation therefore always returns only the original zero-sum quantities q_{10}, q_{20} and q_{30} associated with the original quantities q1r, q2r and q3r.

$$\begin{bmatrix} q_{10} \\ q_{20} \\ q_{30} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} \\ \frac{-1}{2} & \frac{-\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} q_\alpha \\ q_\beta \end{bmatrix} \qquad (9)$$

If the collective instantaneous value of original zero-sum voltages is calculated using α-β-components all original and transformed components contribute in the same way

$$\begin{aligned} q_{\Sigma}^2 &= q_{10}^2 + q_{20}^2 + q_{30}^2 + q_\alpha^2 + q_\beta^2 \\ &\neq q_{1r}^2 + q_{2r}^2 + q_{3r}^2 \end{aligned} \qquad (10)$$

Using α-β-components in three- conductor systems is therefore equivalent to using zero-sum quantities.

Clarke transformation and four-conductor circuits: For four-conductor circuits, the Clarke transformation is often selected. The zero-sequence component (5) complements the α-β-transformation (8):

$$\begin{bmatrix} q_\alpha \\ q_\beta \\ q_{III} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{-\sqrt{3}}{2} \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} q1r \\ q2r \\ q3r \end{bmatrix} \qquad (11)$$

The inverse transformation is given by

$$\begin{bmatrix} q1r \\ q2r \\ q3r \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & \frac{-1}{2} \\ \frac{-1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ \frac{-1}{\sqrt{2}} & \frac{-3}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} q_\alpha \\ q_\beta \\ q_{III} \end{bmatrix} \qquad (12)$$

The four-conductor common mode content is not automatically discarded by the Clarke transformation. The voltages used as original quantities are usually u_{1N}, u_{2N} and u_{3N}. The zero-sum voltages result from (4). In case of N = 4 they can be expressed by the Clarke components:

$$\begin{bmatrix} u_{10} \\ u_{20} \\ u_{30} \\ u_{40} \end{bmatrix} = \begin{bmatrix} \frac{3}{4} & \frac{-1}{4} & \frac{-1}{4} \\ \frac{-1}{4} & \frac{3}{4} & \frac{-1}{4} \\ \frac{-1}{4} & \frac{-1}{4} & \frac{3}{4} \\ \frac{-1}{4} & \frac{-1}{4} & \frac{-1}{4} \end{bmatrix} \begin{bmatrix} u_{1N} \\ u_{2N} \\ u_{3N} \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & 0 & \frac{1}{4\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{2}} & \frac{1}{4\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{\frac{6}{2}}} & \frac{1}{4\sqrt{3}} \\ 0 & 0 & \frac{-\sqrt{3}}{4} \end{bmatrix} \begin{bmatrix} u_{\alpha} \\ u_{\beta} \\ u_{III} \end{bmatrix} \qquad (13)$$

The associated collective instantaneous value is:

$$u_{\Sigma} = \sqrt{u^2_{10} + u^2_{20} + u^2_{30} + u^2_{n0}} = \sqrt{u^2_{\alpha} + u^2_{\beta} + \frac{1}{4} u^2_{III}} \neq \sqrt{u^2_{\alpha} + u^2_{\beta} + u^2_{III}} = \sqrt{u^2_{1r} + u^2_{2r} + u^2_{3r}} \qquad (14)$$

In case of the currents, usually i_1, i_2 and i_3 are selected

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_n \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & -1 & -1 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \\ 0 & 0 & -\sqrt{3} \end{bmatrix} \begin{bmatrix} i_{\alpha} \\ i_{\beta} \\ i_{III} \end{bmatrix} \qquad (15)$$

Giving

$$i_{\Sigma} = \sqrt{i^2_1 + i^2_2 + i^2_3 + i^2_n} = \sqrt{i^2_{\alpha} + i^2_{\beta} + 4 i^2_{III}} \neq \sqrt{i^2_{\alpha} + i^2_{\beta} + i^2_{III}} = \sqrt{i^2_1 + i^2_2 + i^2_3} \qquad (16)$$

It is obvious that for voltages and currents usually chosen the zero-sequence component is trated differently. The collective instantaneous value of the original zero-sum quatities is not linked to the norm $\sqrt{q^2_{\alpha} + q^2_{\beta} + q^2_{III}} = \sqrt{q^2_{1r} + q^2_{2r} + q^2_{3r}}$ of transformed and original quantities. Moreover, while the ideal resistor load leads to proportional original zero-sum currents and voltages. In contrast the vectors or Clarke transformed voltages and currents are not proportional,

$$\begin{bmatrix} i_{p1} \\ i_{p2} \\ i_{p3} \\ i_{pN} \end{bmatrix} = G_p \begin{bmatrix} u_{10} \\ u_{20} \\ u_{30} \\ u_{40} \end{bmatrix}; \begin{bmatrix} i_{p\alpha} \\ i_{p\beta} \\ i_{pIII} \end{bmatrix} = \begin{bmatrix} G_p & 0 & 0 \\ 0 & G_p & 0 \\ 0 & 0 & \frac{G_p}{4} \end{bmatrix} \begin{bmatrix} u_{\alpha} \\ u_{\beta} \\ u_{III} \end{bmatrix} \qquad (17)$$

This can easily be derived using the inverse

$$\begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{6}} & 0 \\ 0 & \frac{1}{\sqrt{2}} & \frac{-1}{\sqrt{2}} & 0 \\ \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{3}} & 0 \end{bmatrix} \begin{bmatrix} \frac{\sqrt{2}}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \\ \frac{-1}{\sqrt{6}} & \frac{-1}{\sqrt{2}} & \frac{1}{\sqrt{3}} \\ 0 & 0 & -\sqrt{3} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (18)$$

Contrary to the α-β-transformation the Clarke transformation does not reject common mode and is therefore not suitable for calculating, e.g., power currents. Either zero-sum quantities have to be used, or a suitable transformation rejecting the common mode content in four-conductor circuits is needed.

Transformation for four-conductor circuits: A transformation automatically discarding a four-conductor common mode content is, e.g., the Hyper Space Vector (HSV) transformation (Depenbrock, 2000; Depenbrock and Staudt, 1997). It treats all original zero-sum quantities equally. The basic Equation for this transformation is:

$$\begin{bmatrix} q_x \\ q_y \\ q_z \end{bmatrix} = \sqrt{\frac{3}{4}} \begin{bmatrix} \sqrt{\frac{8}{9}} & -\sqrt{\frac{2}{9}} & -\sqrt{\frac{2}{9}} & 0 \\ 0 & \sqrt{\frac{2}{3}} & -\sqrt{\frac{2}{3}} & 0 \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} & -1 \end{bmatrix} \begin{bmatrix} q_{1N} \\ q_{2N} \\ q_{3N} \\ q_{4N} \end{bmatrix} \qquad (19)$$

An adaptation to only three measured quantities is easy by a modification of the transformation matrix. If conductor N is selected as a reference, $q_{NN} = u_{NN} = 0$ results, the associated column of the matrix can beomitted

$$\begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \\ \frac{1}{2\sqrt{2}} & \frac{1}{2\sqrt{2}} & \frac{1}{2\sqrt{2}} \end{bmatrix} \begin{bmatrix} u_{1N} \\ u_{2N} \\ u_{3N} \end{bmatrix} \qquad (20)$$

For usually selected currents, $i_N = -(i_1 + i_2 + i_3)$ leads to

$$\begin{bmatrix} i_x \\ i_y \\ i_z \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \sqrt{\frac{3}{2}} & -\sqrt{\frac{3}{2}} \\ \frac{2}{\sqrt{2}} & \frac{2}{\sqrt{2}} & \frac{2}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} \qquad (21)$$

The similarity to the Clarke transformation is obvious, only the third transformed quantity is defined differently.

The collective instantaneous value results to

$$q_{\Sigma} = \sqrt{q^2_{10} + q^2_{20} + q^2_{30} + q^2_{N0}} = \sqrt{q^2_x + q^2_y + q^2_z} \qquad (22)$$

For currents and voltages the ideal resistor load is described by

$$\begin{bmatrix} i_{p1} \\ i_{p2} \\ i_{p3} \\ i_{pN} \end{bmatrix} = G_p \begin{bmatrix} u_{10} \\ u_{20} \\ u_{30} \\ u_{40} \end{bmatrix}; \begin{bmatrix} i_{px} \\ i_{py} \\ i_{pz} \end{bmatrix} = G_p \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \qquad (23)$$

The theory becomes as simple and straighforward as in case of three-conductor circuits described by α-β-components.

Results from transformation: The theoretical considerations summarised above lead to some important conclusions if no severe practical reasons demand something different:

- Only zero-sum original quantities should be used. Either directly or by applying suitable transformations which discard the common mode content of original quantities automatically.
- All conductors have to be treated equally. Changing the names of conductors must not change results.
- Clarke transformation is not helpful to determine power currents in four-conductor circuits, because the common mode is not automatically discarded. Results of compensation are non optimal. They become worse with increasing values of the common mode content of voltages.
- Hyper space vectors discard the common mode content and treat all original zero-sum quantities equally, leading to valid theory and optimal compensation results.
- Instantaneously only powerless currents can be detected and compensated, resulting in pure power currents on the supply side.
- Compensating powerless currents reduces losses of the supply, but may have undesirable consequences.
- Active and nonactive currents can only be determined exactly under periodic conditions, normally one full period of all quantities must be known. Instantaneous compensation of variation currents is generally impossible.
- If non periodic conditions are treated, still a certain time interval, normally the expected period, is needed to determine generalized active and nonactive quantities.
- These results should be kept in mind whenever writing or reading a paper on power theory or designing compensators.

CONVERTER TOPOLOGIES

Compensation strategies for four-conductor systems of course need converter topologies supporting four conductors. Different structures are possible and discussed in literature, which partly impose restrictions on the compensation strategy.

Fourth conductor connected to DC link midpoint: The simplest way is to employ a standard three-phase two-level Voltage Source Converter (VSC). The fourth conductor is then connected to the midpoint of two equal DC-link capacitors (Nabae *et al*., 2000) displayed in Fig. 4.

This method has severe drawbacks, because the compensator current for neutral current compensation i_{CN} passes through the DC link capacitors:

- The AC current rating of the DC link capacitors has to be adjusted according to the expected maximum of the compensator current for neutral current compensation.
- The compensator current for neutral current compensation must not contain any DC content. This imposes restrictions to the compensation strategy. The converter can not be used as universal voltage source, e.g., for uninterruptible power supplies.
- The capacity of the DC link capacitors is determined by 2 effects:

- Enough energy to compensate the variation currents.
- Enough capacity to keep the DC link midpoint potential as constant as necessary. This again depends on the compensator current for neutral current compensation.

Fourth conductor connected to 4th converter leg: The straighforward approach is to add a fourth leg to a standard three-phase VSC, leading to the structure displayed in Fig. 5.

This structure perfectly matches the theoretical demand of treating all conductors equally but is much more expensive, because commercially available standard topologies can not be used easily.

Fourth conductor controlled by cascaded converter: Option number three is to use cascaded converters. These need to be electrically isolated, either on the DC voltage side or on the AC voltage side. The 2 resulting structures can be seen in Fig. 6.

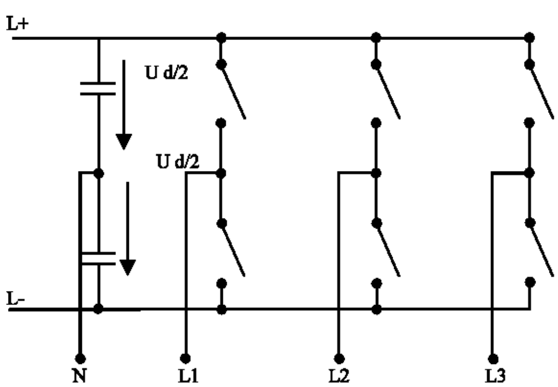

Fig. 4: 4-conductor VSC using DC-link midpoint connetion

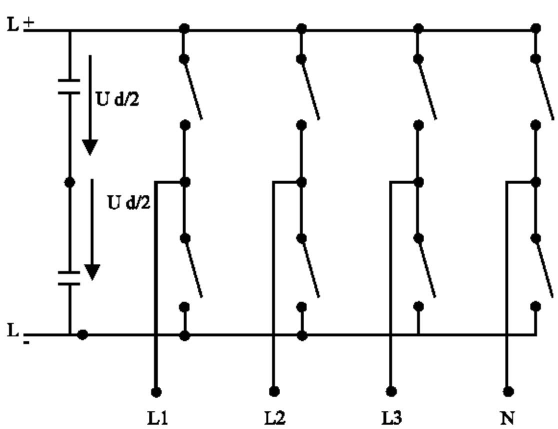

Fig. 5: 4-conductor VSC using fourth leg

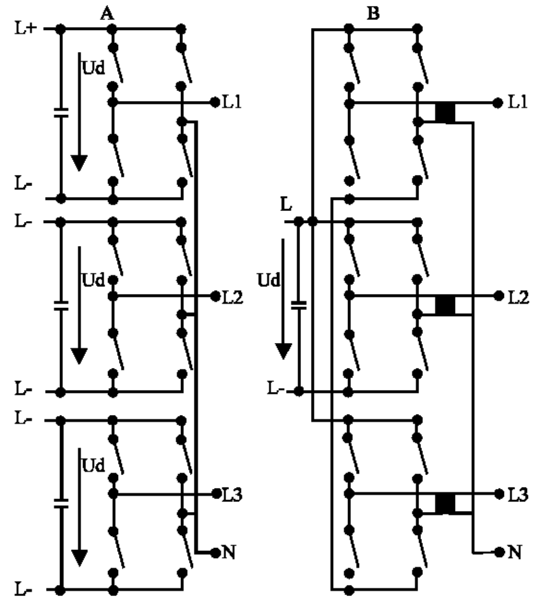

Fig. 6: Cascaded converter structure a: Isolated DC voltage; b: Isolated AC voltage

The cascaded structure offers advantages and disadvantages. On the one hand, the effort is increased with regard to the structures presented before. On the other hand, three-level characteristic is obtained.

AIMS OF COMPENSATION

When searching for the optimal compensator and the optimal compensation strategy, lots of questions have to be answered. One of the main questions is always:

- Which technology delivers the needed results with highest efficiency that is lowest costs at acceptable reliability? This at once opens the question for the needed results: What is the aim of compensation?
- The scope of this study reduces the question to: What should be compensated in the fourth conductor in addition to known aims for three-phase compensators-and why?
- In general two main areas of interest can be found, leading to differents aims of compensation.
- Compensation issues in low-voltage grids with neutral conductor. In this case the current in the neutral conductor can be eliminated completely or controlled.
- Application in medium-voltage grids without explicit neutral conductor, but with star point of transformer connected to ground via a choke. In this case the displacement voltage can be controlled or the ground current can be eliminated in case of faults.

The aim of compensation is then given by one ore more of the following:

- To increase efficiency.
- To avoid neutral conductor overload and destruction.
- To reduce Electromagnetic Interference (EMI).
- To avoid or damp resonances.
- To keep limits set by standards.

Having defined the 2 components of the aim of compensation, the best compensator and compensation scheme has to be found. This is usually a very complex task, some hints concerning the 3 main aims are.

Fourth conductor current elimination: Sufficient elimination of the current in the fourth conductor normally can be done with low effort by a suitable transformer-type compensation device shown in Fig. 7. It is equivalent to the secondary side of a transformer for a line commutated three-pulse Thyristor or diode rectifier.

This passive solution needs no control and is extremely robust. The additional inductances introduced will normally not cause resonance problems, because they are equivalent to those of a transformer. If no very special reasons exist, an active compensator is not necessary. It might even be cheaper to install an additional Z-transformer in parallel to an existing or planned three-conductor compensator instead of installing a four-conductor compensator. High neutral conductor current levels can be reduced by distributing several Z-transformers placing them close to the sources of disturbance.

Control of current in the fourth conductor: From a theoretical as well as from a practical point of view it is not optimal to simply eliminate the current in the neutral conductor by a compensator. If a compensator is used, the current in the fourth conductor can, e.g., be treated in the same way as the other currents. Ideally, it would be controlled according to the theory presented above. The resulting line currents fulfil the equality condition of the Cauchy-Schwarz inequality. They minimise the losses in the feeding conductors at equal conductor resistances.

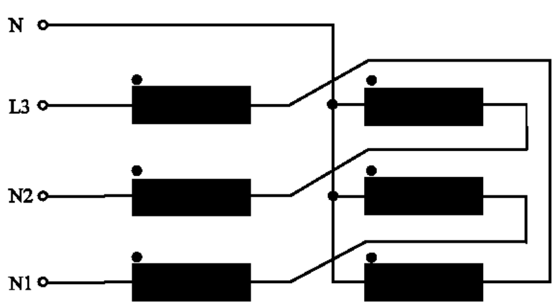

Fig. 7: Z-transformer for common mode current elimination

Two methods of compensation result from the theory discussed: One bases on instantaneous quantities leading to power currents (LI-strategy: Loss minimisation instantaneously), the other treating periodic conditions and giving active currents (LP-strategy: Loss minimization Periodic). From a theoretical point of view, both methods are optimal for their respective scope. In both cases load and compensator together are equivalent to the star connection of equal ohmic resistors. The advantage of this kind of compensation is obvious: A resistor always consumes energy; it is an ideal damping elements. If the neutral conductor current is modified according to this compensation rule, the displacement voltage is loaded by a current determined by a resistive element. The result will always load the displacement voltage and so reduce it-as long as the resistance is positive.

Reducing the neutral conductor current to zero will reduce the displacement voltage, if the load which is compensated and its now-compensated neutral current are the main source for the displacement voltage. If the displacement voltage is generated by other loads, it may even be the cause for the current in the neutral. In this case, reducing the current in the neutral will even enhance the displacement voltage.

Control of the displacement voltage: In industry, medium voltage distribution grids are often grounded via a choke. This choke is selected such, that the resonance frequency of the resonant circuit formed by the choke and the parasitic ground capacitances of the grid is close to-but not exactly-the grid frequency.

In this way, in case of a phase-to-ground fault, uninterrupted operation is possible for a short time, normally even until the fault is cleared. Ground currents resulting from unsymmetric ground capacitances in normal operation lead to an undesirable displacement voltage when flowing through the choke. With the help of a compensator this displacement voltage can be reduced consider-ably. The ground current is only influenced indirectly by the elimination of the displacement voltage.

In case of a fault, it is possible to reduce the current at the location of the fault even more than by earthing the star point of the transformer via a choke (residual current compensation).

CONCLUSION

Theory and good practice of compensation in case of four-conductor circuits is the main scope of this study.

Starting from well-known concepts for three-conductor circuits it is shown, why these concepts have to be extended carefully to four-conductor circuits. The main reason is that only zero-sum quantities should be used in power theory. The α-β-transformation, which gives the first two components of the Clarke transformation, does this automatically. It discards the common mode content. Most users do not realize this feature. It is clearly pointed out that the Clarke transformation, if applied in full to four-conductor circuits, misses this special property of automatically discarding the common mode content, leading to non optimal compensation results and errors in theory.

A transformation which is the extension of space vectors to four-conductor circuits with zero-sum quantities in mind is recalled. This transformation, called Hyper Space Vector (HSV) transformation, makes power theory for four-conductor circuits as simple and easily understandable as in the case of only 3 conductors. This power theory can be used directly as a compensator control scheme or for the assessment of other compensator control schemes.

Compensation in case of four-conductor circuits requires special compensators. The main converter topologies are shortly discussed. A special, inexpensive and robust solution for the reduction of neutral conductor currents is recalled.

Aims of compensation with special regard to the neutral conductor current are discussed. As a result, elimination of the neutral conductor current by a transformer-type device is often most cost effective. The control of the displacement voltage is of interest for distribution grids in industry applications. The control of the neutral conductor current in the same way as the other currents, making compensator and load together purely resistive, leads to optimal currents from the point of losses and damps all undesirable voltage components. Care, however, has to be taken if the resistance becomes negative, in recuperating mode.

The main overall result is that in case of four-conductor circuits all conductors should preferably be treated equally, even if in practical energy distribution the neutral conductor plays a special role. This point of view is supported by theo retical and practical considerations.

REFERENCES

Akagi, H., Y. Kanazawa and A. Nabae, 1983. Generalized Theory of the Instantaneous Reactive Power in Three-Phase Circuits. Int. Conf. Power Elec. Tokyo, pp: 1375-1386.

Buchholtz, F., 1950. Das Begriffsystem Rechtleistung, Wirkleistung, totale Blindleistung. Selbstverlag, München.

Depenbrock, M. and V. Staudt, 1997. Hyper Space Vectors: A New Four-Quantity-Extension of Space Vector Theory. 4th Int. Workshop on Power Def. Meas. Under nonsinusoidal Cond., Milano, pp: 1-7.

Depenbrock, M., 1962. Untersuchungen über die Spannungs-und Leistungsverhältnisse bei Umrichtern ohne Energiespeichen Dissertation, TH Hannover, pp: 15-25.

Depenbrock, M., 1993. The FBD-Method, a Generally Applicable Tool for Analysing Power Relations. IEEE. Trans. Power Sys., 8: 381-386.

Depenbrock, M., 2000. Variation Power, Variation Currents: Physical Background and Compensation Rules. Fifth International Workshop on Power Definitions and Measurement under Nonsin-usoidal Conditions, Milano Conf. Rec., pp: 19-25.

Depenbrock, M., V. Staudt and H. Wrede, 2002. A Concise Assessment of Original and Modified Instantaneous Power Theory Applied to Four-conductor Systems Power Conversion Conference (PCC) Osaka, pp: 60-67.

DIN 40110 Teil 2, 2002. Mehrleiter- Stromkreise. Beuth-Verlag, Berlin.

DIN 40110, Teil 1, 1994. März, Berlin.

Fryze, S., 1932. Wirk-Blind-und Scheinleistung in elektrischen Stromkreisen mit nicht-sinusförmigem Verlauf von Strom und Spannung. ETZ-A Elektrotech. Z., 53: 596-599, 625-627, 700-702.

IEEE Std 1459-2000: Trial use Standard on definitions for the Measurement of Electric Power Quantities under Sinusoidal, Nonsinusoidal, Balanced, or Unbalanced Conditions.

Nabae, A., T. Tanaka and F. Shigeyuki, 2000. A New Approach to Individual-Phase Reactive Power Compensator for Non-Sinusoidal and Unbalanced Three-Phase Systems. A Quasi-Instantaneous Reactive Power Compensator. Fifth International Workshop on Power Definitions and Measurement under Nonsinusoidal Conditions, Milano.