On the Assessment of Three-Phase Delta Voltages' Unbalance

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***Abstract*—Several existing three-phase delta voltages' unbalance factors, including the "true unbalance factor" (the negative sequence voltage unbalance factor) and its complex form, are considered. New geometric criteria of delta voltages' balance and unbalance, based on the dealing with delta voltages' triangles of equal perimeters and different areas are offered. All the unbalance factors are shown in their dependences on one particular phase voltage (and also on one particular delta voltage), separately on the magnitude (for the case of a single-phase magnitude unbalance) and on the initial phase angle value (for the case of a single-phase angle unbalance). Also the fragment of a LabVIEW virtual instrument for the assessment of the negative sequence voltage unbalance factor and the new geometric factors is offered.**

Keywords—three-phase delta voltages' unbalance, negative sequence voltage unbalance factor, complex-valued voltage unbalance factor, isoperimetric principle, geometric criteria of delta voltages' balance and unbalance

I. INTRODUCTION

The intrinsic feature of polyphase power supply systems and the critical issue for the efficient and safe operation of three-phase power loads is the aspect of the electromagnetic compatibility problem related to the unbalance of voltages and currents of the three-phase system. The corresponding European regulations [1-3] and one way or another related to three-phase unbalance numerous publications both here and abroad confirm the complexity of the tasks in this area and the urgent need to solve them.

The main issues of the both early and comparatively recent researches can be categorized as follows (the publications list is far from exhaustive):

- impact of voltage asymmetry on equipment derating, lifetime and efficiency reduction etc. and unbalance causes [7-17];
- comparisons and simplifications of various existing unbalance factors, revealing of their advantages and new applications, consideration of new offered factors [17-27];
- problems in unbalance measurements, its modelling and the signals' processing and solving these problems through new methods and approaches [28, 29];
- approaches to the definition and reducing of the unbalance in the presence of higher harmonics [26, 28, 30-32];
- implementing some technique (or techniques) for voltage or current unbalance compensations [26, 33, 34].

Cases of three-phase delta voltages' unbalances are the most severe ones that require fast responses of some compensators and voltage quality conditioners, which means the respective measurement information should be used in the best way.

The objectives of this paper are to consider several existing three-phase delta voltages' unbalance factors, to offer a new geometric criterion and to show in a visible manner their dependences on magnitude values (in a single-phase magnitude unbalance mode) and on initial phase angle values (in a single-phase angle unbalance mode) of one particular phase voltage. The mode of sinusoidal voltages and currents is assumed.

Also the LabVIEW implementation, based on the only three delta voltages' RMS readings, of assessing the negative sequence voltage unbalance factor and the new geometric factors is demonstrated.

II. MAIN THREE-PHASE DELTA VOLTAGE UNBALANCE INDICES

Here a brief overview of some voltage unbalance factors relating to the three-phase line-to-line (delta) voltages is listed.

A. NEMA Line-to-Line Voltage Unbalance Rate

The National Electrical Manufacturers Association (NEMA) is the largest trade association of electrical equipment manufacturers in the United States. The NEMA line-to-line voltage unbalance rate (*LVUR*) assesses the relative value of the maximum delta voltage deviation from the average delta voltage value $U_{\Delta avg}$ [4] and, like the others unbalance factors, usually is being presented as the percent voltage unbalance, *LVUR*%:

$$LVUR\% = \frac{\max\left(|\Delta U_{AB}|,|\Delta U_{BC}|,|\Delta U_{CA}|\right)}{U_{\Delta avg}} \cdot 100\,, \qquad (1)$$

$$\Delta U_{XY} = U_{XY} - U_{\Delta avg}\,,$$

$$U_{\Delta avg} = \frac{U_{AB} + U_{BC} + U_{CA}}{3}\,,$$

here U_{XY} is the RMS value of some line-to-line voltage, $X,Y \in \{A,B,C\}$.

Introducing the designations

$$U^*_{XY} = \frac{U_{XY}}{U_{\Delta avg}}\,,\ \delta_{XY} = \frac{\Delta U_{XY}}{U_{\Delta avg}} = U^*_{XY} - 1\,,$$

we can rewrite (1) as follows:

$$LVUR\% = \max\left(\left|\delta_{AB}\right|,\left|\delta_{BC}\right|,\left|\delta_{CA}\right|\right)\cdot 100 . \quad (2)$$

B. IEEE Voltage Unbalance Ratio as Second Line-to-Line Voltage Unbalance Rate

This factor, the second line-to-line voltage unbalance rate (*LVUR2),* assesses the relative value of the difference between the maximum and the minimum RMS voltage values [34, 5]. Its percentage form is

$$LVUR2\% = \frac{\max\left(U_{AB},U_{BC},U_{CA}\right)-\min\left(U_{AB},U_{BC},U_{CA}\right)}{U_{\Delta avg}}\cdot 100 =$$

$$=\left(\max\left(U^*_{AB},U^*_{BC},U^*_{CA}\right)-\min\left(U^*_{AB},U^*_{BC},U^*_{CA}\right)\right)\cdot 100 . \quad (3)$$

Both *LVUR* and *LVUR2* unbalance factors had also been considered and used by American National Standards Institute (ANSI).

C. Negative Sequence Voltage Unbalance Factor

This factor is the most widely used, it is the conventional unbalance criterion adopted in exact or approximate form by many standards including IEC [1], CIGRE [18] and IEEE [6]. The voltage unbalance factor (*VUF*), also known as "true unbalance factor" [35, 36], can be expressed by the general equation and its percentage form:

$$VUF = U_n/U_p \text{ , } VUF\% = \frac{U_n}{U_p}\cdot 100 , \quad (4)$$

where U_n and U_p are respectively the negative sequence voltage component (NSVC) and the positive sequence voltage component (PSVC) RMS values [37-39].

The direct use of (4) is cumbersome process due to treating complex numbers and simple RMS-meters are unsuitable, because it needs phases metering.

Since the system of delta voltages is free of zero-sequence voltage component, (4) leads to the enough simple exact formula [40, 41, 20] that needs the only three delta voltages' RMS readings:

$$VUF\% = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}}\cdot 100 , \quad (5)$$

where

$$\beta = \frac{U_{AB}{}^4 + U_{BC}{}^4 + U_{CA}{}^4}{\left(U_{AB}{}^2 + U_{BC}{}^2 + U_{CA}{}^2\right)^2} .$$

It should be noted that several approximated variants of (5) exist [18, 22], but use of them means a loss of accuracy and is not the best way of processing the RMS readings as measurement information.

D. Complex-Valued Voltage Unbalance Factor

The complex-valued voltage unbalance factor (*CVUF*) is a natural extension of *VUF* and provides information not only on magnitude *VUF* of the result of the negative $\dot{U}_n$ and the positive $\dot{U}_p$ sequences voltage phasors' ratio, but also on the phase difference of these phasors:

$$CVUF = \dot{U}_n/\dot{U}_p = VUF\cdot e^{j\cdot\psi_u} \text{ , } CVUF\% = CVUF\cdot 100 , \quad (6)$$

where $\dot{U}_n = U_n\cdot e^{j\cdot\alpha_n}$, $\dot{U}_p = U_p\cdot e^{j\cdot\alpha_p}$ and $\psi_u = \alpha_n - \alpha_p$.

Thus, *CVUF* is treated as the static phasor.

The NSVC and PSVC phasors' phase angles considerations and even references to some possibility and future trend to use *CVUF* for any particular voltage unbalance identification have been made since 1930s by many researchers [38, 41, 7, 8, 19, 9, 11, 20, 22, 24, 42, 43, 34, 14, 17] (the references list is here chronologized).

The method for determining the values of ψ_u for the worst and the most favorable cases of voltage unbalance impact on some motor load is offered in [7]. The failed attempt to use *CVUF* as a performance indicator of adjustable speed drives is shown in [17]. Despite this, the particular *CVUF* phase data make it possible to compensate the particular voltage unbalance in closed-loop systems with power converters.

The pre-announced characteristics of some unbalance factors will be shown in Section IV.

III. Geometric Criterion for Three-Phase Delta Voltages' Unbalance Assessment

The new geometric criterion of the delta voltages' unbalance is intended for different modes with sinusoidal voltages and currents waveforms. It is based on the principle of triangles of equal perimeters (i.e. the isoperimetric principle) and seems to be reasonable.

Let's consider such two triangles of the three-phase delta voltages that have the same perimeters value *P*, with the arbitrary sides' values of the first triangle and the equal sides' values $U_{\Delta eq}$ of the second triangle. Thus,

$$P = U_{AB} + U_{BC} + U_{CA} = 3U_{\Delta eq} \text{ , } U_{\Delta eq} = U_{\Delta avg} , \quad (7)$$

and so, the second triangle is the equilateral triangle with the sides' value $U_{\Delta eq}$ equal to average value $U_{\Delta avg}$ of the RMS delta voltages' values.

The corresponding areas' ratio of the triangles can serve as the degree of the first triangle symmetry and the geometric three-phase delta voltages' balance factor:

$$GVBF = S_\Delta/S_{\Delta eq} , \quad (8)$$

where, in accordance with Heron's formula, the arbitrary triangle's area is

$$S_\Delta = \sqrt{p\left(p-U_{AB}\right)\left(p-U_{BC}\right)\left(p-U_{CA}\right)} \text{ , } p = P/2 , \quad (9)$$

and the equilateral triangle's area is

$$S_{\Delta eq} = \frac{\sqrt{3}}{4}U_{\Delta eq}{}^2 = \frac{\sqrt{3}}{4}U_{\Delta avg}{}^2 . \quad (10)$$

After substitutions in (8) from (9) and (10) we can obtain enough simple equations:

$$GVBF=\sqrt{8\left(\frac{3}{2}-\frac{U_{AB}}{U_{\Delta avg}}\right)\left(\frac{3}{2}-\frac{U_{BC}}{U_{\Delta avg}}\right)\left(\frac{3}{2}-\frac{U_{CA}}{U_{\Delta avg}}\right)}= \quad (11)$$

$$=\sqrt{\frac{(U_{BC}+U_{CA}-U_{AB})(U_{AB}+U_{CA}-U_{BC})(U_{AB}+U_{BC}-U_{CA})}{U_{\Delta avg}{}^{3}}}=$$

$$=\sqrt{(U^*_{BC}+U^*_{CA}-U^*_{AB})(U^*_{AB}+U^*_{CA}-U^*_{BC})(U^*_{AB}+U^*_{BC}-U^*_{CA})}.$$

The simplest form in terms of relative values U^*_{XY} can still be derived from the first equation of (11):

$$GVBF=\sqrt{(3-2U^*_{AB})(3-2U^*_{BC})(3-2U^*_{CA})}. \quad (12)$$

Also $GVBF$ can be written in terms of δ_{XY}:

$$GVBF=\sqrt{(1-2\delta_{AB})(1-2\delta_{BC})(1-2\delta_{CA})}. \quad (13)$$

Since the area of some triangle with the specified perimeter value is accepting the maximum value exactly in case where the triangle is equilateral, $S_\Delta|_{max}=S_{\Delta eq}$ [44], the limit of this criterion $GVBF$ as all the values U_{AB}, U_{BC} and U_{CA} approach $U_{\Delta avg}$ equals 1.

At last, the new, geometric, based on that isoperimetric concept three-phase delta voltages' unbalance factor $GVUF$ can be defined as follows (including the percentage form):

$$GVUF=\frac{S_{\Delta eq}-S_\Delta}{S_{\Delta eq}}=1-GVBF, \quad (14)$$

$$GVUF\%=GVUF\cdot 100. \quad (15)$$

The characteristics of the isoperimetric criterion $GVUF$ will also be considered in the next section.

IV. Mathcad Simulations of Voltage Single-Phase Unbalance

By seizing the approach of [23], but in more wide ranges and in more visible manner, namely, in graphical form, the Mathcad-simulated characteristics of the delta voltages' main unbalance factors *LVUR*%, *LVUR2*%, *CVUF*% (*VUF*% and ψ_u) and the new isoperimetric factor *GVUF*% will be shown separately for the cases of the single-phase voltage magnitude unbalance and its initial phase unbalance. So, one of the delta voltages continues to be undistorted, while two others changes their magnitudes and phase angles.

A. Single-Phase Magnitude Unbalance

The triangles of the delta voltages RMS values in a balanced mode (ΔABC), an undervoltage mode (ΔABC_1) and an overvoltage mode (ΔABC_2) of phase C voltage are shown in Fig. 1.

Let's introduce here the designations for the phase voltages U'_X and the delta voltages U''_{XY} RMS relative values:

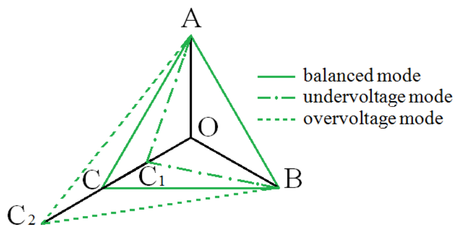

Fig. 1. Triangles of delta voltages in single-phase (phase C) magnitude unbalance modes.

$$U'_X=\frac{U_X}{U_{Y\_base}},\; U''_{XY}=\frac{U_{XY}}{U_{\Delta\_base}}=\frac{U_{XY}}{\sqrt{3}\cdot U_{Y\_base}}, \quad (16)$$

where U_{Y_base} and U_{Δ_base} are the base values of the phase and delta voltage RMS values, respectively.

So, in this simulation $U'_A=U'_B=1$, and the relative phase C voltage RMS value U'_C is changed from zero ($C\equiv O$) to some its maximum value ($C\equiv C_2$).

The nature of the changes in RMS values of the positive sequence delta voltage component $U''_{\Delta p}$ and in the negative sequence delta voltage component $U''_{\Delta n}$ and also in the delta voltage *VUF* value is demonstrated in Fig. 2.

The similar way dependences of the phase angles of the negative sequence delta voltage component $\alpha_{\Delta n}$, positive sequence delta voltage component $\alpha_{\Delta p}$ and the delta voltage *CVUF* $\psi_{\Delta u}$ on the U'_C value are shown in Fig. 3.

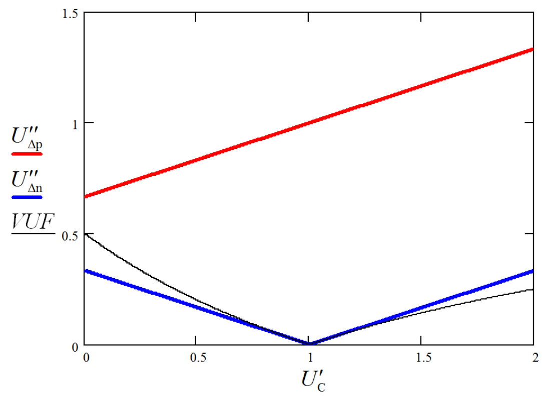

Fig. 2. Relative RMS values of positive and negative sequence delta voltage components and delta voltage unbalance factor versus relative phase C voltage RMS value.

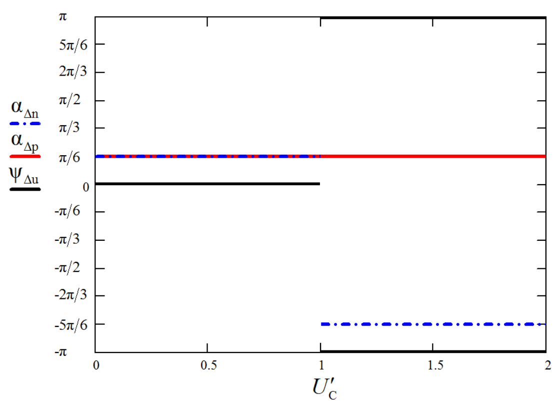

Fig. 3. Phase angles of negative and positive sequence delta voltage components and of delta voltage complex-valued unbalance factor versus relative phase C voltage RMS value.

Here the initial phase angle of the phase A voltage is assumed to be zero. Hereinafter should be taken into account that there is not principal difference for variables of sinusoidal functions between values, shifted by 2π, in this case between π and $-\pi$.

The respective dependences on a relative delta voltage RMS value, for example on U''_{BC} (here, due to the Fig. 1 symmetry, $U''_{CA} = U''_{BC}$), do not have qualitative differences from those shown in Fig. 2 and Fig. 3. Namely, the zero value of *VUF* and the threshold between the $\psi_{\Delta u}$ values of 0 and $\pm\pi$ correspond to $U''_{BC} = 1$.

Also, again due to the choice of the base values of phase and delta voltages RMS in (16), dependences of the positive sequence phase voltage component RMS value U'_{Yp}, the negative sequence phase voltage component U'_{Yn} RMS value and of the phase voltage *VUF* value are the same as the respective delta voltage dependences in Fig. 2.

Since the phase angle of the positive sequence phase voltage component α_{Yp} is always zero, $\alpha_{Yp} = 0$, the phase voltage *CVUF* phase angle ψ_{Yu} is equal to the phase angle of the negative sequence phase voltage component α_{Yn}, and their simulated results are as follows:

$$\psi_{Yu} = \alpha_{Yn} = \begin{cases} \pi/3 & if \quad 0 \le U'_C < 1 \\ -2\pi/3 & if \quad U'_C > 1. \end{cases} \tag{17}$$

The percentage forms of the delta voltages' main unbalance factors *LVUR%, LVUR2%, VUF%* and of the new isoperimetric factor *GVUF%* are shown in Fig. 4 for a quite narrow range of the U'_C values, in Fig. 5 for the three-times wider range of the values, and in Fig. 6 for their dependences on the relative RMS values not of the phase voltage U'_C, but of the delta voltage U''_{BC}.

B. Single-Phase Angle Unbalance

The triangles of the delta voltages RMS values in a balanced mode (ΔABC), a clockwise angle shift mode (ΔABC_1) and a counterclockwise angle shift mode (ΔABC_2) of phase C voltage are shown in Fig. 7.

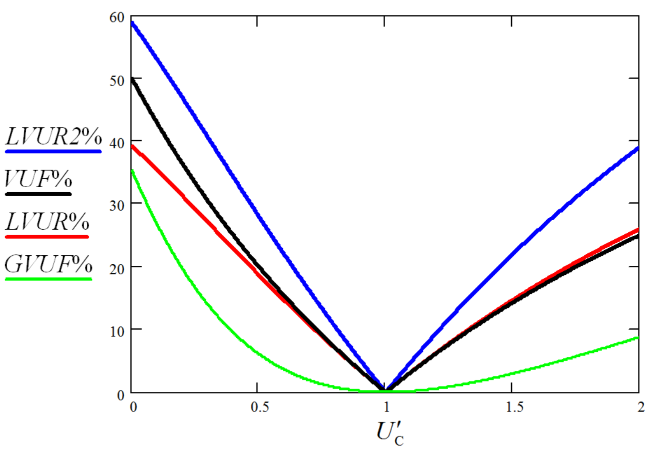

Fig. 4. Percentage forms of delta voltages' main unbalance factors and of new isoperimetric factor versus relative phase C voltage RMS value in the range of 0 to 2 relative units.

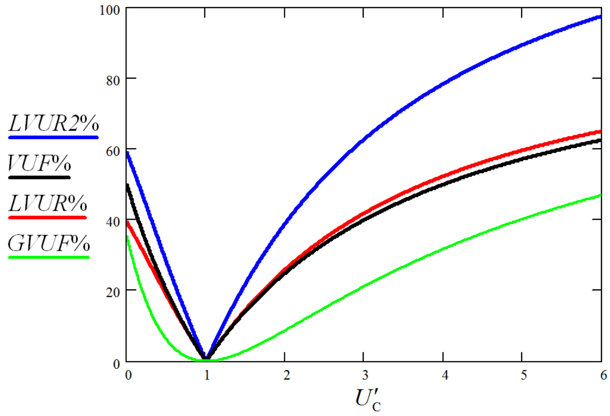

Fig. 5. Percentage forms of delta voltages' main unbalance factors and of new isoperimetric factor versus relative phase C voltage RMS value in the range of 0 to 6 relative units.

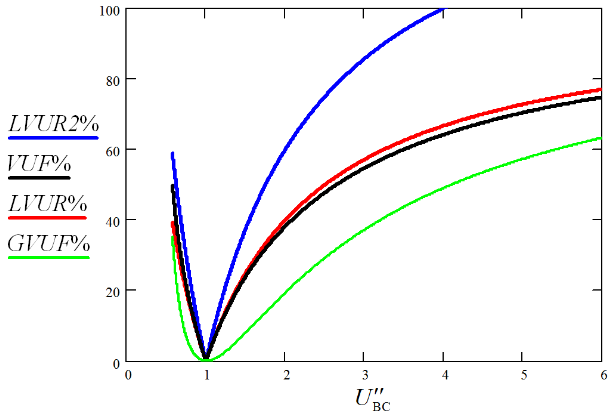

Fig. 6. Percentage forms of delta voltages' main unbalance factors and of new isoperimetric factor versus relative delta voltage RMS value.

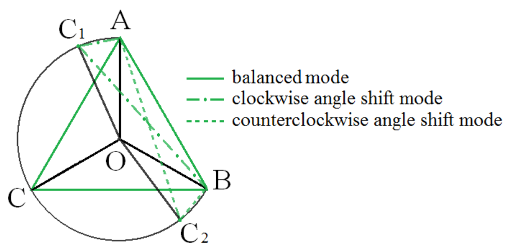

Fig. 7. Triangles of delta voltages in single-phase (phase C) angle unbalance modes.

As can be seen, a value of the shift $\Delta\alpha_C$ from the balanced mode initial phase angle of phase C voltage $\alpha_C = 2\pi/3$ can potentially vary from $-2\pi/3$ (C_1 approaches A) to $2\pi/3$ (C_2 approaches B).

The dependences on the phase shift $\Delta\alpha_C$ of the positive sequence delta voltage component $U''_{\Delta p}$, the negative sequence delta voltage component $U''_{\Delta n}$ and the delta voltage *VUF* value are shown in Fig. 8, of the phase angles of the negative sequence delta voltage component $\alpha_{\Delta n}$, positive sequence delta voltage component $\alpha_{\Delta p}$ and the delta voltage *CVUF* $\psi_{\Delta u}$ are shown in Fig. 9, and of the phase angles of the negative sequence phase voltage component α_{Yn}, positive sequence phase voltage component α_{Yp} and the phase voltage *CVUF* ψ_{Yu} are shown in Fig. 10.

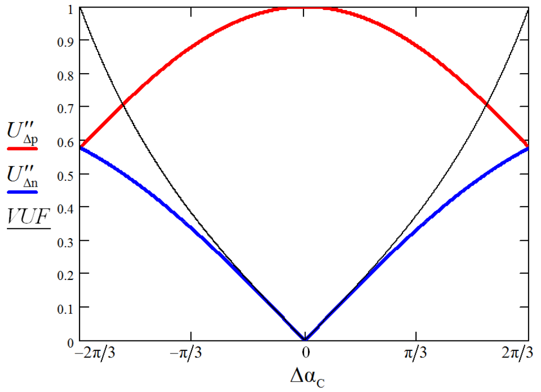

Fig. 8. Relative RMS values of positive and negative sequence delta voltage components and delta voltage unbalance factor versus value of shift from balanced mode initial phase angle of phase C voltage.

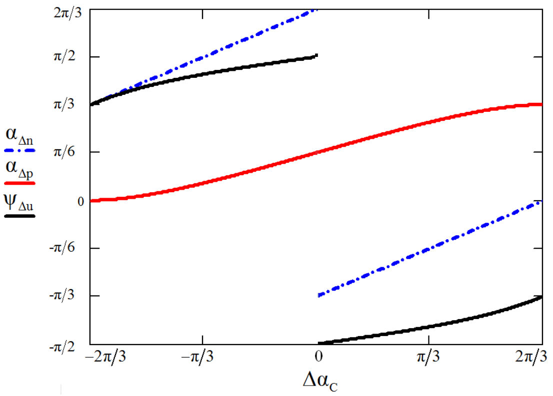

Fig. 9. Phase angles of negative and positive sequence delta voltage components and of delta voltage complex-valued unbalance factor versus value of shift from balanced mode initial phase angle of phase C voltage.

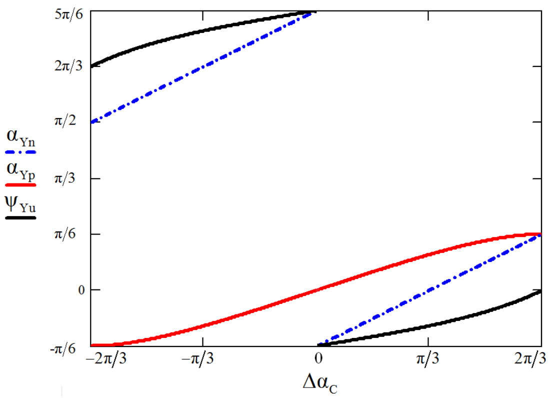

Fig. 10. Phase angles of negative and positive sequence phase voltage components and of phase voltage complex-valued unbalance factor versus value of shift from balanced mode initial phase angle of phase C voltage.

Since $\alpha_{Yp} = \alpha_{\Delta p} - \pi/6$ and $\alpha_{Yn} = \alpha_{\Delta n} + \pi/6$, the relationship between the phase angles of the phase voltage *CVUF* and the delta voltage *CVUF* is here as follows:

$$\psi_{Yu} = \alpha_{Yn} - \alpha_{Yp} = \psi_{\Delta u} + \pi/3 \,. \qquad (18)$$

The percentage forms of the delta voltages' main unbalance factors *LVUR%*, *LVUR2%*, *VUF%* and of the new isoperimetric factor *GVUF%* are shown in Fig. 11 for the range of the phase angle shift from $-\pi/3$ to $\pi/3$.

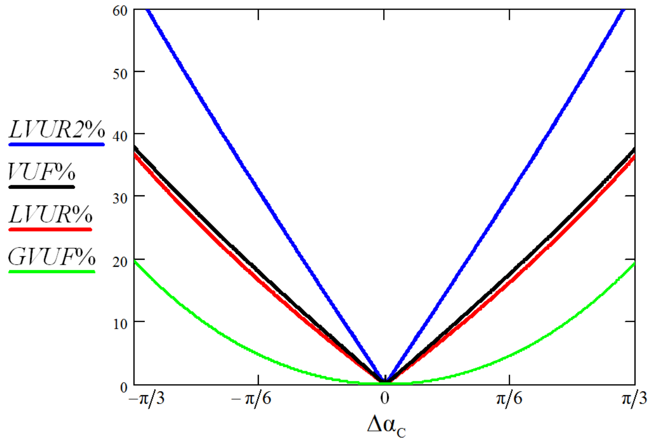

Fig. 11. Percentage forms of delta voltages' main unbalance factors and of new isoperimetric factor versus value of shift from balanced mode initial phase angle of phase C voltage in range of -60° to 60°.

The same dependences for the range of the phase angle shift from $-2\pi/3$ to $2\pi/3$ are presented in Fig. 12. At last, the dependences of those same values on the relative delta voltage RMS value U''_{BC} under the changing of the phase angle shift $\Delta\alpha_C$ in the same (full) range are shown in Fig. 13.

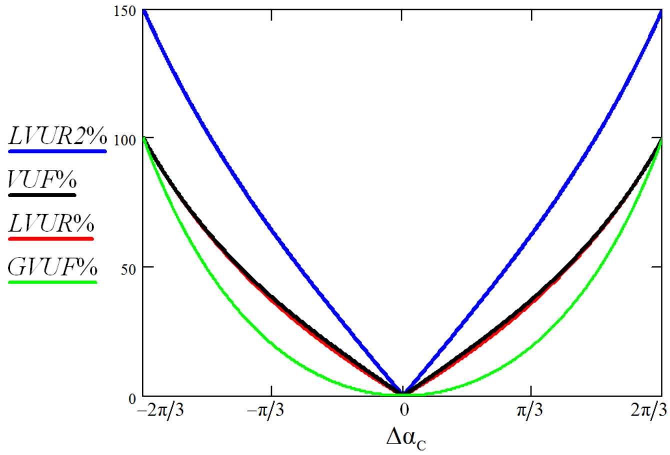

Fig. 12. Percentage forms of delta voltages' main unbalance factors and of new isoperimetric factor versus value of shift from balanced mode initial phase angle of phase C voltage in range of -120° to 120°.

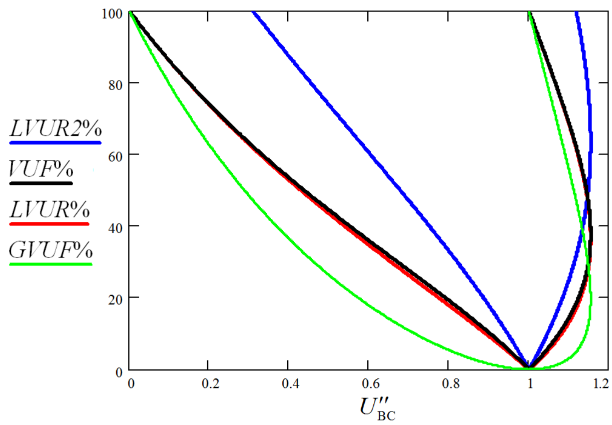

Fig. 13. Percentage forms of delta voltages' main unbalance factors and of new isoperimetric factor versus relative delta voltage RMS value under the changing of shift from balanced mode initial phase angle of phase C voltage in range of -120° to 120°.

C. Some Comments

As can be seen from the figures, the conventional delta voltage unbalance factors near their zero value point have the curves enough close to line form with a nearly constant slope.

For both considered kinds of the delta voltages' unbalance, values of the *VUF%* and *LVUR%* factors are enough close to each other, except in the case of phase voltage relative RMS value approaches to zero.

The factor *LVUR2%* has the steepest curve slope. The ratio *LVUR2%* / *LVUR%* is changing its values as almost a linear function, from 2 exact value at the zero phase angle shift $\Delta\alpha_C$ to 1.5 exact value at the phase angle shift $\Delta\alpha_C = \pm 2\pi/3$.

The new factor *GVUF%* has the least steep curve slope, its derivative is continuously changing and reaching zero at the factor's zero value point. This could be helpful for some compensating closed-loop systems with some enough low regular sampling rate.

In addition, instead of treating the delta voltage unbalance factors, which are the close to zero and zero-approaching values, it should be reasonable to perform the tracking of the isoperimetric delta voltage balance factor *GVBF* ((8), (11)-(13)) and to tune in to its maximum value, that is approaching to one, see Fig. 14.

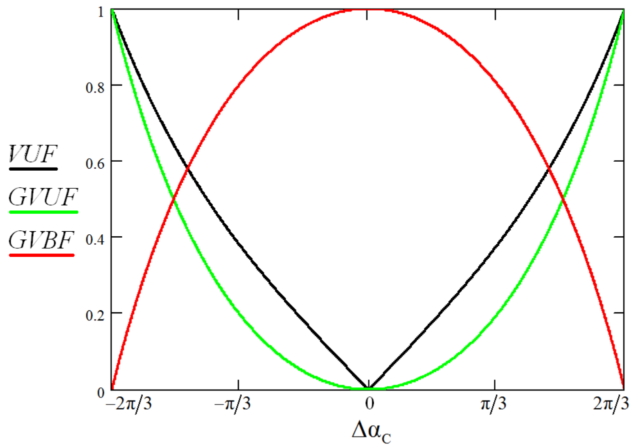

Fig. 14. Delta voltages' conventional unbalance factor *VUF* and new isoperimetric delta voltages' unbalance factor *GVUF* and balance factor *GVBF* versus value of shift from balanced mode initial phase angle of phase C voltage in range of -120° to 120°.

On the other hand, there is a need to use the complex-valued voltage unbalance factor *CVUF*, due to its providing the coordinate positioning of an unbalance voltage static phasor, namely the negative sequence delta voltage component $U_{\Delta n}$ phasor, and some prospects in the field of the voltage unbalance compensation by means of new specialized power electronics equipment.

V. On Construction of Virtual Instrument for Assessment of Unbalance Factors

The unbalanced three phase systems' voltage quality can be assessed by various (in terms of both functionality and cost) virtual instruments (VI) [45-47] which could be developed, in particular, inside the National Instruments LabVIEW software environment (Laboratory Virtual Instrument Engineering Workbench). It is a widespread powerful monitoring and analysis tool, which can provide processing of both simulated and captured signals including a real time data acquisition and measurement due to the numerous specially developed and compatible hardware products.

Let's here concentrate on some simple and cheap in sensors' cost VI that is able to assess the main delta voltage unbalance factor *VUF* and the new isoperimetric factors, the geometric delta voltage unbalance factor *GVUF* and the geometric delta voltage balance factor *GVBF*. The core fragment of the virtual instrument, which needs the three delta voltages' RMS readings as input data, is demonstrated in Fig. 15.

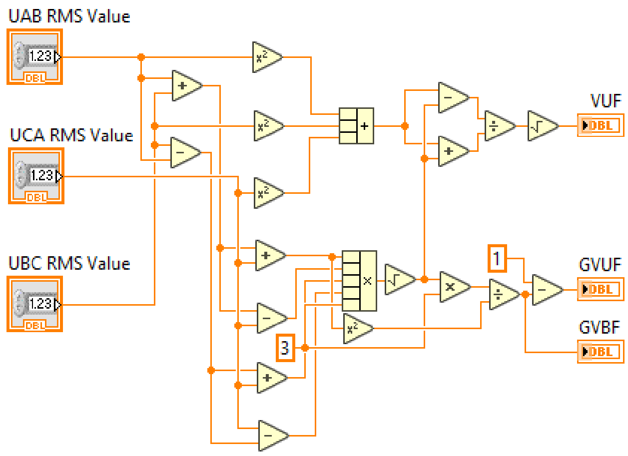

Fig. 15. Fragment of VI for assessing main delta voltage unbalance factor *VUF* and new isoperimetric factors *GVUF* and *GVBF*.

Here the laconic LabVIEW visual program code for *VUF* is the result of (5) simplification in accordance with [40, 20] and after them, which makes is possible to avoid calculations with the voltages' RMS values raised to the power of four:

$$VUF = \sqrt{\frac{U_{AB}{}^2 + U_{BC}{}^2 + U_{CA}{}^2 - \sqrt{3A}}{U_{AB}{}^2 + U_{BC}{}^2 + U_{CA}{}^2 + \sqrt{3A}}}, \tag{19}$$

where

$$\mathrm{A} = P(P-2U_{AB})(P-2U_{BC})(P-2U_{CA}) =$$
$$= (U_{AB}+U_{BC}+U_{CA})(U_{BC}+U_{CA}-U_{AB}) \times$$
$$\times (U_{AB}+U_{CA}-U_{BC})(U_{AB}+U_{BC}-U_{CA}).$$

Due to approach in [20, 38, 39], the further extension of this VI can be done toward the phase relationships calculations and assessment of the complex-valued phase and delta voltage unbalance factors *CVUF*, namely their phase angles, under continued applying the only cheap RMS voltage sensors with some enough low regular sampling rate.

VI. Conclusions

The main issues of researches, related to three-phase voltage unbalance, are categorized. The conventional (standard) factors of the three-phase delta voltages' unbalance are considered. The new isoperimetric criteria of delta voltages' balance and unbalance are presented. The conclusion regarding the applicability of the new geometric factors is made.

The curves of the values' changings of the considered delta voltages' unbalance factors in the cases of a single-phase magnitude unbalance and of a single-phase angle unbalance are presented and briefly discussed.

The core fragment of the LabVIEW virtual instrument for the assessment of the negative sequence voltage unbalance factor and new isoperimetric criteria of the delta voltages' balance and unbalance is demonstrated. It needs the only three delta voltages' RMS readings as input data.

The possibility of the further extension of the virtual instrument for the values' reconstruction of the phase angles of the complex-valued phase and delta voltage unbalance factors is shown.

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