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Application of Hyperphasor Representation of Transients' Parameters during Analysis of UPS Operation Modes

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1 INTRODUCTION

One of the main problems in organization of electrical power system (EPS) operation modes parameters measurement process is the choice of measurement results representation way which helps to correctly display measured parameters' values for their further effective use. Development of digital signal processing, synchronization and communication technologies enables to expand the range of application of traditional for power engineering vector forms of data representation. It also enables development and implementation of new forms of complex measurement, monitoring and EPS transients handling problems.

A method of graphical electrical quantities (currents and voltages) representation, which are measured during EPS transients as a four-dimensional hyperphasor is observed in this report. This method is applicable if electrical quantities can be represented as a sum of complex magnitudes with complex frequency.

2 MAIN PART

As known use of vector diagrams and vector measurements in power engineering, theory and practice of relay protection and system automation is wide spread [1]. Excepting scientific and technical and methodical literature, use and measurement of electrical quantities in vector form has been used for several decades for development, implementation and adjustment of relay protection and system automation. From the prewar times volt-ampere-phasometers (VAP) of different generations are known including modern digital devices, digital oscillograph software, development of control systems based on vector measurements [2]. For several recent years abroad as well as in UPS of Russia systems of synchronized (GPS, GLONASS) vector electrical quantities measurement (wide-area measurement system (WAMS)) have been used [3]. Thereby it can be concluded that use of vector measurements and diagrams is an important component of the theory of relay protection and system automation, monitoring and control.

At the same time magnitudes and phase angles between electrical currents and voltages are measured. Results of measurements are represented as totality interconnected vectors in the form of vector diagrams. The comparison of vector diagrams of different effects and events in electrical circuits under consideration is performed, for example under different types of short circuit [1].

One of drawbacks of traditional two-dimensional vector form is impossibility to use it for adequate graphical representation of electrical values of currents and voltages in transients when they are accompanied by several free components in measured current and voltages.

Scrupulous consideration of dynamic characteristics of electromechanical and electromagnetic transients in power systems is one of the modern relay protection development ways. Results of currents and voltages measurements in transient modes are defined by two groups of factors:

- First group of factors is defined by close relationship between sets of EPS modes parameters, and in the first place values of branch currents and node voltages in the electrical power system scheme. Indicated parameters' values are time functions $i(t)$, $u(t)$ and are formed depending on EMF of synchronous generators equipped with sophisticated excitation and power control systems.
- Second group of factors is defined by set of elements' parameters of electrical power system scheme. Values of most of them are considered conditionally-constant in given system topology, but parameters of a set of elements vary during transients (e.g. FACTS) and their values should be considered as time functions.

Transients' analysis in power systems is a well-developed science intensive discipline. It is known that during transients theoretical waveforms of electrical currents and voltages in linear systems containing resistors, electrical capacities and inductances can be presented as a sum of components having complex magnitudes with complex frequency [5].

$$i_{\Sigma}(t) = \text{Im} \left\{ \sum_{k=1}^n \underline{I}_{m,k} \exp \left[t \left(-\frac{1}{T_k} + j\omega_k \right) \right] \right\}, \quad (1)$$

where $\underline{I}_{m,k} = I_{m,k} \angle \varphi_k$ - complex magnitude of k^{th} component;

$-\frac{1}{T_k} + j\omega_k = \underline{s}_k = s_k \angle \alpha_{s,k}$ - complex frequency of k^{th} component.

It should be noticed that such analytical presentation of electrical quantity waveform has wide but not all covering importance. There is a number of problems linked with electrical calculations (e.g. consideration of non-linearity, time delays and many other electrical phenomenon) where solutions requires application of other analytical expressions and application of complex magnitudes with complex frequency is unreasonable.

Thereby the following actual problem is revealed: to modify commonly-known method of representation of currents and voltages in the form of complex numbers and two-dimensional vectors on complex plane, which show magnitude and initial phase, and provide representation of four-dimensional hyperphasors showing not only magnitude and initial phase but also frequency and pumping time constant of transient currents and voltages. Requirement to sought-for method is fulfillment of conformity principle: two-dimensional vector should be a particular case of four-dimensional vector without damping.

To draw values of electrical quantities of transient currents and voltages which can be presented as time functions (1) a hyperphasor diagram was offered [6] and developed [7-10]. This diagram is shown on hypersurface with two coordinate systems and comprises development and generalization of traditional two-dimensional vector diagram.

A method of four-dimensional hyperphasor drawing is shown in fig. 1. Fig. 1, *a* shows digital oscillogram of measured transient current $i_{\Sigma}(t)$, comprising three components: $i_1(t)$ – sinusoidal component of system frequency (314 radian/s), $i_2(t)$ – exponent and $i_3(t)$ – damped sinusoidal component of double frequency (628 radian/s).

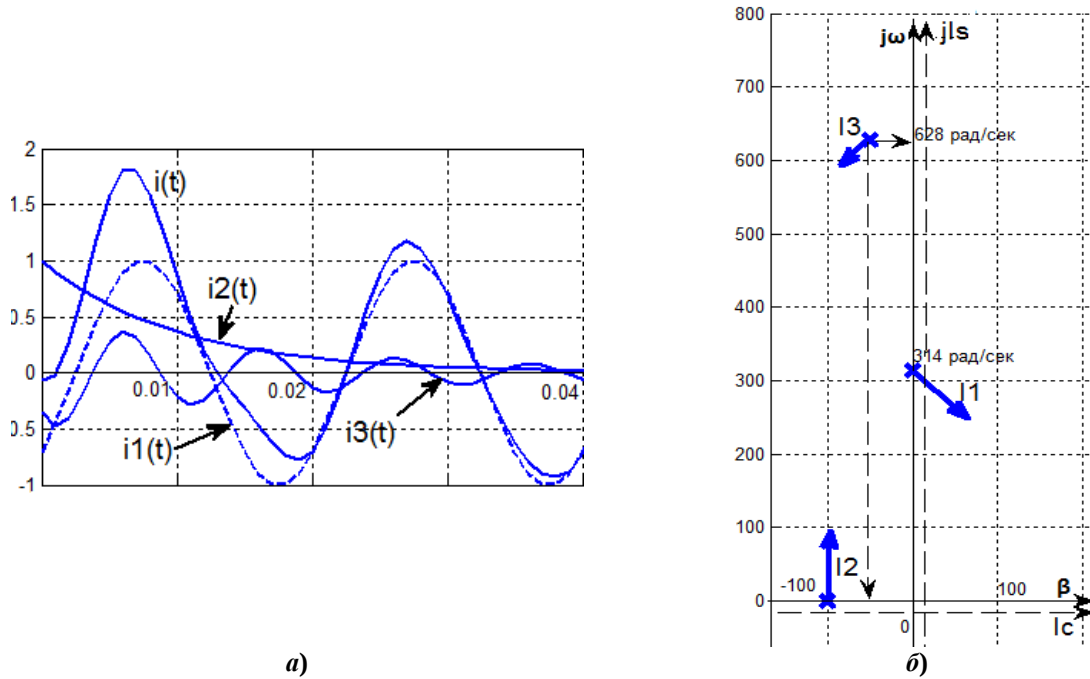


Fig. 1: *a* – oscillograms of measured transient current $i_2(t)$ and its components;
b – hyperphasor diagram of $i_2(t)$ components.

Fig 1,b shows hyperphasor diagram of $i_2(t)$ components on complex plane with dual coordinate system.

First coordinate system of complex frequency is formed by:

- Abscissa axis – exponential process damped indicator $1/T$, s^{-1} (real part of complex frequency);
- Ordinate axis – angular frequency of oscillations ω , radian/s (imaginary part of complex frequency).

Second coordinate system of complex magnitude is matched on complex plane with the first system and is formed by:

- Abscissa axis – real part of complex magnitude;
- Ordinate axis – imaginary part of complex magnitude. Projection of rotating counter-clockwise with angular frequency ω hyperphasor on this axis corresponds in accepted scale to current instant value of electrical quantity. Length of this rotating vector fades exponentially with the time constant T .

Thereby in considered dual coordinate system each hyperphasor is four-dimensional and represents values of a pair of complex numbers – complex magnitude and complex frequency.

If the process shown is not damped ($T \rightarrow \infty$), then the beginning of the hyperphasor is placed in the point ω on imaginary axis. Length of this rotating hyperphasor is not decreasing (fig. 2, $b - \tilde{I}_1$). If an exponent is shown, then the beginning of the hyperphasor moves to real axis to the point $1/T$, $\omega=0$ (in fig. 2, $b - \tilde{I}_2$), hyperphasor is not rotating. If the process shown is a damped sinusoid ($1/T < 0$, $\omega > 0$, on fig. 2, $b - \tilde{I}_3$), then beginning of the hyperphasor is in the second quadrant of the complex plane and shows random values of four damped sinusoidal process parameters: initial magnitude, initial phase, frequency and damping time constant.

It should be noticed that values of continuous current (voltage) can also be presented as hyperphasor having its beginning in zero point of complex plane with coordinates $1/T=0$, $\omega=0$. Hyperphasor of a constant component is neither damping nor rotating.

Let's consider representation of transient current $i_2(t)$ in Fig. 1 in detail.

Sinusoidal component $i_1(t)$ is undamped, has magnitude $\tilde{I}_1$, initial phase $-\varphi_1$ and frequency 314 rad/s. Oscillogram of $i_1(t)$ component in Fig. 1,a and hyperphasor $\tilde{I}_1$ are in one-to-one correspondence. Value $T_1 = \infty$, so the beginning of hyperphasor $\tilde{I}_1$ is on ordinate axis.

$i_2(t)$ component is damped exponentially, in Fig. 1,a it has initial value $\tilde{I}_1 = 1$ kA and damping time constant $T = 10$ ms. These values are represented by hyperphasor $\tilde{I}_2$ in Fig. 1,b. $i_2(t)$ component oscillogram in Fig. 1,a and hyperphasor $\tilde{I}_2$ are also in one-to-one correspondence. Value $\omega_2=0$, so the beginning of hyperphasor $\tilde{I}_2$ is on the abscissa axis.

$i_3(t)$ component is damped sinusoid with initial magnitude $\tilde{I}_3$ and initial phase $-\varphi_3$, frequency $\omega_3 = 628$ rad/s and damping time constant $T_3 = 20$ ms. Hyperphasor $\tilde{I}_3$ shows these very values in Fig. 1,b. Oscillogram $i_3(t)$ in Fig. 1,a and hyperphasor $\tilde{I}_3$ are in one-to-one correspondence. Values of $\tilde{I}_3$ hyperphasor parameters in all four coordinates are non-zero, so the beginning of hyperphasor $\tilde{I}_3$ is in the second quadrant of complex plane – where fading sinusoidal components are.

Hyperphasor diagram shown in Fig. 1,b is characterized by coordinate values of three hyperphasors $\tilde{I}_1$, $\tilde{I}_2$ and $\tilde{I}_3$, being in one-to-one correspondence with transient current $i_2(t)$ components on time interval from 0,00 to 0,04 s according to data in Fig. 1,a. On «before» time interval and on «after» time interval the values of electrical currents can correspond to other hyperphasor diagrams with different coordinate values of hyperphasors of components.

That is why under implementation of data compression algorithms [10] representation of electrical quantities in the form of hyperphasor coordinate values and extra auxiliary data concerning the time of beginning and end of each representation interval is used instead of sequence of instantaneous values.

Calculated evaluations of data compression efficiency for digital oscillograms of currents and voltages using replacement of sequence of instantaneous values by values of hyperphasor coordinates received in [10], are characterized by compression ratio 30 to 100. This helps to unload communication links and size of archives during data storage with the possibility of reverse conversion to digital oscillogram with limited error.

Analyzing quantitative correlations between hyperphasor coordinates in Fig. 1,b one can notice that:

- as frequency of multiple and aliquant harmonics increases the beginnings of hyperphasors of corresponding components is moving upwards from abscissa axis towards higher frequencies. As frequency of subharmonics decreases the beginnings of hyperphasors are approaching abscissa axis. As the limit the beginning of constant and exponent components will be on the abscissa axis when $\omega=0$;

- as damping speed of exponential components increases, i.e. when $T \rightarrow 0$, the beginning of exponentially damped component hyperphasor is moving away from ordinate axis towards left to negative values $-1/T$. As damping speed of exponential components decreases, i.e. when $T \rightarrow \infty$, the beginning of exponentially damped component hyperphasor is moving towards ordinate axis. As the limit if damping is absent ($T=\infty$) the beginning of hyperphasor will be on ordinate axis.

For constant component with concurrent execution of two utmost correlations $\omega=0$ and $T=\infty$ the beginning of hyperphasor is in the only point of origin of complex plane. At the same time representation of constant component on hyperphasor diagram shows the sign and value of constant component.

Thus transient current $i_2(t)$ in Fig. 1,a is represented in Fig. 1,b by three hyperphasors $\tilde{I}_1$, $\tilde{I}_2$ and $\tilde{I}_3$, which by their projections on imaginary axis represent instantaneous values of three components $i_1(t) + i_2(t) + i_3(t)$. The scale of electrical currents is shown in Fig. 1,b.

It should be noticed that projection of vectors to imaginary axis – ordinate axis – according to (1) under representation of sinusoidal electrical quantities in the form of vectors (hyperphasors) is not the only variant. Alternative variant wide used in radio engineering and foreign literature as well as in WAMS is the projection of vectors on real axis – abscissa axis – under representation of cosine electrical quantities in the form of vectors (hyperphasors) [8].

Graphical hyperphasor transformations correspond to the following linear operations:

- addition (subtraction) of complex hyperphasor magnitudes in case of coincidence of frequencies according to parallelogram rule, like usual vectors;
- complex hyperphasor magnitude multiplication by a real number like usual vectors;
- differentiation of hyperphasors by multiplying complex magnitude by complex frequency along with rotating of initial phase by complex frequency angle forward (counter-clockwise). For

undamped sinusoid this angle is $\pi/2$ just like in case of two-dimensional vectors. For an exponent this angle is π (backward direction), while for damped sinusoid it is from π to $\pi/2$;

- integration of hyperphasors by dividing complex magnitude by complex frequency along with rotating of initial phase backwards (clockwise). In this case this angle for an undamped sinusoid is $-\pi/2$, like in case of two-dimensional vectors. For an exponent this angle is $-\pi$ (backward direction), while for damped sinusoid it is from $-\pi$ to $-\pi/2$.

Graphical conversion rules mentioned above form a correspondence principle which consists in match of considered properties of a four-dimensional hyperphasor of a sustained sinusoid and that of a commonly known vector of a sinusoidal quantity. Consequently commonly known vectors of sinusoidal functions are a particular case of four-dimensional hyperphasors.

3 CONCLUSION

Application of hyperphasor diagrams expands possibilities for visual, figurative and informational displaying of currents and voltages in EPS transient modes. Four-dimensional hyperphasors can be used:

- For visualization of electrical parameters of transients [6-8];
- For fault oscillograms analysis [7-9];
- For fast digital oscillogram transmission using hyperphasor data compression and their transmission and compression with a compression ratio from 30 to 100 [9, 10];
- For educational purposes like training of power engineering specialists [4-10].

Hyperphasor measurements are promising also in WAMS, WACS and WAPS development.

It should be noticed that not only transient currents and voltages can be represented in a form of hyperphasor, but also electric power, phase shift angles, mechanical displacements, shifts, pressures and any other non-sinusoidal aperiodic physical quantities described by corresponding class of differential equations solutions being presentable by complex magnitudes with complex frequency. Verification of power system models is possible using coordinate by coordinate comparison of measured and calculated transients.

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