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Method for Calculating Electromagnetic Compatibility Indicators of Nonlinear Consumers of Common DC Bus with PWM

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***Abstract*—Based on the general method of differential equations algebraization, the method for the assessment of DC-circuit THD-analogues for voltage and current is offered. This technique is intended for the mono-bus DC system, i.e. a common DC bus, feeding some nonlinear consumers, and it can be simply generalized to the case of any number of consumers. The expression of the DC-circuit n-order integrated signal harmonics factor as a function of the known similar AC-circuit factor is shown. Furthermore, the coefficients of participation of certain individual nonlinear consumers in the overall distortion of power quality (ripples), namely to the total signal harmonic distortion (the individual relative share contributions of nonlinear loads to the AC component), are considered. The authors perform experimental verification of the proposed calculation method on the PSIM computer model, including the feeding pulse-width power DC-DC converter with an output LC-filter and two current sources of different types. The obtained formulas for electromagnetic compatibility indicators allow predicting the quality of power supply at the design stage for the power supply system with known analytical descriptions of any form of currents at non-linear consumers.**

Keywords*—common DC bus, nonlinear consumers, pulse-width power DC-DC converter, DC-circuit THD analogue, DC-circuit n-order integrated signal harmonics factor, individual load relative share contribution to AC component, method of differential equations algebraization

I. INTRODUCTION

Coordination of the parameters of the electric energy with the parameters of the consumer is a means of providing for electric energy saving, increase in the efficiency of its use, increase of service life of the consumer equipment and improvement of its functional characteristics. Therefore, the conducted emission aspect of electromagnetic compatibility has been and remains of high importance both in power systems and power supply devices. In particular, harmonic emissions, related to nonlinear consumers, should be limited in accordance with the European regulations [1–3].

The issues, related to nonlinear consumers (loads), including their individual impact to the decline in power quality, have been actively discussed in numerous papers throughout the world, see, for example [4–12].

Some new calculation and measurement techniques [13–22] have been offered on the base of the developed authored direct methods of electric energy quality analysis, mostly on the base of the general method of the differential equations algebraization (ADE) [23, 24]. Among other matters, concerning higher harmonics, the analytically-grounded method for definition of the contributions of customers and AC mains in voltage quality change has been proposed and considered in publications of the NSTU research laboratory of conversion systems energy optimisation [24–32].

However, the conducted emission problem of electromagnetic compatibility also takes place in DC power supply. Previously electronic power supply systems used mainly multi-bus solutions. An example is the power supply of industrial computers. Today's innovations often use the distributed power structure, when an intermediate bus is formed from the input power source by lowering the voltage, from which individual consumers are then powered, if necessary, through their DC step-down converters [33]. Thus, there is a problem of providing electromagnetic compatibility of the bus of the common power supply with a set of the nonlinear consumers connected to it.

A developed method for finding the quality of electrical energy in this mono-bus DC system by calculating the DC-circuit THD-similar value of the bus voltage and the DC-circuit THD-similar value of the source current is offered in the paper. The method is one of the specialized methods that are based on the ADE, namely on the direct transformation procedure of differential equations without their solution into algebraic equations with respect to the RMS values of the required non-sinusoidal voltages and currents [23, 24].

The coefficient of participation of the certain individual nonlinear consumer in the overall distortion of power quality, namely to the total signal harmonic distortion (the individual relative share contribution of nonlinear load), is also considered.

II. THEORY

Fig. 1 shows the equivalent circuit of the power supply system with a common bus of the device circuit board.

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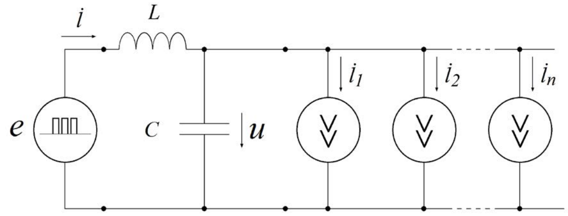

Fig. 1. Equivalent circuit of pulse-width power converter with output LC-filter loaded by nonlinear consumers.

The respective differential equations for the voltage u across the capacitor C (the bus voltage) and the current i in the filter reactor L of the PWM power supply e are as follows:

$$C\frac{d^2u}{dt^2}+\frac{u}{L}=\frac{e}{L}-\frac{di_1}{dt}-\frac{di_2}{dt}, \tag{1}$$

$$L\frac{d^2i}{dt^2}+\frac{i}{C}=\frac{de}{dt}+\frac{i_1}{C}+\frac{i_2}{C}. \tag{2}$$

Here we limit ourselves to the case of two nonlinear consumers, and further the result will be generalized to the case of n consumers.

Equations (1) and (2) are valid not only for instantaneous values of variables, but also for their components, i.e. separately for DC and AC components of all the variables in the equations.

According to the ADE 2 method [23, 24], we algebraize (1) and (2) for AC components by squaring them and averaging over a period.

As a result, we obtain algebraic equations regarding to the AC components RMS values of voltages $e_{\mathrm{AC}}, u_{\mathrm{AC}}$ and currents $i_{1\mathrm{AC}}, i_{2\mathrm{AC}}, i_{\mathrm{AC}}$, i.e. ripple voltages and ripple currents:

$$\begin{gathered}U_{\mathrm{AC}}^2=\frac{I_{1\mathrm{DC}}^2}{\omega_1^2C^2}\overline{K}_{\mathrm{hi1DC}}^2+\frac{I_{2\mathrm{DC}}^2}{\omega_2^2C^2}\overline{K}_{\mathrm{hi2DC}}^2+\frac{2}{C^2}(\bar{i}_{1\mathrm{AC}},\bar{i}_{2\mathrm{AC}})+\\+\frac{E_{\mathrm{DC}}^2}{\omega^4L^2C^2}\overline{\overline{K}}_{\mathrm{heDC}}^2-\frac{2}{LC^2}\left(\left(\bar{i}_{1\mathrm{AC}}+\bar{i}_{2\mathrm{AC}}\right),\bar{\bar{e}}_{\mathrm{AC}}\right)\end{gathered} \tag{3}$$

$$\begin{gathered}I_{\mathrm{AC}}^2=\frac{I_{1\mathrm{DC}}^2}{\omega_1^4L^2C^2}\overline{\overline{K}}_{\mathrm{hi1DC}}^2+\frac{I_{2\mathrm{DC}}^2}{\omega_2^4L^2C^2}\overline{\overline{K}}_{\mathrm{hi2DC}}^2+\\+\frac{2}{L^2C^2}(\bar{\bar{i}}_{1\mathrm{AC}},\bar{\bar{i}}_{2\mathrm{AC}})+\frac{E_{\mathrm{DC}}^2}{\omega^2L^2}\overline{K}_{\mathrm{heDC}}^2+\frac{2}{L^2C}\left(\left(\bar{\bar{i}}_{1\mathrm{AC}}+\bar{\bar{i}}_{2\mathrm{AC}}\right),\bar{e}_{\mathrm{AC}}\right)\end{gathered} \tag{4}$$

Here $\overline{K}_{\mathrm{hi1,2DC}}$, $\overline{\overline{K}}_{\mathrm{hi1,2DC}}$ and $\overline{K}_{\mathrm{heDC}}$, $\overline{\overline{K}}_{\mathrm{heDC}}$ are the DC-circuit first and second order integrated current harmonics factors of consumer currents i_1, i_2 and first and second order integrated voltage harmonics factors of the equivalent EMF e of the power supply voltage, respectively;
the expressions in parentheses are scalar products of the corresponding variables, in particular,

$$(\bar{i}_{1\mathrm{AC}},\bar{i}_{2\mathrm{AC}})=\frac{1}{T}\int_0^T\bar{i}_{1\mathrm{AC}}\bar{i}_{2\mathrm{AC}}dt, \tag{5}$$

$$\left(\left(\bar{i}_{1\mathrm{AC}}+\bar{i}_{2\mathrm{AC}}\right),\bar{\bar{e}}_{\mathrm{AC}}\right)=\frac{1}{T}\int_0^T\left(\bar{i}_{1\mathrm{AC}}+\bar{i}_{2\mathrm{AC}}\right)\bar{\bar{e}}_{\mathrm{AC}}dt; \tag{6}$$

X_{DC} means an average value (DC component) of an exposure x; ω, ω_1 and ω_2 are the circular frequencies of the fundamental harmonics of the change of the PWM-modulated voltage e and the AC components of nonlinear consumers currents i_1 and i_2, respectively; $\bar{x}$ and $\bar{\bar{x}}$ are the variables equal to variable x after single and twice taking of indefinite integral.

For some exposure variable x (specified value) and some arbitrary order n the DC-circuit factor $\overline{K}_{\mathrm{hxDC}}^{(n)}$ is defined as follows:

$$\overline{K}_{\mathrm{hxDC}}^{(n)}=\frac{\overline{X}_{\mathrm{AC}}^{(n)}\cdot\omega_x^n}{X_{\mathrm{DC}}}, \tag{7}$$

where $\overline{X}_{\mathrm{AC}}^{(n)}$ is an RMS value of n times integrated AC component of x, and ω_x is its circular frequency.

The DC-circuit n-order coefficient $\overline{K}_{\mathrm{hxDC}}^{(n)}$ can be expressed by means of the long been known n-order coefficient $\overline{K}_{\mathrm{hx}}^{(n)}$, related to higher harmonics of x in AC circuit [23, 24]:

$$\overline{K}_{\mathrm{hxDC}}^{(n)}=\frac{X_{(1)}}{X_{\mathrm{DC}}}\cdot\sqrt{1+\left(\overline{K}_{\mathrm{hx}}^{(n)}\right)^2}, \tag{8}$$

where $X_{(1)}$ is the fundamental harmonic of x.

The values of the integrated harmonics factor $\overline{K}_{\mathrm{hx}}^{(n)}$ of the four lower order n values (including the zero-order factor, i.e. THD) and some general equations for some typical waveforms are given in [24, 21].

Now the sought indicators of electromagnetic compatibility of the power supply with nonlinear load, namely the DC-circuit THD analogue for the bus voltage (load voltage) and the DC-circuit THD analogue for the power supply current, can be determined analytically:

$$K_{\mathrm{huDC}}=\frac{U_{\mathrm{AC}}}{U_{\mathrm{DC}}},\ K_{\mathrm{hiDC}}=\frac{I_{\mathrm{AC}}}{I_{\mathrm{DC}}}, \tag{9}$$

where the average values of the required variables are calculated in the following way:

$$U_{\mathrm{DC}} = E_{\mathrm{DC}}\,,\; I_{\mathrm{DC}} = I_{1\mathrm{DC}} + I_{2\mathrm{DC}}\,. \tag{10}$$

The coefficients K_{huDC} and K_{hiDC} can be treated as zero-order integrated harmonics factors or general ripple factors, that, in contrast to the conventional ripple factor, take into account not only the harmonics with the highest signal value but also all the other harmonics.

The obtained formulas for the electromagnetic compatibility indicators allow to predict the quality of power supply at the design stage for the power supply system with known analytical descriptions of any form currents of nonlinear consumers.

The method can be simply generalized to the case of any number of nonlinear consumers of the common power bus. For example, in the presence of N consumers represented by the sum of the currents of the current sources in the right part of equation (2), in the algebraization process of this equation the terms corresponding to this sum and to its interaction with the term relating to the supply EMF in the right part of (2) will appear in the right part of the resulting algebraic equation of type (4).

Another way of generalization of the method to the case of any number of nonlinear consumers of the common power bus is related to the modification of the conversion (2) to (4) by combining the currents of all consumers, except the first, into the second current.

And the one more important, declared in introduction, application of the constructed calculation method, can be seen in the obtained formulas (3) and (4). From these formulas we can deduce the coefficients of participation of individual nonlinear consumers in the overall distortion of power quality in the power supply system. For example, to determine the share contribution of the first nonlinear consumer i_1 to the square of the bus voltage AC component (the left part of (3)), we represent the right part of this equation in the form of the sum of its six local terms $U_1 \ldots U_6$:

$$\begin{aligned} U_{\mathrm{AC}}^2 = {} & \frac{I_{1\mathrm{DC}}^2}{\omega_1^2 C^2}\overline{K}_{\mathrm{hi1DC}}^2 + \frac{I_{2\mathrm{DC}}^2}{\omega_2^2 C^2}\overline{K}_{\mathrm{hi2DC}}^2 + \frac{2}{C^2}(\bar{i}_{1\mathrm{AC}}, \bar{i}_{2\mathrm{AC}}) + \\ & + \frac{E_{\mathrm{DC}}^2}{\omega^4 L^2 C^2}\overline{\overline{K}}_{\mathrm{heDC}}^2 - \frac{2}{LC^2}\left(\bar{i}_{1\mathrm{AC}}, \bar{\bar{e}}_{\mathrm{AC}}\right) - \\ & - \frac{2}{LC^2}\left(\bar{i}_{2\mathrm{AC}}, \bar{\bar{e}}_{\mathrm{AC}}\right) = \sum_{k=1}^{6} U_k\,. \end{aligned} \tag{11}$$

Hence, the share contribution $K_U(i_{1\mathrm{AC}})$ of the first nonlinear consumer i_1 to the square of the bus voltage AC component U_{AC}^2 can be defined through the three shares, namely, the share made by this current (share U_1) and the shares of its interactions with the current of the second consumer (share U_3) and with the source voltage (share U_5). In so doing, the fractions of the interactions U_3 and U_5 are taken with the corresponding weight coefficients:

$$K_U(i_{1\mathrm{AC}}) = U_1 + U_3\frac{U_1}{U_1 + U_2} + U_5\frac{U_1}{U_1 + U_4}\,. \tag{12}$$

The same transformation of (4) determines the share contribution of the first nonlinear consumer i_1 to the square of the power supply current AC component I_{AC}^2 in the form

$$K_I(i_{1\mathrm{AC}}) = V_1 + V_3\frac{V_1}{V_1 + V_2} + V_5\frac{V_1}{V_1 + V_4}\,, \tag{13}$$

where the components V_{k} are the corresponding terms of the right side of (4) written for them in a form similar to (11).

The corresponding relative share contributions (the individual coefficients of participation) to the overall DC voltage and current distortions (ripples) can be defined as follows:

$$K_U^{\,*}(i_{1\mathrm{AC}}) = \frac{K_U(i_{1\mathrm{AC}})}{U_{\mathrm{AC}}^2}\,,\; K_I^{\,*}(i_{1\mathrm{AC}}) = \frac{K_I(i_{1\mathrm{AC}})}{I_{\mathrm{AC}}^2}\,. \tag{14}$$

Obviously, for the relative share contributions of the three exposures e, i_1 and i_2 the following equations in similar designations are true:

$$K_U^{\,*}(e_{\mathrm{AC}}) + K_U^{\,*}(i_{1\mathrm{AC}}) + K_U^{\,*}(i_{2\mathrm{AC}}) = 1\,, \tag{15}$$

$$K_I^{\,*}(e_{\mathrm{AC}}) + K_I^{\,*}(i_{1\mathrm{AC}}) + K_I^{\,*}(i_{2\mathrm{AC}}) = 1\,. \tag{16}$$

III. SIMULATION RESULTS

An experimental verification of the proposed calculation method is performed on the PSIM computer model shown in Fig. 2.

The mode with the PWM carrier triangle signal of frequency 5 kHz at the pulse amplitude of 60 V, the duty cycle value of the pulse sequence of 0.8 and the typical supply bus average voltage level of about 48 V, with the filter parameters L = 0.01 H, C = 80 μF and R = 0.02 Ohm, is considered. The current of the first consumer was also set as the PWM-modulated pulse signal of 1 A with the PWM carrier frequency of 5 kHz, the duty cycle value of 0.7 and the phase shift of the carrier triangular signal relative to the carrier signal of the supply pulse EMF by $\pi/2$. The set current of the second consumer contains the variable component of higher up frequency:

$$i_2(t) = 1 + 0.5\sin(2\pi \cdot 10000 \cdot t)\,.$$

The resulting currents and voltages curves of the model of the power supply system with a common bus of the device circuit board are shown in Fig. 3. All the measurements were performed in the time window shown.

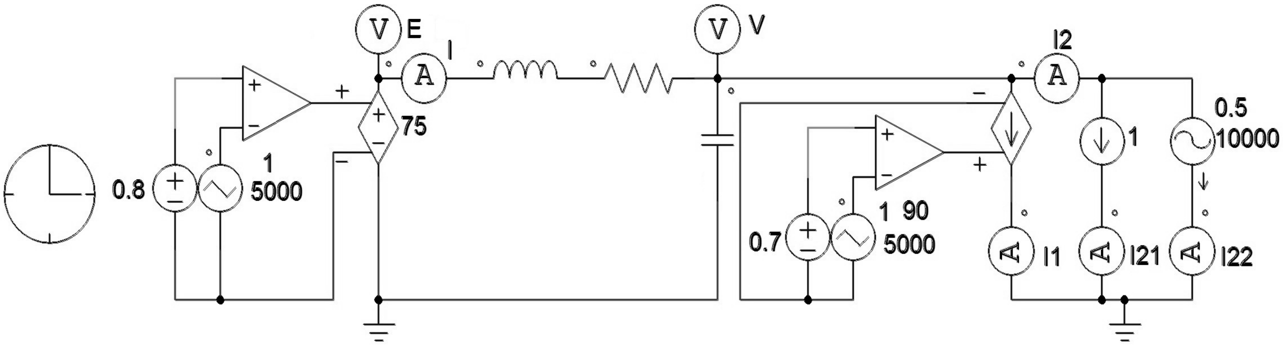

Fig. 2. PSIM computer model of pulse width converter loaded by nonlinear consumers.

At average values $U_{\mathrm{DC}} \approx 48.57$ V, $I_{\mathrm{DC}} \approx 1.76$ A, the following values of the harmonic coefficients of the supply voltage and the current consumed from the pulse-width converter were found:

a) for U_{AC} and I_{AC} values, obtained from direct measurements of the average and RMS values of the model voltage and current, according to (9) $K_{\mathrm{huDC}} \approx 0.003383$, or about 0.34%, $K_{\mathrm{hiDC}} \approx 0.032$, or 3.2%;

b) for U_{AC} and I_{AC} values, obtained by calculation using (3) and (4), through the average values of the exposure quantities e, i_1 and i_2, their harmonic coefficients and the corresponding scalar products, $K_{\mathrm{huDC}} \approx 0.003032$, or about 0.30%, $K_{\mathrm{hiDC}} \approx 0.031$, or 3.1%.

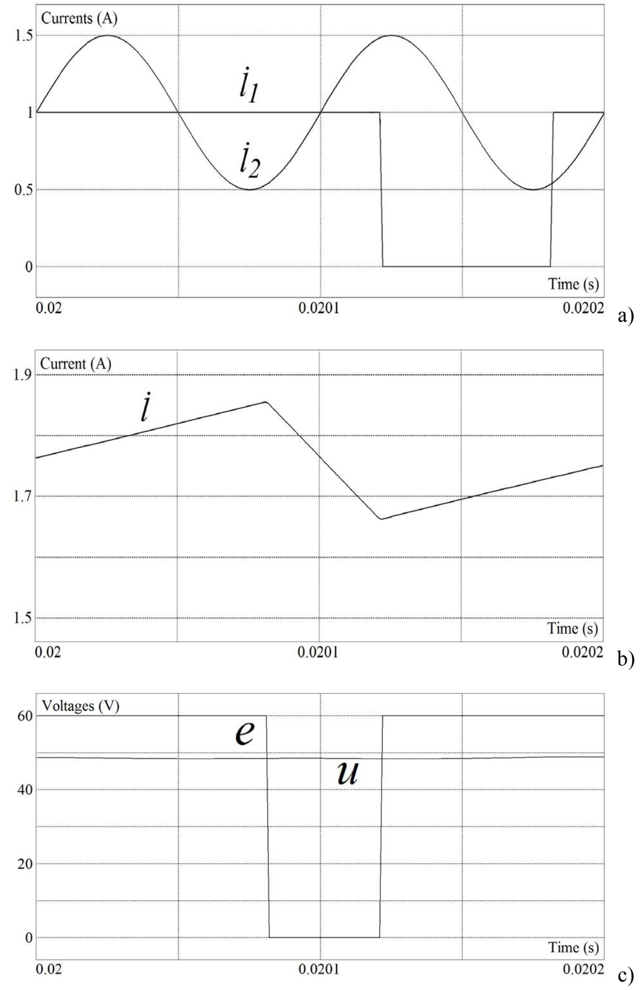

Fig. 3. PSIM-simulated currents and voltages waveforms: a) currents of nonlinear consumers, b) inductive element current consumed from the pulse width converter, c) PWM-modulated voltage at the input of the filter and voltage provided to consumers at the output of the filter.

Accordingly, the deviations of the calculated values from the base values obtained from the measurements (ratio errors) were, respectively, 10.4% for the voltage harmonics coefficient K_{huDC} and 3.1% for the current harmonics coefficient K_{hiDC}. Note that the mode with relatively low distortions is considered, and the formulas (3) and (4) are obtained from (1) and (2) when adopting the first, the roughest level of approximation of the ADE method [24], so such experimental results should be considered more than satisfactory.

The values of the relative share contributions of the exposure variables e, i_1 and i_2 to the voltage u and current i AC components are adduced in Table I.

The Table I data demonstrate for this particular circuit example that the pulse width modulated current i_1 is making the dominant contribution to the decline in voltage u quality, and the pulse width modulated voltage e is making the dominant contribution to the decline in current i quality. It has been to be expected, since the EMF e ripples generate the ripples of the consumed current i, and the current i_1 discharges the capacitance C and distortes the voltage across it.

TABLE I. RELATIVE SHARE CONTRIBUTIONS TO THE AC COMPONENTS

Exposure Variable x_{AC}	**Relative Share Contribution**	
	$K_U^{*}(x_{\mathrm{AC}})$	$K_I^{*}(x_{\mathrm{AC}})$
e_{AC}	0.0183970265	0.9999272311
$i_{1\mathrm{AC}}$	0.8406153563	0.0000722306
$i_{2\mathrm{AC}}$	0.1409876172	0.0000005383

IV. CONCLUSIONS

The assessment method of the DC-circuit THD-analogues for voltage and current is proposed for a mono-bus DC system, i.e. a common DC bus, feeding some nonlinear consumers. It can be simply generalized to the case of any number of the consumers. The expression of the DC-circuit n-order integrated signal harmonics factor as a function of the known similar AC-circuit factor is shown. The obtained formulas allow to predict the quality of power supply at the design stage for the power supply system with known analytical descriptions of any form currents of nonlinear consumers.

The coefficients of participation of the certain individual nonlinear consumers in the total signal harmonic distortion, i.e. the individual relative share contributions of nonlinear loads to the signal AC component (ripples), are suggested.

PSIM computer simulation results proved viability of the offered method and prospects of its use for circuits with multiple harmonic-producing loads.

As in the case of AC circuits, additional studies are required of the conditions under which the effects that reduce the quality of the energy process in DC circuits partially extinguish each other. This can lead to some progress in the development of new techniques for stabilizing the DC supply voltage, especially if it is generated with use of some equipment or methods of power electronics.

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