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2018 IEEE 3rd International Conference on Intelligent Energy and Power Systems (IEPS)

Voltage Harmonic Distortion in Autonomous Electric Power System with an Adjustable Power Line Conditioner

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***Abstract*— An improved analytical method for estimating of voltage harmonic distortions in autonomous electric power system (AEPS) with powerful semiconductor converter (SC) and hybrid adjustable power line conditioner (APLS) had been proposed. APLC consists an uncontrolled resonant filter and PWM controlled reactor compensator. An analysis of piecewise function of voltage in steady state regime of the system is fulfilled. The analysis is taking into account the influence of its elements and their parameters. Analytical expressions for the voltage harmonic distortion factor were obtained taking into account the entire voltage harmonics spectrum in a closed finite form. The comparison of analytical calculations and computer simulation results had been executed.**

Keywords*— *adjustable power line conditioner (APLC), inactive components of the total power, reactive power (RP), power quality (PQ), voltage and current harmonic distortion factors, pulse-width modulation (PWM), controlled reactor compensator (CRC)

I. Introduction

A. General Terms and Definitions

The resulting distorted form of grid voltage from higher harmonic emissions and the consumption of reactive power (RP) on the main harmonic is accompanied by the operation of powerful installations with semiconductor converters (SC). To reduce these negative effects and to ensure the conditions of electromagnetic compatibility active and hybrid adjustable power line conditioners (APLC) are used [1,2,3,4]. The safety of the operation of modern seagoing vessels and structures with powerful SC depends on the successful solution of the actual tasks of APLC improvement and methods of assessing their effectiveness. Some autonomous electric power systems (AEPS) of these objects contain frequency converters according to the scheme "controlled rectifier – load-driven current inverter". Rowing and technological synchronous motors with a total capacity of tens of MW are such load.

Total harmonic distortion (THD) factor of voltage is one of the main conditions of the electricity quality deterioration. Sometimes it results in an AEPS accident. Its integral index is determined by the distortion coefficient of sinusoidality, which is normalized by territorial and international standards [4],

$$K_U = \left(\sqrt{\sum_{\nu=2}^{\nu_{max}} U_{S(\nu)}^2} \,/\, U_{S(1)} \right) \cdot 100\%, \qquad (1)$$

where $U_{S(1)}$, $U_{S(\nu)}$ is RMS primary and ν-th harmonic voltage respectively, ν_{max} is the highest harmonic order that is taken into account. The values of ν_{max} adopted in different normative documents differ significantly. For example, [5] and [6] take into account 40 and 200 in respectively.

To prevent unacceptable errors in determining K_U, the following factors should be taken into account [7]:

– mutual influence of power sources, SC, APLC on real electromagnetic processes in AEPS at finite (non-zero) switching angles;

– commensurability voltage harmonics in a very wide range of frequencies and therefore need to consider the whole range of harmonics.

B. Research Tasks and Objectives

The purpose of this work is to obtain analytical expressions of determination of K_U in a finite closed form by analysis of electromagnetic processes in AEPS with SC and APLC; comparison of analytical calculations with the results of computer simulation.

II. Definition of Total Harmonic Distortion Factor

The single-line equivalent scheme of AEPS with SC and hybrid APLC for phase A is depicted in Fig. 1. The generator (power grid) is represented by a sinusoidal EMF $e_A = E_m \sin\Theta$ and a short-circuit resistance X_S, SC is the source of the periodic nonsinusoidal current i_{SCA} of the primary winding and the short-circuit resistance X_{SC} of transformer. The hybrid APLC includes a resonant LC filter (RF) (X_{C0}, X_{L0}) and a controlled reactor compensator (CRC), which contains a reactor with impedance X_{LK} and a dual-operational semiconductor switch keys with pulse-width modulation (PWM). CRC is an adjustable equivalent

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impedance $X_{RC} = X_{LK} / s^2$ at high switching frequency ($f_s = 10 \ldots 20$ kHz), where s is duty ratio of PWM. Simultaneously RF is an impedance filter for CRC with PWM by connecting the CRC to the point of connection of the inductance and capacitance of RF [8].

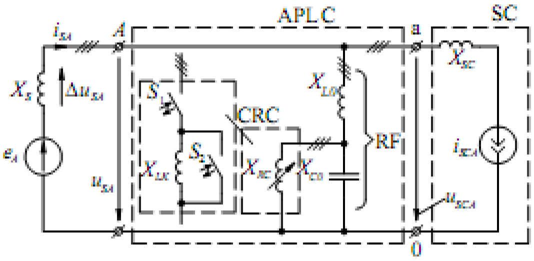

Fig. 1. The single-line equivalent scheme of autonomous AEPS with SC and APLC

The setting of frequency order of RF $\nu_0 = \sqrt{X_{C0} / X_{L0}} \leq m - 1$ (m is pulse of SC). The frequency response characteristic of the system relative to the nodes a and 0 has a zero of order $\xi = \sqrt{X_{C0}(X_{L0} + X_{RC}) / (X_{L0} \cdot X_{RC})}$ and a pole of order $\mu = \sqrt{X_{C0}(X_S + X_{L0} + X_{RC}) / ((X_S + X_{L0}) X_{RC})}$.

If SC is made on a three-phase bridge circuit with single type transformer windings the current shape i_{SCA} can be considered as blocks of equal trapezoid (Fig. 2). The bases $2\pi/3 \pm \gamma$ and height $I_{dSC} = I_d / k_T$ of trapezoid (I_d is rectified current, k_T is transformation ratio, α and γ is control angle and switching angle).

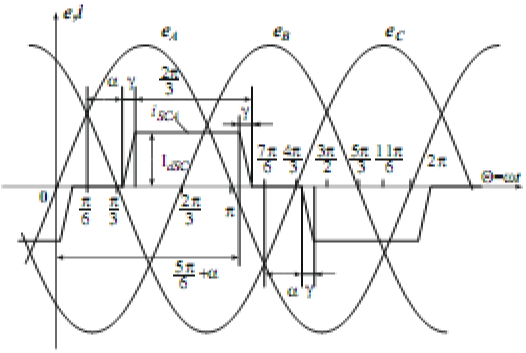

Fig. 2. Diagram of instantaneous values of the generator phase voltages and load current i_{SCA}

The assumption of the linear nature of switching current does not cause significant errors and allows to apply the operator method of separate components to determine the instantaneous value of the grid voltage u_{SA} considering current i_{SCA} as the known perturbation [7]. Based on the principle of imposing u_{SA} is defined as the difference between two components. The first (sinusoidal) is the source of EMF e_A and the second (distorting) is the source of current Δu_{SCA}

$$u_{SA} = K_E E_m \sin\Theta - \Delta u_{SA}, \tag{2}$$

where $K_E = X_{L0}(\xi^2 + 1) / ((X_{L0} + X_S)(\mu^2 + 1))$.

In steady state the value Δu_{SA} on each N continuous interval of current i_{SCA} is determined by the method of separate components [9]

$$\Delta u_{SA}^{(N)} = \sum_{p=\pm\mu i} \mathrm{Res}\left[Z_{a0}(p) I_{SCAan}^{(N)}(p) e^{pt}\right] - \\ - \sum_{p=} \mathrm{Res}\left[Z_{a0}(p) I_{SCAT}^{(N)}(p) e^{pt}\right], \tag{3}$$

where $I_{SCAan}^{(N)}(p)$, $I_{SCAT}^{(N)}(p)$ is operator image of the current i_{SCA} in this interval as an analytic and as a periodic function, respectively; $Z_{a0}(p)$ is operator resistance of the system defined through the inductance and capacity of its elements relative to the nodes a and 0:

$$Z_{a0}(p) = \frac{pL_S\left[p^2 L_0 C_0 L_{RC} + (L_0 + L_{RC})\right]}{p^2 C_0 L_{RC}(L_0 + L_S) + (L_0 + L_S + L_{RC})}. \tag{4}$$

The first component of (3) is the sum of residues at all poles of both functions $I_{SCAan}^{(N)}(p)$ and $Z_{a0}(p)$. Only the poles of function $Z_{a0}(p)$ take into account the residuals of the second component. The operator images of current i_{SCA} is given in Table 1. There are the beginning of the count coincides with the beginning of each interval. Expressions for the instantaneous values of Δu_{SA} on the intervals of continuity in accordance with (3) are presented in Table 2.

Following designations is accepted:

$$a = (X_{L0} + X_{RC}) / (X_S + X_{L0} + X_{RC}); \; M = 1 - \mu^2 / \xi^2;$$

$$N_1 = \sin(\mu\gamma/2) \cdot \sin(\mu\pi/3) / \cos(\mu\pi/2);$$

$$N_2 = \sin(\mu\gamma/2) \cdot \cos(\mu\pi/6) / \cos(\mu\pi/2).$$

At the switching interval $\pi/6 + \alpha \leq \Theta \leq \pi/6 + \alpha + \gamma$ the ratio for the phases A and C is executed

$$u_{SA} - u_{SB} = 2X_{SC}\, di_{SCA} / d\Theta. \tag{5}$$

The equation for determining the switching angle γ is obtained by integration (5):

$$\sqrt{3} K_E E_m \sin\left(\alpha + \frac{\gamma}{2}\right) \sin\frac{\gamma}{2} + \frac{a X_S I_{dSC}}{\mu\gamma} M \sin\mu\gamma = \\ = (X_{SC} + a X_S) I_{dSC}. \tag{6}$$

TABLE I. THE OPERATOR IMAGES OF CURRENT i_{SCA}

Interval	Θ	$I^{(N)}_{SCAm}(p)$	$I^{(N)}_{SCAT}(p)$
I	$\frac{\pi}{6}+\alpha \le \Theta \le \frac{\pi}{6}+\alpha+\gamma$	$\frac{I_{dSC}\omega}{\gamma p^2}$	$\frac{I_{dSC}\omega}{\gamma p^2}\left(1-e^{-\gamma\frac{p}{\omega}}\right)\left(1-e^{-\frac{2\pi p}{3\omega}}\right)/\left(1+e^{-p\frac{\pi}{\omega}}\right)$
II	$\frac{\pi}{6}+\alpha+\gamma \le \Theta \le \frac{5\pi}{6}+\alpha$	$\frac{I_{dSC}}{p}$	$\frac{I_{dSC}}{p}-\frac{I_{dSC}\omega}{\gamma p^2}\left(e^{\gamma\frac{p}{\omega}}-1\right)\left(e^{-\frac{\pi p}{3\omega}}+1\right)e^{-\frac{2\pi p}{3\omega}}/\left(1+e^{-p\frac{\pi}{\omega}}\right)$
III	$\frac{5\pi}{6}+\alpha \le \Theta \le \frac{5\pi}{6}+\alpha+\gamma$	$\frac{I_{dSC}}{p}-\frac{I_{dSC}\omega}{\gamma p^2}$	$\frac{I_{dSC}}{p}+\frac{I_{dSC}\omega}{\gamma p^2}\left(e^{-\gamma\frac{p}{\omega}}-1\right)\left(e^{-\frac{\pi p}{3\omega}}+1\right)/\left(1+e^{-p\frac{\pi}{\omega}}\right)$
IV	$\frac{5\pi}{6}+\alpha+\gamma \le \Theta \le \frac{7\pi}{6}+\alpha$	0	$\frac{I_{dSC}\omega}{\gamma p^2}\left(1-e^{\gamma\frac{p}{\omega}}\right)\left(1-e^{-\frac{2\pi p}{3\omega}}\right)e^{-\frac{\pi p}{3\omega}}/\left(1+e^{-p\frac{\pi}{\omega}}\right)$

TABLE II. THE INSTANTANEOUS VALUES OF Δu_{SA}

Interval	Θ	Δu_{SA}
I	$\frac{\pi}{6}+\alpha \le \Theta \le \frac{\pi}{6}+\alpha+\gamma$	$\frac{I_{dSC}X_S}{\gamma}a\left\{1-M\left[\cos\mu(\Theta-\alpha-\frac{\pi}{6})-2N_1\cos\mu(\Theta-\alpha-\frac{\gamma}{2})\right]\right\}$
II	$\frac{\pi}{6}+\alpha+\gamma \le \Theta \le \frac{5\pi}{6}+\alpha$	$\frac{2I_{dSC}X_S}{\gamma}aMN_2\sin\mu\left(\Theta-\alpha-\frac{\gamma}{2}-\frac{\pi}{2}\right)$
III	$\frac{5\pi}{6}+\alpha \le \Theta \le \frac{5\pi}{6}+\alpha+\gamma$	$-\frac{I_{dSC}X_S}{\gamma}a\left\{1-M\left[\cos\mu(\Theta-\alpha-\frac{5\pi}{6})-2N_2\sin\mu\left(\Theta-\alpha-\frac{\gamma}{2}-\frac{\pi}{2}\right)\right]\right\}$
IV	$\frac{5\pi}{6}+\alpha+\gamma \le \Theta \le \frac{7\pi}{6}+\alpha$	$\frac{2I_{dSC}X_S}{\gamma}aMN_1\cos\mu(\Theta-\alpha-\frac{\gamma}{2}-\pi)$

The angle γ can't be found explicitly directly from the transcendental equation (6).

Taking into account the smallness of angle γ in real modes ($\gamma \le 20^\circ$) and replacing the sinus and cosine functions by the first definition terms of the corresponding power series the equation (6) is reduced to square equation. The solution of (6) is

$$\gamma=\left(-B+\sqrt{B^2-4AC}\right)/2A, \quad (7)$$

where $A=\left(\sqrt{3}/4\right)K_E E_m\cos\alpha$; $B=\left(\sqrt{3}/2\right)K_E E_m\sin\alpha$; $C=-\left(X_{SC}+aX_S\mu^2/\xi^2\right)I_{dSC}$.

Expression (1) can be depicted in a finite form based on the Parseval's equality. It allows to determine the THD of voltage taking into account the entire harmonic spectrum:

$$K_U=\left(\sqrt{\Delta U_S^2-\Delta U_{S(1)}^2}/U_{S(1)}\right)\cdot 100\%, \quad (8)$$

where ΔU_S is full RMS value of the fundamental harmonic and $\Delta U_{S(1)}$ is the RMS value of the fundamental harmonic of the phase voltage distorting component Δu_S.

As a piecewise-continuous function in half of the period of component Δu_{SA} is defined for phase A (Table 2), then

$$\Delta U_S^2=\frac{1}{\pi}\int_{\pi/6+\alpha}^{7\pi/6+\alpha}\Delta u_{SA}^2 d\Theta. \quad (9)$$

Taking into account Table 2 expression (9) is reduced to

$$\Delta U_S^2=\frac{X_S^2 I_{dSC}^2}{\pi\gamma^2}a^2\left[2\gamma-4\frac{M}{\mu}\sin\mu\gamma+M^2\left[\gamma+\frac{1}{2\mu}\sin 2\mu\gamma-\right.\right.$$

$$-2N_2\left(\gamma-\frac{1}{\mu}\sin\mu\gamma\right)\sin\mu\frac{\gamma}{2}+2\left[\frac{\pi}{3}\left(N_1^2+2N_2^2\right)+\right.$$

$$\left.+\frac{1}{\mu}\cos\mu\gamma\left(N_1^2\sin\mu\frac{\pi}{3}-N_2^2\sin\frac{2\pi}{3}\right)\right]\Bigg]\Bigg]. \qquad (10)$$

The RMS values of the grid voltage main harmonics and its distorting component are determined as follows

$$U_{S(1)}=K_E\left[\left[E-X_S I_{SC(1)}\sin\left(\alpha+\frac{\gamma}{2}\right)\right]^2+\right.$$

$$\left.+\left[X_S I_{SC(1)}\cos\left(\alpha+\frac{\gamma}{2}\right)\right]^2\right]^{1/2}, \qquad (11)$$

$$\Delta U_{S(1)}=K_E X_S I_{SC(1)}, \qquad (12)$$

where $I_{SC(1)}=\left(\sqrt{6}/\pi\right)I_{dSC}\sin(\gamma/2)/(\gamma/2)$ is the RMS value of the main harmonic of SC consumed current; $E=E_m/\sqrt{2}$ is the RMS value of the main harmonic of source EMF.

Expressions (2-12) are also valid for AEPS without APLC. In this case follow parameters is: $X_{L0}\to\infty$; $X_{C0}\to\infty$; $X_{RC}\to\infty$ and in the above expressions $a=1$, $K_E=1$, $\mu/\xi=1$, $M=0$.

III. Analitycal Calculation and Simulation Modelling. Selecting the System Parameters

The values of K_U are found by described analytical calculations method and by simulation in MATLAB (Simulink). Its are compared in Table. 3. AEPS and APLC parameters is: $S_S=1\,\text{MVA}$, $U_s=220\,\text{V}$, $X_s=0,02$ Ohm, $X_{SC}=0,01$ Ohm, $I_{dnom}=1400\,\text{A}$, $U_{dnom}=440\,\text{V}$, $k_T=1$, $X_{C0}=0,227$ Ohm, $X_{L0}=9,07\cdot10^{-3}$ Ohm, $X_{LK}=0,218$ Ohm, $f_k=19800\,\text{Hz}$.

Two modes of SC were investigated:

Mode 1: $\alpha=30^\circ$, $I_{dSC}=1400\,\text{A}$;

Mode 2: $\alpha=60^\circ$, $I_{dSC}=1400\,\text{A}$

TABLE III. THD factor K_U in APS

Mode	K_U, %			
	APS without APLC		**APS with APLC**	
	Analytical calculation	**Modeling**	**Analytical calculation**	**Modeling**
1	16,93	17,84	5,97	5,93
2	22,56	23,47	8,61	8,68

The graphs of voltage u_S and current i_S are obtained by mode 2 in the system with the absence and with the presence of APLC. The comparison of the results of calculation the graph of u_S that is built by simulation modelling and analytical calculations in fig. 3 are given.

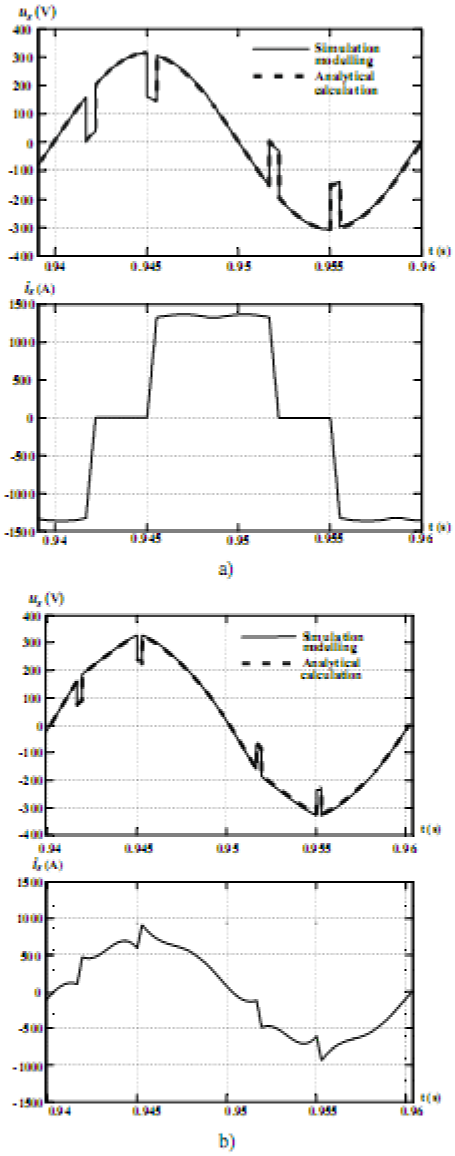

Fig. 3. The diagram of voltage u_S and current i_S in AEPS without (a) and with (b) APLC

The calculation of K_U by commonly used simplified technique based on the assumption of instant switching [10] leads to almost twice the overestimation of the result compared to the real value. The error is caused by the assumption that the voltage harmonics are determined by expression

$$U_{S(\nu)} = \nu^{-1}\left[(\nu X_S)^{-1} + \left[\nu X_{L0} - \left[(\nu X_{RC})^{-1} - \right.\right.\right.$$

$$\left.\left.\left. - \nu / X_{C0}\right]^{-1}\right]^{-1}\right]^{-1} \cdot \sqrt{6} I_{dSC} / \pi \tag{13}$$

and it form a divergent series.

The above results shows that the proposed analytical method is sufficiently accurate and general. It is very convenient for solving the problems of estimating the power quality indicators (voltage distortions) depending on the circuit and mode parameters of the AEPS with SC and APLC.

The choice of APLC parameters is performed under two conditions. The first is the compensation of RP Q_{SC} and the second is the necessary limitation of THD voltage factor K_U. The condition of full RP compensation for any mode of the system is

$$Q_{RF\max} = Q_{RC\max} = Q_{SC\max},$$

where $Q_{SC\max}$ is the maximum RP of SC; $Q_{RF\max}$ and $Q_{RC\max}$ is required maximum capacities of the RF and CRC; $N \geq 1$ is the required multiplicity of the compensation reserve.

Full RP compensation is already possible at $N = 1$. Sometimes an increase in this value is needed to achieve the required limit of THD K_U.

If in the whole range of regulation DC current is equal to nominal ($I_{dSC} = I_{dSCnom}$), then

$$Q_{SC\max} = I_{dSCnom}\sqrt{U_{d0}^2 - U_{d\min}^2} \tag{14}$$

where U_{d0} and $U_{d\min}$ is the maximum and minimum value of the rectified voltage at the control angles $\alpha_{\min} = 0$ and $\alpha_{\max}$ respectively.

Thus, the parameters of the elements of the RF can be found in the expression

$$X_{L0} = 3U_S^2 / \left((\nu_0^2 - 1) N Q_{SC\max}\right), \tag{15}$$

$$X_{C0} = X_{L0}\nu_0^2. \tag{16}$$

The required inductance of CRC

$$X_{LK} = 3s^2 U_S^2 / N Q_{SC\max} \tag{17}$$

if duty ratio of PWM $s = 1$.

The results of voltage distortion studies in Table. 3 and Fig. 3 corresponds to the APLC parameters according to the multiplicity of the compensation reserve $N = 1$.

Fig. 4 constructed dependences K_U from N for regimes 1 and 2. Dependences indicate an effective reduction of I with increasing N.

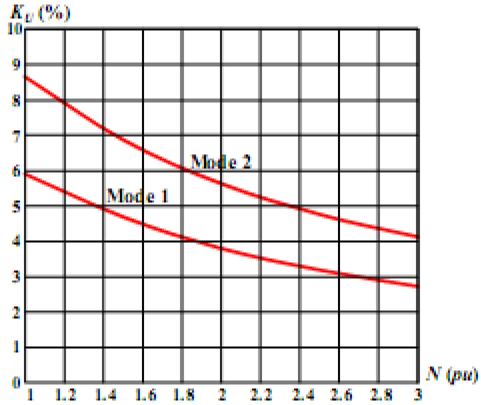

Fig. 4. The dependences voltage THD K_U from N in the AEPS with APLC

The graphs show that if the APLC has a 3-fold compensation reserve of reactive power, then Ku is reduced more than twice.

The proposed analytical method allows estimating the effect of the technological spread of the RF parameters on the voltage THD.

The surfaces that illustrates the dependence of K_U on the parameters of the resonant branch (C_0, L_{L0}), when the deviation of these parameters from exactly calculated values in the range of ±10% is shown in Fig. 5 and Fig. 6. The surfaces correspond to the considered example of the system with APLC in mode 1 and mode 2 in respectively.

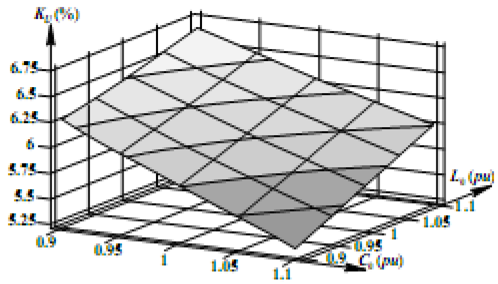

Fig. 5. The dependence of K_U on the parameters L_0 and C_0 of the resonant filter in mode 1

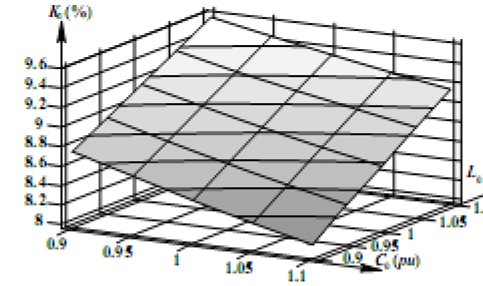

Fig. 6. The dependence of K_U on the parameters L_0 and C_0 of the resonant filter in mode 2

The form of the surfaces is explained as follows. Deviations in the parameters of RF elements (L_0 and C_0) cause changes in the frequency response characteristic of the system's resistance. Its is the zero position and the angle of asymptote of this characteristic, which in turn affect the grid voltage distortions.

At constant values of C_0 and change the values of L_0 the main influence is exerted by the position of the asymptote. If L_0 decreases the angular coefficient decreases also. Therefore, all harmonics and the total harmonic distortion factor decreases. The opposite deviation of L_0 causes an increase in K_U.

If L_0 and the position of the asymptote is unchanged, the shift in the zero of the frequency response characteristic of the system's resistance has a determining effect on the harmonic distortion. If C_0 increases the order of the zero frequency shifts to the left with respect to the order $\nu_0 = m-1$ of the lowest-frequency of the higher harmonics (in our case $\nu_0 = 5$). With the opposite deviation of C_0 the zero shift occurs to the right. In both cases, a non-zero harmonic of the order of ν_0 appears in the spectrum. However, in the first case, the value of this harmonic is somewhat less than in the second. Correspondingly, K_U decreases with increasing C_0 and increases with decreasing C_0.

Conclusions

This paper explores the features of the change in total harmonic distortion (THD) factor of voltage in the autonomous electric power system (AEPS) with powerful semiconductor converters (SC) and hybrid adjustable power line conditioner (APLC). The work allows drawing the following conclusions:

1. Based on the Laplace transform the analysis of electromagnetic processes in AEPS with SC and APLC is performed. The analysis takes into account the mutual influence of the system elements. Expressions for the harmonic distortion coefficient of voltage in the final form are obtained taking into account the entire spectrum of harmonics.

2. The proposed method is sufficiently general and acceptable for AEPS with APLC and without APLC. The use of the method also allows further theoretical analysis of the voltage quality when the parameters of the scheme and operating conditions of the system is changed.

3. Testing on the MATLAB model confirms the reliability of the obtained analytical expressions and the efficiency of APLC. K_U is reduced by almost three times with full compensation of the reactive component of the current K_U.

4. A significant decrease in K_U can be achieved by increasing the reactive power of the APLC relative to its sufficient value.

5. The changes in K_U due to the permissible technological dispersion of the RF parameters in the APLC structure is well correlated with this spread and does not exceed $\pm 10\%$. The smallest value of K_U reaches at simultaneous maximum deviations L_0 in the decreasing direction and C_0 in the increasing direction. The largest value of K_U reaches in opposite deviations of these parameters.

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