Comparison of Three-Phase Rectifiers with Improved EMC with the Mains

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Abstract – The appearance of new standards on quality of electric energy in the West and in Russia has demanded new technical decisions for power converters. In this report results of the comparative analysis of a number of non-classical (active) rectifiers of a three-phase voltage are submitted at which the input power factor is approximately equal to unity.

I. INTRODUCTION

Stricter standards on quality of electrical energy (Std IEEE-519 1992, Std IEC 1000-3-6 1996) became valid in the West during last decade. This sharply has strengthened the interest into the development of rectifiers of three-phase current with improved electromagnetic compatibility to the supply network. There were some survey clauses [1-3] where - basically at a qualitative level - the analysis of non-classical circuits of rectifiers having entrance factor of capacity about equal unity will be carried out.

In Russia, 5-10 years later new GOST (13109-97 with 01.01.2000г. and 51317 with 01.07.2002г.) were accepted. Therefore, the wide interest on such rectifiers only begins to be shown [4-6] in Russia. In the report, the results of research are submitted for a line perspective not classical respectively active (as this name appears in the West) three-phase rectifiers with improved electromagnetic compatibility with the mains. The analytical expressions for the basic power characteristics of these circuits are obtained by direct methods of the analysis [7] and are checked by mathematical modeling in the program Parus-Pargraph.

The expressions for the basic static characteristics of the selected circuits of three-phase rectifiers are given in Table 1 The symmetry of parameters of phases and control (switching functions SF of phase voltages and currents of the bridge circuit f_a, f_b and f_c) is considered. The circuits of rectifiers under consideration are divided into two classes. There is a class of the circuits with the soft idealized external characteristic (EC), with similar characteristics of a current source (Table 2), and there is a class with rigid idealized EC, with similar characteristics of a voltage source (Table 3).

II. DESIGNATIONS

The results are submitted in relative sizes (are marked by an asterisk). As a basis, the following sizes are accepted: $Ub=E$ - effective value of phase emf, $Rb=\omega L$, $Ib=Ub/Rb$. Phase SF of the circuits are given in parameter of loading - voltage or current (see SF in the Tables 2 and 3).

For absolute sizes the following designations are accepted: u_0, i_0, and U_0, I_0, - accordingly, instant and average values of output voltage and current; i_{Ld}, I_{Ld} and u_{Cd1}, U_{Cd1} - instant and average values of a current and voltage reactive elements in the appropriate circuits; ω - circular frequency; I_h and $I_{(1)}$ -effective values of high harmonics and basic harmonic of an input current of a phase (i_a, i_b and i_c), is received by ADE method for $N=1$ [7].

For control and other parameters concerning to SF, the following designations are entered: $F_{(1)}$ and $\Psi_{f(1)}$ - parameters of the basic harmonic $f_{a(1)} = \sqrt{2}F_{(1)}\,sin(\omega t + \psi_{f(1)})$ of SF f_a; $\bar{K}_{hf}^{(q)}$ - integrated factor of harmonics (IFH) about q-order of SF f_a $\bar{K}_{hf}^{(q)} = \frac{\bar{F}_{(h)}^{(q)}}{F_{(1)}}\omega^q = \sqrt{\sum_{k=2}^{\infty}\left(\frac{F_{(k)}}{F_{(1)}k^q}\right)^2}$. (Here $\bar{F}_{(h)}^{(q)}$ - EV of integral q-order from the high harmonics (HH) $f_{(h)}$ SF f_a, $F_{(k)}$ -EV of a k- harmonic of last). Factor of harmonics K_{hf} corresponds $q = 0$.

III. ANALYSIS

The value of $F_{(1)}$, describing PWM depth, and the values $\Psi_{f(1)}$ and $\bar{K}_{hf}^{(q)}$ also depend on a defined PWM method and, just as average value F_T of SF of a key T in the appropriate circuits, are assumed being given. The tables and formulas can be used for a choice of one of the considered circuits and parameters of its elements depending on a required range of regulation of a voltage, rigidity EC (characterized by R_E^* value) and quality of energy on an input and an output of the rectifier.

TABLE 1
THE BASIC STATIC CHARACTERISTICS OF TWO CLASSES OF CIRCUITS OF THREE-PHASE RECTIFIERS

Class of rectifier circuit Characteristics		Circuits with the soft idealized external characteristic	Circuits with the rigid idealized external characteristic
Output voltage U_o^* as R_o^* function under $R=0$		$I_o^* R_o^* = -\dfrac{3F_{(1)}^* \sin\psi_{f(1)}}{1+L_1^*-n_1^2} R_o^*$	$\dfrac{3F_{(1)}^* \cos\psi_{f(1)}}{\left(1-n_0^2\right)\left(1+R_{LT}^*/R_o^*\right)}$
Output voltage as R_o^* function: $U_o^* = 3F_{(1)}^* R_o^* \dfrac{A}{B}$, $R \neq 0$	A	$\left(1-n_1^2\right)R^* \cos\psi_{f(1)} - \left(1+L_1^*-n_1^2\right)\sin\psi_{f(1)}$	$\left(1-n_0^2\right)\cos\psi_{f(1)} - R^* n_0^2 \sin\psi_{f(1)}$
	B	$3\left(F_{(1)}^*\right)^2 R^* R_o^* + \left[\left(1-n_1^2\right)R^*\right]^2 + \left(1+L_1^*-n_1^2\right)^2$	$3\left(F_{(1)}^*\right)^2 R^* + \left[\left(R^* n_0^2\right)^2 + \left(1-n_0^2\right)^2\right]\left(R_o^* + R_{LT}^*\right)$
Output voltage as I_o^* function: $U_o^* = E_o^* - R_E^* I_o^*$, $R \neq 0$	E_o^*	$\dfrac{A}{F_{(1)}^* R^*}$	$\dfrac{3F_{(1)}^* A}{\left(R^* n_0^2\right)^2 + \left(1-n_0^2\right)^2}$
	R_E^*	$\dfrac{\left[\left(1-n_1^2\right)R^*\right]^2 + \left(1+L_1^*-n_1^2\right)^2}{3R^*\left(F_{(1)}^*\right)^2}$	$\dfrac{3\left(F_{(1)}^*\right)^2 R^*}{\left(R^* n_0^2\right)^2 + \left(1-n_0^2\right)^2} + R_{LT}^*$
Input current THD $K_{hI} = \dfrac{I_{(h)}^*}{I_{(1)}^*} = \dfrac{B}{\sqrt{D^2+G^2}} I_{(h)}^*$	$I_{(h)}^*$	$k_n \bar{K}_{hf}^{(q)} F_{(1)}^* U_o^*$	$\dfrac{1}{n_0^2} \bar{K}_{hf}^{(2)} F_{(1)}^* I_o^*$
	D	$3\left(F_{(1)}^*\right)^2 \sin^2\psi_{f(1)} R_o^* + \left(1-n_1^2\right)^2 R^*$	$3\left(F_{(1)}^*\right)^2 \cos^2\psi_{f(1)} + R^* n_0^4\left(R_o^* + R_{LT}^*\right)$
	G	$\dfrac{3}{2}\left(F_{(1)}^*\right)^2 \sin 2\psi_{f(1)} R_o^* + \left(1-n_1^2\right)\left(1+L_1^*-n_1^2\right)$	$\dfrac{3}{2}\left(F_{(1)}^*\right)^2 \sin 2\psi_{f(1)} + n_0^2\left(1-n_0^2\right)\left(R_o^* + R_{LT}^*\right)$
Displacement factor $\cos\varphi_{(1)}$ and power factor χ		$\cos\varphi_{(1)} = \left[1+\left(\dfrac{G}{D}\right)^2\right]^{-\frac{1}{2}}$	$\chi = \dfrac{D}{\sqrt{D^2+G^2+\left(BI_{(h)}^*\right)^2}}$
Limitation on the unity displacement factor ($\cos\varphi_{(1)} = 1$) mode	R_o^*	$\geq \dfrac{2}{3}\left\|\left(1-n_1^2\right)\left(1+L_1^*-n_1^2\right)\right\| \dfrac{1}{\left(F_{(1)}^*\right)^2}$	$\leq \dfrac{3}{2}\dfrac{\left(F_{(1)}^*\right)^2}{n_0^2\left\|\left(1-n_0^2\right)\right\|} - R_{LT}^*$
	I_o^*	$\leq \dfrac{3AF_{(1)}^*}{\left(R^*\left\|1-n_1^2\right\| + \left\|1+L_1^*-n_1^2\right\|\right)^2}$	$\geq \dfrac{A}{F_{(1)}^*}\left[R^* + \dfrac{\left(R^* n_0^2\right)^2 + \left(1-n_0^2\right)^2}{2n_0^2\left\|1-n_0^2\right\|}\right]^{-1}$
Values, optimized in accordance with the condition of $\cos\varphi_{(1)} = 1$ ($G=0$)	$F_{(1)}^*$	$\sqrt{-\dfrac{2}{3}\left(1-n_1^2\right)\left(1+L_1^*-n_1^2\right)\dfrac{1}{\sin 2\psi_{f(1)}}\dfrac{1}{R_o^*}}$	$\sqrt{-\dfrac{2}{3}n_0^2\left(1-n_0^2\right)\dfrac{1}{\sin 2\psi_{f(1)}}\left(R_o^* + R_{LT}^*\right)}$
	$\psi_{f(1)}$ from $[-\pi,\pi]$	$-H$, $-\pi/2+H$ under $n_1 < 1$, $-\pi/2+H$, $-\pi-H$ under $1 < n_1 < \sqrt{1+L_1^*}$, $\pi/2+H$, $\pi-H$ under $n_1 > \sqrt{1+L_1^*}$, where $H = \dfrac{1}{2}\arcsin\left(\dfrac{2}{3}\left(1-n_1^2\right)\left(1+L_1^*-n_1^2\right)\dfrac{1}{\left(F_{(1)}^*\right)^2}\dfrac{1}{R_o^*}\right)$	$-H$, $-\pi/2+H$ under $n_0 < 1$, $-\pi/2+H$, $-\pi-H$ under $n_0 > 1$, where $H = \dfrac{1}{2}\arcsin\left(\dfrac{2}{3}n_0^2\left(1-n_0^2\right)\dfrac{1}{\left(F_{(1)}^*\right)^2}\left(R_o^* + R_{LT}^*\right)\right)$

A. Circuits with the Soft Idealized External Characteristic

The given circuits allow to operate as soft EC (large values of a voltage without load and of internal resistance of an equivalent source), and rigid EC, by changing the value of adjustable parameter $F_{(1)}^*$.

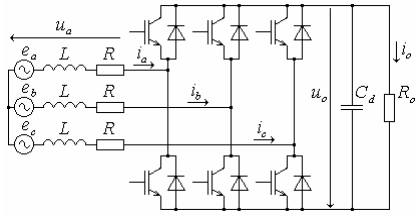
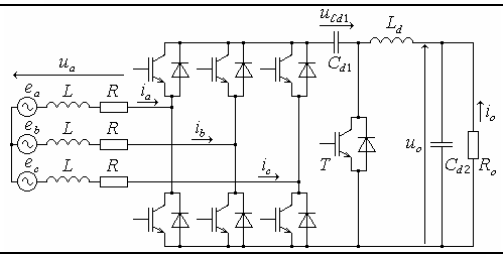
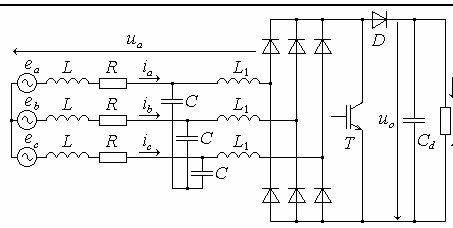
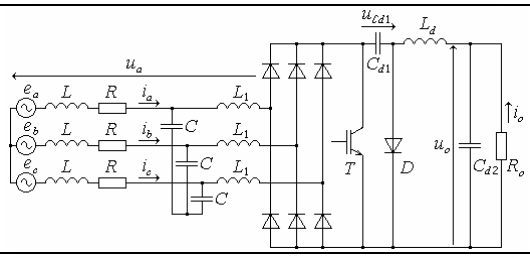
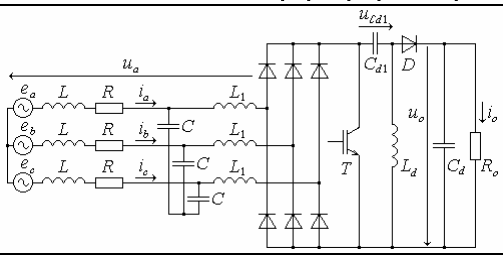
In all subsequent illustrations (for two classes of the circuits) it is given $R^* = 0.2$.

In Fig. 1 and 2 for the circuits of the given class with switches the families EC (continuous lines) dependencies on a load current of factor of harmonics of an input current K_{hI} (dotted line, it is accepted $\bar{K}_{hf}^{(1)} = 0.01$) at the fixed value $F_{(1)}^*$ and regulate characteristics (all for a case $\psi_{f(1)} = -\pi/4$) are shown.

Fig. 3 demonstrates an opportunity of regulation of a output voltage by change of value $\psi_{f(1)}$.

All above mentioned diagrams are constructed for a case that the filter L1C on an input of the bridge is absent, that is corresponding to the circuits 1 and 2 of Table 2 (base for the given class to the circuit on the basis of the inverted voltage source inverter IVSI and circuit on the basis of the Cuk converter).

TABLE 2
INDIVIDUAL PARAMETERS OF THE CIRCUITS OF THREE-PHASE RECTIFIERS
WITH THE SOFT IDEALIZED EXTERNAL CHARACTERISTIC

№	Parameter / Topology	$F^*_{(1)} = \frac{U_{a(1)}}{U_o}$	$F_{(1)}$	n_1	L^*_1	k_n	q
1		$F_{(1)}$	$\frac{U_{a(1)}}{U_o}$	0	0	1	1
2		$\frac{F_{(1)}}{1-F_T}$	$\frac{U_{a(1)}}{U_{Cd1}}$				
3		$F_{(1)}$	$\frac{U_{a(1)}}{U_o}$	$\omega\sqrt{L_1 C}$	$\frac{L_1}{L}$	$\frac{1}{n_1^2}$	3
4		$\frac{F_{(1)}}{F_T}$	$\frac{U_{a(1)}}{U_{Cd1}}$				
5		$\frac{F_{(1)}}{F_T}$	$\frac{U_{a(1)}}{U_{Cd1}+U_o}$				

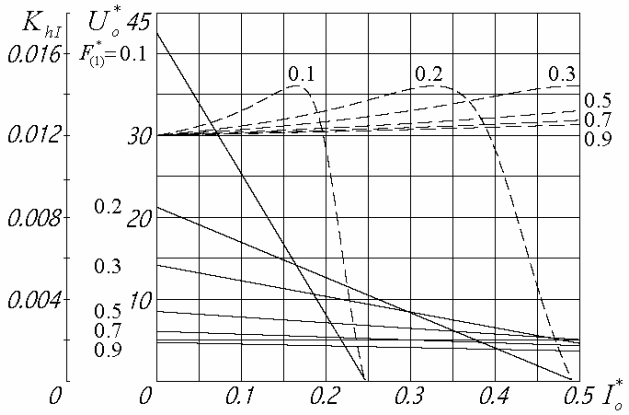


Fig. 1

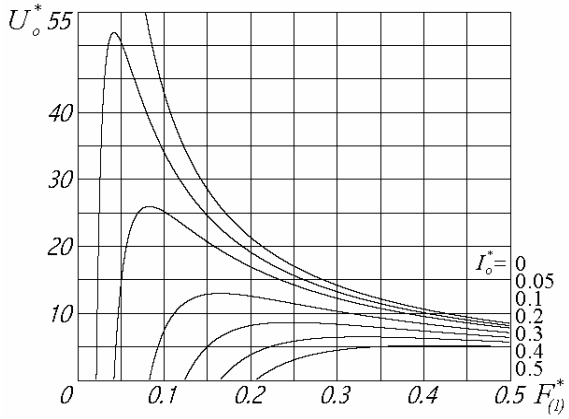


Fig. 2

TABLE 3
INDIVIDUAL PARAMETERS OF THE CIRCUITS OF THREE-PHASE RECTIFIERS
WITH THE RIGID IDEALIZED EXTERNAL CHARACTERISTIC

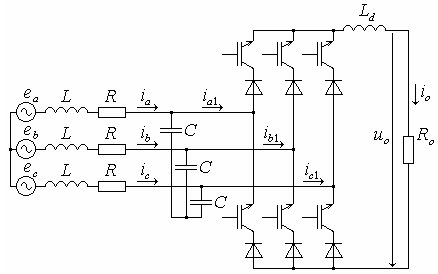
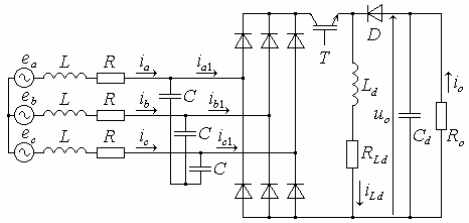
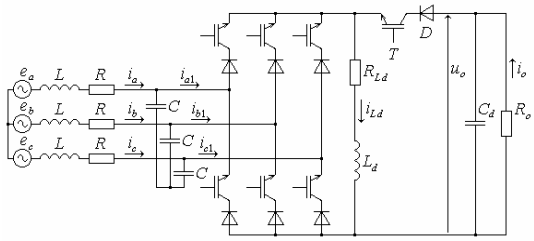
№	Parameter / Topology	$F^*_{(1)} = \frac{I_{a1(1)}}{I_o}$	$F_{(1)}$	n_0	R^*_{LT}
6		$F_{(1)}$	$\frac{I_{a1(1)}}{I_o}$	$\omega\sqrt{LC}$	0
7		$\frac{F_{(1)}}{1-F_T}$	$\frac{I_{a1(1)}}{I_{Ld}}$ $\sqrt{\frac{2}{3}\frac{F_T}{1+K^2_{hf}}}$		$\frac{R^*_{Ld}}{(1-F_T)^2}$
8		$\frac{F_{(1)}}{F_T}$	$\frac{I_{a1(1)}}{I_{Ld}}$ $\sqrt{\frac{2}{3}\frac{1-F_T}{1+K^2_{hf}}}$		$\frac{R^*_{Ld}}{F_T^2}$

Fig. 4 and 5 demonstrate EC of the given circuits in case of stabilization $cos\,\varphi_{(1)} = 1$, accordingly, at the expense of change (tuning) of values $F^*_{(1)}$ at fixing $\Psi_{f(1)}$, and at the expense of tuning values $\Psi_{f(1)}$ at fixing $F^*_{(1)}$ (under the Table 1 for $n1=0$ is accepted the law of change $\Psi_{f(1)} = -H$). The similar dependencies can be constructed for the circuits of the second class.

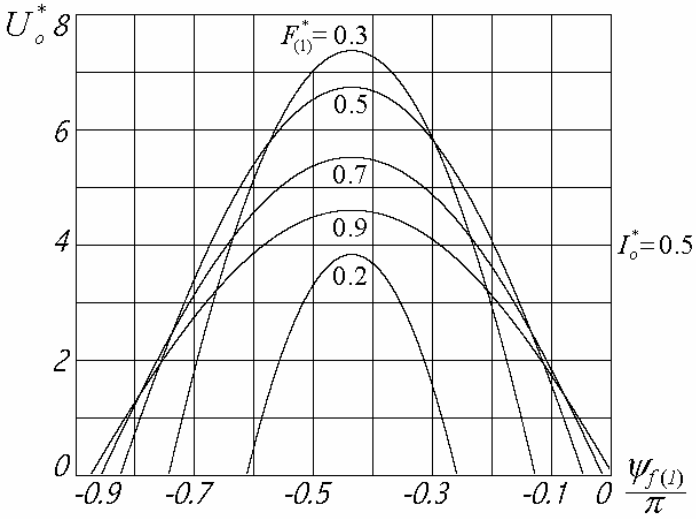


Fig. 3

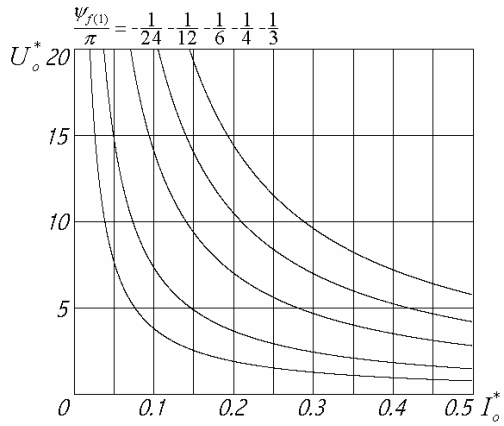


Fig. 4

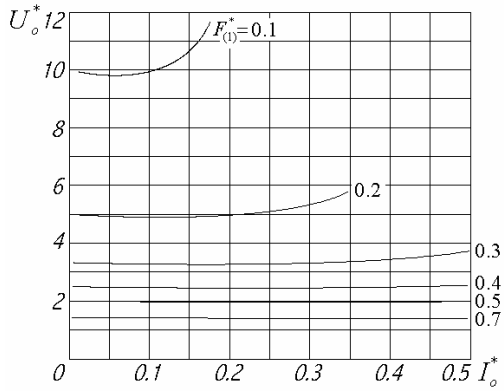


Fig. 5

The algorithm of control of the circuit 2 is such that the value $F^*_{(1)}$ is rigidly connected to value F_T, therefore the regulate dependencies U^*_o and K_{hI} from F_T are of interest and represented for $\psi_{f(1)} = -\pi/4$ in a Fig. 6, accordingly, by continuous lines and by dotted lines.

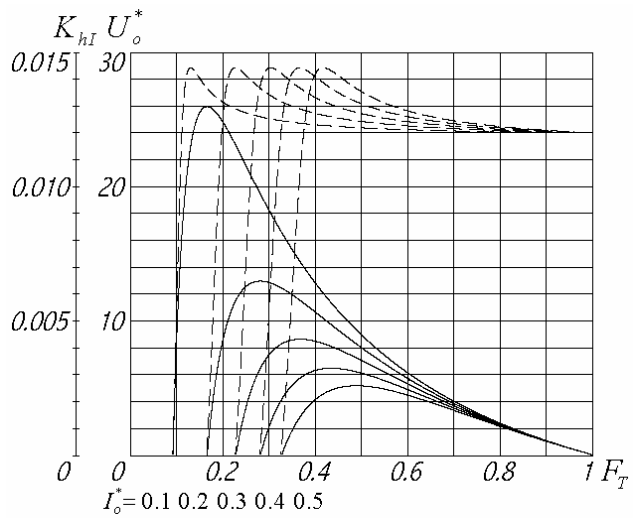


Fig. 6

We see, that at the large values F_T appropriate area of rather low voltage, the characteristics lowly depend on value of a output current.

The bridge circuits 3-5 of Table 2 (on the basis of the raising converter, one more variant of the Cuk converter and the Sepic converter) are executed on diodes, however an input filter in these converters is obligatory for achievement of $\cos\varphi_{(1)} = 1$.

The values $F_{(1)}$ and $\psi_{f(1)}$ simultaneously change with change F_T, therefore the given circuits are suitable only for systems of stabilization of a direct voltage.

In case of small value of R^* for all given class of the circuits at presence of the input filter the approximate condition $n_1 < \sqrt{L^*_1}$ or $n_1 < \sqrt{L^*_1}$, that is, corresponds to increase both dummy voltage E^*_o, and equivalent internal resistance R^*_E in comparison with the circuits without the filter (that is to the greater approach of EC to the characteristic of a current source), and condition $n_1 > \sqrt{L^*_1}$ - their reduction.

B. The Circuits with the Rigid Idealized External Characteristic

The given circuits (circuit 6-8 of Table 3) allow to receive rigid EC. As in contrast to the circuits of the first class the rigidity EC grows not with increase, and with reduction of value $F^*_{(1)}$.

Base the circuit 6 here is on the basis of the inverted current source inverter ICSI. For it the following diagrams are shown: in a Fig. 7 - EC (continuous lines) and dependencies K_{hI} from I^*_o (the dotted line, is accepted $\bar{K}^{(2)}_{hf}$ =0.001), in a Fig. 8 -regulate characteristics at value $\psi_{f(1)} = -3\pi/4$, and in a Fig. 9 - dependencies U^*_o from $\psi_{f(1)}$ at $I^*_o = 0.5$.

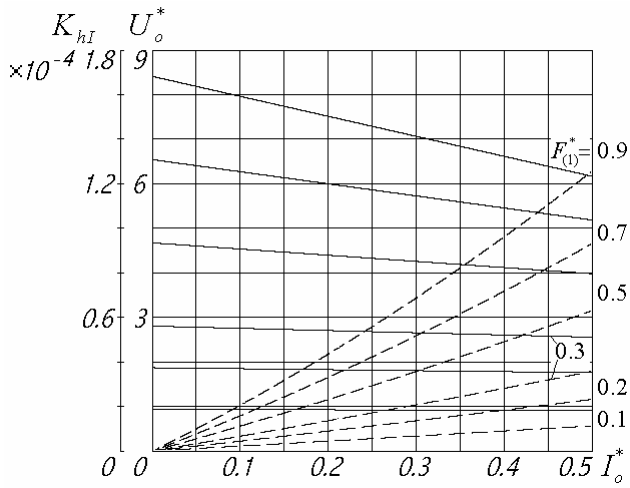


Fig. 7

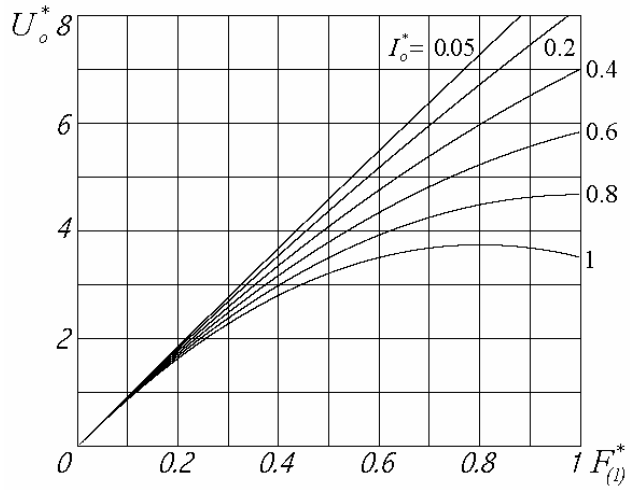


Fig. 8

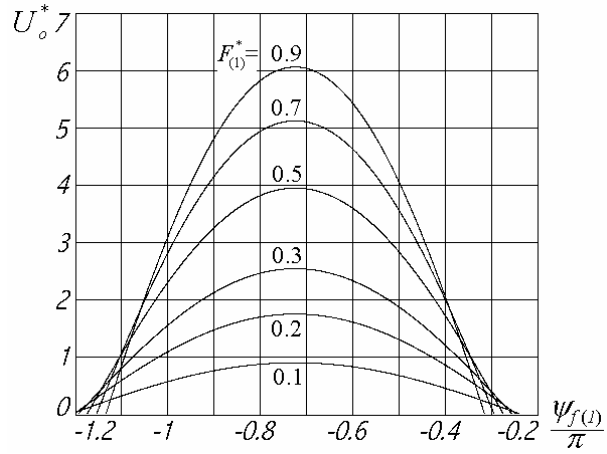


Fig. 9

All diagrams for the circuit 6 are constructed for a case $n_0=1.1$. At $n_0 > 1$ values K_{hI} are less, than at $n_0 < 1$, but the required value of capacity of the filter is higher and the

range of values of a current, in which value $cos\varphi_{(1)}$ = 1 practically can be realized, is narrower.

The circuit 7 of Table 3 has in the class the same advantages and disadvantages, as the circuits 3-5 – in first one. In Fig. 10 and 11 the dependencies U_o^* and K_{hI} from F_T are shown at $\psi_{f(1)} = -3\pi/4$ and n_0 = *1.1*.

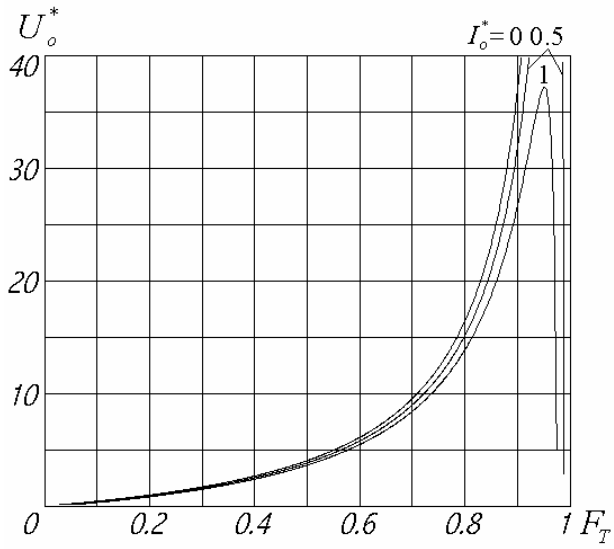


Fig. 10

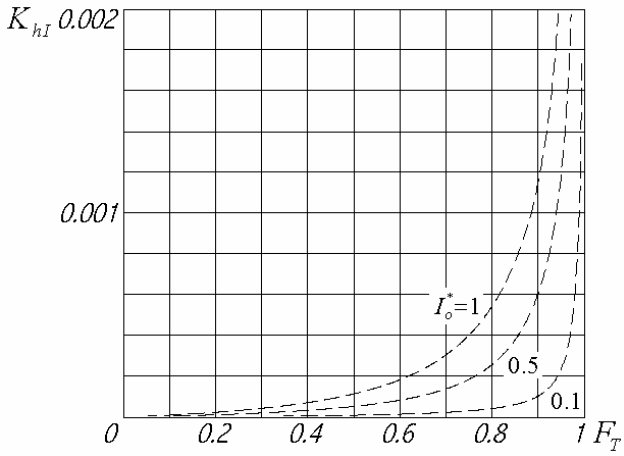


Fig. 11

Circuit 8 of Table 3 allows - at asymmetrical feed - to regulate consumption of energy on separate phases.

IV. CONCLUSION

Obtaining a high value of power factor [8] is possible in the circuits with diode bridges through the presence of the input filter (such circuits are suitable for stabilization of a output voltage), and in the circuits of the bridges with the keys - at the expense of control algorithm (the circuits are suitable for regulation of a voltage). In the circuits of the first class the filter is not obligatory.

Soft EC is provided by the circuits of the first class, and rigid EC by both second and first classes. Conditions of achievement of value $cos\varphi_{(1)}$ =1 of Table 1 assume restriction of value of resistance R_o^* and load current I_o^*. An expediently first class of the circuits operates in the field of small values of current I_o^*, and the second class in the field of the large values of current I_o^*,

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