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Х А Б А Р Л А Р Ы

ИЗВЕСТИЯ

РОО «НАЦИОНАЛЬНОЙ
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КАЗАХСТАН»

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COMPARATIVE ANALYSIS OF AMPLITUDE-MODULATION TYPE FREQUENCY CONVERTERS

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Abstract: *Relevance.* Currently, the problem of environmental pollution from traditional energy sources is particularly relevant. In gas turbine installations with an amplitude-modulating frequency converter, precise control of the power and speed of the GTI is performed, reducing the amount of fuel burned at incomplete loads and, most importantly, leads to a reduction in pollutant emissions. The additional load on the electrical components of a gas turbine installation due to current distortion has negative consequences affecting the efficiency, reliability and service life of the equipment. Despite the existing research and development work on AMPF, the task of recording the output current spectrum remains unresolved, which complicates the optimal design of the GTI. Thus, the issue of optimal design of the GTI using an amplitude-modulated frequency converter, which would ensure the least distortion and stable operation of the GTI, is relevant. *Goal.* The aim of the work is to develop scientifically based recommendations to stabilize the load on the electrical components of the GTI to reduce emissions, noise and thermal pollution. An amplitude-modulation frequency converter in the form of a modulation generator with a sinusoidally pulsating excitation current was chosen as the object of the study. *Methods.* The article proposes a method for determining the distortion of the load current of amplitude-modulating frequency converters with direct coupling to optimize the control system of the GTI. The paper provides a comparative analysis of an amplitude-modulating frequency converter and a frequency converter with direct coupling and artificial switching of thyristors to determine load current distortions. *Results and conclusions.* The analysis and calculation results show that the amplitude-modulation frequency converter ensures the least distortion and stable operation of the GTI and, as a result, a reduction in emissions of pollutants into the atmosphere. The methods and conclusions can be applied to solve actual practical problems in the design of geoecological, energy-efficient energy supply systems.

Key words: gas turbine installations, frequency converter, load distortion, harmonics, modulation generator.

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АМПЛИТУДАЛЫҚ-МОДУЛЯЦИЯЛЫҚ ТИПТЕГІ ЖИІЛІК ТҮРЛЕНДІРГІШТЕРДІҢ САЛЫСТЫРМАЛЫ ТАЛДАУЫ

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Аннотация. *Өзектілігі.* Қазіргі уақытта дәстүрлі энергия көздерінің қоршаған ортаны ластау мәселесі ерекше өзекті болып табылады. Амплитудалық модуляциялаушы жиілік түрлендіргіші бар газ турбиналы қондырғыларда қуаты мен айналу жиілігін дәл реттеу жүзеге асырылады, бұл толық емес жүктемелер кезінде жанатын отын мөлшерін азайтады және ең бастысы ластаушы заттар шығарындыларының азаюына әкеледі. Газ турбиналық қондырғының электр компоненттеріне токтың бұрмалануына байланысты қосымша жүктеме жабдықтың тиімділігіне, сенімділігіне және қызмет ету мерзіміне әсер ететін жағымсыз салдарға әкеледі. АМЖТ бойынша қолданыстағы ғылыми-зерттеу және тәжірибелік-конструкторлық жұмыстарға қарамастан, шығыс ток спектрін тіркеу міндеті шешілмеген күйінде қалып, оңтайлы ГТҚ құрылымын қиындатады.Осылайша, ең аз бұрмалануды және тұрақты ГТҚ жұмысын қамтамасыз ететін амплитудалық модуляцияланған жиілік түрлендіргішін қолданатын оңтайлы ГТҚ құрылысы туралы мәселе өзекті болып табылады. *Мақсаты.*Жұмыстың мақсаты шығарындыларды, шуды және жылу ластануын азайту үшін ГТҚ электр компоненттеріне жүктемені тұрақтандыру бойынша ғылыми негізделген ұсыныстар әзірлеу болып табылады. Зерттеу нысаны ретінде синусоидалы импульстік қоздыру тогы бар модуляциялық генератор түріндегі амплитудалық модуляцияланған жиілік түрлендіргіші таңдалды.*Әдістері.* Мақалада ГТҚ басқару жүйесін оңтайландыру үшін тікелей байланысқан амплитудалық модуляциялық жиілік түрлендіргіштерінің жүктеме тогының бұрмалануын анықтау әдісі ұсынылған. Мақалада жүктеме тогының бұрмалануын анықтау үшін амплитудалық модуляцияланған жиілік түрлендіргіші мен тікелей байланысқан жиілік түрлендіргіші және тиристорлардың жасанды ауысуы салыстырмалы талдау жасалды.*Нәтижелер мен қорытындылар.* Талдау және есептеу нәтижелері амплитудалық модуляцияланған жиілік түрлендіргіші ГТҚ-ның ең аз бұрмалануын және тұрақты жұмысын қамтамасыз ететінін және нәтижесінде атмосфераға ластаушы заттардың шығарындыларын азайтатынын көрсетеді.Алынған әдістер мен қорытындыларды энергиямен жабдықтаудың геоэкологиялық, энергия тиімді жүйелерін жобалау кезінде өзекті практикалық міндеттерді шешу үшін қолдануға болады**.**

Түйін сөздер: газ турбиналық қондырғылар, жиілік түрлендіргіші, жүктеме бұрмалануы, гармоника, модуляция генераторы.

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СРАВНИТЕЛЬНЫЙ АНАЛИЗ ПРЕОБРАЗОВАТЕЛЕЙ ЧАСТОТЫ АМПЛИТУДНО-МОДУЛЯЦИОННОГО ТИПА

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Аннотация. *Актуальность.* В настоящее время проблема загрязнения окружающей среды традиционными источниками энергии является особенно актуальной. В газотурбинных установках с амплитудно-модулирующим преобразователем частоты осуществляется точное регулирование мощности и частоты вращения ГТУ, что сокращает количество сжигаемого топлива при неполных нагрузках и, самое главное, приводит к снижению выбросов загрязняющих веществ. Дополнительная нагрузка на электрические компоненты газотурбинной установки из-за искажения тока имеет негативные последствия, влияющие на эффективность, надежность и срок службы оборудования. Несмотря на существующие научно-исследовательские и опытно-конструкторские работы по АМПЧ, задача регистрации спектра выходного тока остается нерешенной, что усложняет оптимальную конструкцию ГТУ. Таким образом, вопрос об оптимальной конструкции ГТУ с использованием амплитудно-модулированного преобразователя частоты, который обеспечивал бы наименьшие искажения и стабильную работу ГТУ, является актуальным. *Цель.* Целью работы является разработка научно обоснованных рекомендаций по стабилизации нагрузки на электрические компоненты ГТУ для снижения выбросов, шума и теплового загрязнения. В качестве объекта исследования был выбран преобразователь частоты с амплитудной модуляцией в виде модуляционного генератора с синусоидально пульсирующим током возбуждения. *Методы.* В статье предложен метод определения искажений тока нагрузки амплитудно-модулирующих преобразователей частоты с прямой связью для оптимизации системы управления ГТУ. В статье проведен сравнительный анализ преобразователя частоты с амплитудной модуляцией и преобразователя частоты с прямой связью и искусственным переключением тиристоров для определения искажений тока нагрузки. *Результаты и выводы.* Результаты анализа и расчетов показывают, что преобразователь частоты с амплитудной модуляцией обеспечивает наименьшие искажения и стабильную работу GTI и, как следствие, снижение выбросов загрязняющих веществ в атмосферу. Полученные методы и выводы могут быть применены для решения актуальных практических задач при проектировании геоэкологических, энергоэффективных систем энергоснабжения.

Ключевые слова: газотурбинные установки, преобразователь частоты, искажение нагрузки, гармоники, генератор модуляции.

Introduction. The geo-ecological situation associated with the use of traditional powerful energy sources is deteriorating every year. In this regard, back in 1997 in Kyoto, Japan, the Kyoto Protocol, an international agreement, was adopted within the framework of the UN Convention on Climate Change. One of the key features of the Kyoto Protocol was the commitments of the participating countries to reduce greenhouse gas emissions, with specific quotas for developed countries (Strovsky, 2004). To comply with the agreement, the participating countries began to increase the share of non-traditional energy sources. But they are inferior in power to traditional ones and are also tied to weather conditions. The use of gas turbine installations that provide quick start and power control makes them ideal for covering peak loads of electric energy consumers (Campbell,1998). In general, although gas turbine installations (GTI) represent a more environmentally friendly alternative to many other energy sources, they can still have an impact on the environment. With precise and smooth control of the start and stop of the GTI, the risk of fuel leaks or other pollutants that may enter the soil can be reduced (Tolubayeva,2024). Currently, in a number of cases, an amplitude-modulated frequency converter (AMFC) is used to control the GTI, which allows not only frequency control, but also solves a number of problems related to emissions that affect atmospheric conditions and cause global warming and a decrease in air quality during operation and management of the GTI (Manezhnov, 2016; Karsakova, et al., 2024:11).

Research materials and methods. In one of the variants that has recently attracted the most attention of researchers, AMFC contains a (GM) modulation generator and a K(2,3,6) thyristor switch (Fig. 1, a). In this case, the frequency conversion (Makarenko, 2019; Beisembetov, et al., 2013:6; Khayitov, et al., 2024:10), which affects the efficiency of fuel combustion and emissions, is carried out by amplitude modulation of the output voltage of phase m_1 GM by exciting it with an alternating current of the required frequency, but with a value equal to the output frequency of the system f_2, followed by rectification of the high-frequency voltage of the generator and cyclic repolarization relative to the load of half-waves of the output frequency using a switch (Fig.1, b)

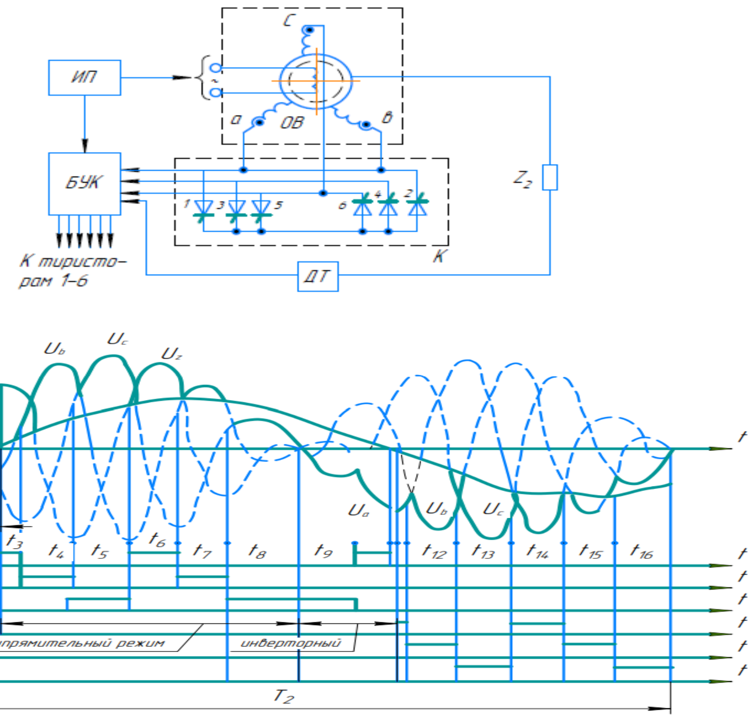

Figure 1- shows a block diagram of one of the AMFC variants with m_1=3, m_2=1 (a) and time diagrams of AMFC output voltages and currents (b).
GM – modulator generator, K-switchboard, EW- excitation winding, PS- f_2 frequency power supply, CS- current sensor, SCU – switchboard control unit

To form an m_2–phase voltage system using such a device, an m_2–phase alternating current source with excitation power and an m_2 – phase K are used, and the GM is made in the form of a number of synchronous machines structurally combined by means of a shaft and a body m_2. Some principles of GM excitation and improvement of its energy parameters affecting the geo-ecological situation are considered in (Ivanchin,2017; Sherov, et al., 2021a:7; Absadykov, et al., 2024:9).

The switch can be made on thyristor with artificial (Popov, 1971) or natural switching. The simplest K circuit with a sufficiently high output voltage quality is obtained at m_1=3 (Fig.1, a). With natural switching of thyristors for control. The most effective principle of separate control can be applied, reducing the negative impact on the environment, which has recently been used to control reversible rectifiers and frequency converters with direct connection. This principle is illustrated in Fig.1b, which shows the output voltages U_2 and current i_2, as well as the switching laws $\Psi_1 - \Psi_6$ of thyristors 1-6. Such a system is of particular interest, in particular, for autonomous power supply systems for mobile facilities with variable rotation speed of the generator drive, with the aim of rational use of resources and minimizing environmental risks (Allison, 1972; Sherov, et al., 2022b:13; Sherov, et al., 2022:8). The main advantages of this system, compared, for example, with a similar system without modulating the excitation flow of the generator, are the comparative simplicity of the control system and a significantly higher quality of the output current, all other things being equal, which in some cases makes it possible to dispense with filters. The slightly higher weight of the GM compared to a generator without flow modulation is a known disadvantage of the system. The task here is not to determine the appropriate areas of application of AMFC of all known types. The given example of an AMFC in the form of a GM with a sinusoidally pulsating excitation current and K is taken for illustration.

Despite the available research and development work on AMPF, the task of recording the output current spectrum K remains unresolved for the general case of the ratio of input and output frequencies ω_1/ω_2 and for an arbitrary number of phases of GM - m_1, which makes it difficult to optimally design, control and compare such devices with others to minimize emissions into the atmosphere. The present work is devoted to solving this problem. The method of switching functions, or otherwise the method of mathematical description of signals with amplitude-pulse modulation, is used as the research apparatus. In the analysis, we make assumptions about the ideality of thyristors (instantaneous switching, no voltage drop), zero reactants GM (switching angle $\gamma = 0$) and neglect the pause between half-waves of the load current, which, depending on the type of thyristor, is (20-100) microseconds. The output voltage U_1 of the switch can be represented by the product of two functions:

$$U_2 = U_{1B}\Psi_2 \tag{1}$$

where U_{1b} is the rectified voltage; Ψ_2 is the modulating effect.

The rectified m_1 pulse voltage can be written as follows [L. 4]:

$$U_{1B} = \frac{U_{1m}m_1}{\pi}\sin\frac{\pi}{m_1}\left[1 + 2\sum_{k=1}^{\infty}\frac{(-1)^{k+1}}{m_1^2k^2-1}\cos m_1 k(\omega_1 t + \theta_1)\right], \tag{2}$$

where k= 1, 2, 3, ..., ∞; m1 =2, 3, 4, 5, 6 and so on . The function Ψ_2 in this case is a unit sinusoidal

$$\psi_2 = \sin(\omega_2 t + \theta_2), \tag{3}$$

Here θ_1 in (2) and θ2 in (3) are the reference angles, and U_1m in (2) is the amplitude value of the rectified voltage.

Substituting (2) and (3) into (1), we get:

∞,(1a)

Results. As can be seen from expression (1a), the amplitudes of the fundamental and higher harmonics of the voltage are determined only by the phase of GM-m_1.

It should also be noted the advantage of this frequency conversion method, which affects the operation of fuel combustion in the GTI, which consists in the fundamental absence of subharmonics in the output voltage, since according to the principle of operation, the condition $\omega_2<\omega_1$ must be fulfilled. When $\omega_2=0$ and $\theta_2=\pi/2$, expression (1a) turns into the spectrum of the m1 pulse rectified voltage. Based on (1a) voltage harmony coefficient

$$K_{\Gamma(u_2)} = \sqrt{\sum_{k=1}^{\infty}\frac{2}{\left(m_1^2k^2-1\right)^2}}, \tag{4}$$

The graph of this dependence is shown in Fig. 2. For comparison, the dependence $K_{\Gamma(u_2)} = f(m_1)$ is shown for a frequency converter with direct coupling and artificial switching of thyristors (FCDCA) with the most efficient control algorithm by cyclically connecting the network phases to the load at regular intervals to determine the geo-ecological aspects (Barbosa,2019; Ängquist,2013).

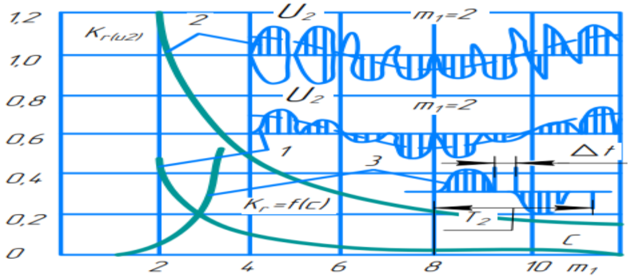

Figure 2 – Dependences of harmonic coefficients
1,2 – from the number of input phases m1 for AMFC and FCAS, controlled by the method of cyclic connection at regular intervals and network phases to the load phase; 3 – from the pause value between half-waves of voltage (current)

For $m_1 = 2$, the sum is found by reducing the method of indefinite coefficients of the initial fraction representing the common term of the series to the sum of more elementary fractions describing the common terms of the series, the sums of which are known from the reference literature:

$$\sum_{k=1}^{\infty}\frac{1}{(4k^2-1)} = -\frac{1}{2}\sum_{k=1}^{\infty}\frac{1}{4k^2-1} + \frac{1}{4}\sum_{k=1}^{\infty}\frac{1}{(2k-1)^2} + \frac{1}{4}\sum_{k=1}^{\infty}\frac{1}{(2k+1)^2} = -\frac{1}{2}\left(\frac{1}{2}\right) + \frac{1}{4}\left(\frac{\pi^2}{8}\right) + \frac{1}{4}\left(\frac{\pi^2}{8}-1\right) = \frac{\pi^2}{16} - \frac{1}{2},$$

Thus, for $m_1=2$, the coefficient, i.e., is the same as that of the meander (Espinoza,2001). Calculating the exact value at $m_1 = 3.6$, etc. by a similar method causes difficulties. Taking into account only the first three terms for $m_1 = 3$, and for

m_1 = 6. Using an estimate of the sum of the unaccounted-for terms of the series, using inequalities, it can be shown that the calculation error in the first case does not exceed 1.7%, and in the second 0.47%. For example, let m_1 = 3. Let 's estimate the relative error allowed in this case. Because when k>1

$$\frac{1}{(9k^2-1)} = \theta_k < \frac{1}{9}\left(\frac{1}{k^2-1} - \frac{1}{k^2}\right) \text{ и } \theta_k > \frac{2}{81k^2},$$

$$\delta K_{\Gamma(u_2)} = \frac{\sqrt{\sum_{k=1}^{\infty}\theta_k} - \sqrt{\sum_{k=1}^{3}\theta_k}}{\sqrt{\sum_{k=1}^{\infty}\theta_k}} \frac{\sqrt{\sum_{k=1}^{3}\theta_k + \frac{1}{9}\left(\sum_{k=4}^{\infty}\frac{1}{k^2-1} - \sum_{k=4}^{\infty}\frac{1}{k^2}\right)}}{\sqrt{\sum_{k=1}^{\infty}\theta_k} + \frac{2}{81}\sum_{k=4}^{\infty}\frac{1}{k^4}} - \sqrt{\sum_{k=1}^{3}\theta_k} = 0{,}017.$$

The output current is determined in expression (1a) by dividing each voltage harmonic by the complex load resistance corresponding to its frequency, followed by summing the resulting harmonic currents. For convenience of calculations, the complex resistance module for the fundamental harmonic.

$$|Z_{21}| = \sqrt{r_2^2 + (\omega_2 L_2)^2}, \tag{5}$$

with an argument

$$\psi_{21} = \operatorname{arctg}\frac{\omega_2 L_2}{r_2}, \tag{6}$$

We take it equal to one and express it in terms of the parameters of the resistance modulus for harmonics of the lower and upper side frequencies:

$$|Z_{21}| = \frac{\sqrt{1+\left(1-m_1 k\frac{\omega_1}{\omega_2}\right)^2 \operatorname{tg}^2\phi_{21}}}{1+\operatorname{tg}^2\phi_{21}}; \tag{7}$$

(7a)

The harmonic coefficient of the current is determined by the formula

$$K_{\Gamma(i_2)} = \frac{1}{I_{21m}}\sqrt{\sum_{k=1}^{\infty} I_2^2\text{km} + \sum_{k=1}^{\infty}(I_2\ \text{km})^2}, \tag{8}$$

where

$$I_{2\text{km}} = \frac{m_1}{\pi}\sin\frac{\pi}{m_1} = \frac{m_1}{\pi}\sin\frac{\pi}{m_1}\frac{(-1)^{k+1}}{(m_1^2k^2-1)|Z_{2k}|}; \tag{9}$$

$$I_{2\text{km}} = \frac{m_1}{\pi}\sin\frac{\pi}{m_1} = \frac{m_1}{\pi}\sin\frac{\pi}{m_1}\frac{(-1)^{k+1}}{(m_1^2k^2-1)|Z_{2k}|}; \tag{9a}$$

$$I_{2\text{km}} = \frac{m_1}{\pi}\sin\frac{\pi}{m_1}\frac{(-1)^{k+1}}{(m_1^2k^2-1)} \tag{9б}$$

- the amplitudes of the fundamental and higher harmonics, respectively. Substituting (9), (9a), (96) into (8), taking into account (7), (7a), we obtain:

$$K_{\Gamma(i_2)} = \sqrt{(1+\mathrm{tg}^2\phi_{21})\sum_{k=1}^{\infty}\frac{1}{(m_1^2k^2-1)^2}\left\{\frac{1}{|1+(1-m_1ka)^2\mathrm{tg}^2\phi_{21}}+\frac{1}{|1+(1+m_1ka)^2\mathrm{tg}^2\phi_{21}}\right\}}, \quad (10)$$

where it is indicated for convenience $a=\frac{\omega_1}{\omega_2}$.

Discussion

The calculation results for three values m_1 =2, 3, 6 in the range of parameter changes $a = 2 \div 10$и $\varphi_{21} = 0 \div 85^{\circ}$ are shown in Fig. 3.4. Taking into account the rapid convergence of the radius (10), the nearest 10 harmonics were taken into account.

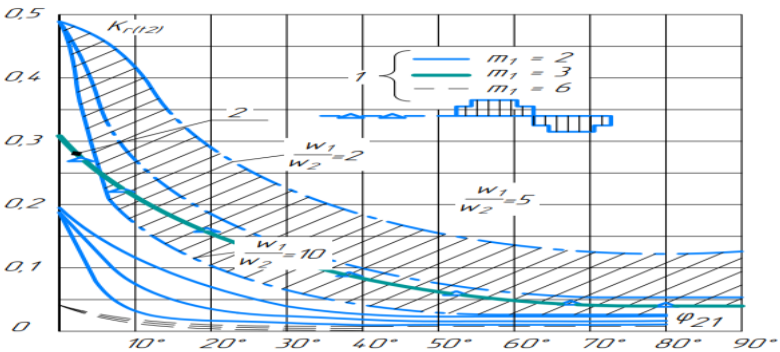

Figure 3 – Dependences of the harmonic coefficients of the phase current on the load angle according to the fundamental harmonic 1- for an AMFC with m_1 =2,3,6 in the parameter range ω_1/ω_2 = 2-10; 2 – for a three-phase inverter with φ = 180⁰. Static load

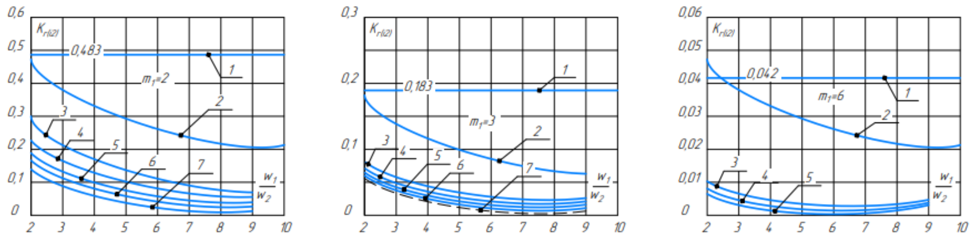

Figure 4 – Dependences of the harmonics coefficients of the AMFC load current on the parameter ω_1/ω_2 at different load angles

1- φ_{21} = 0; 2 - $\varphi_{21}=6^0$; 3- $\varphi_{21}=20^0$; 4- $\varphi_{21}=30^0$; 5- $\varphi_{21}=40^0$; 6- $\varphi_{21}= 60^0$; 7- $\varphi_{21}=85^0$

Additional distortions due to the omission of the Δt pause between the half-waves of the load current can be determined with sufficient accuracy by neglecting the current ripples and representing it as half-cycles of a harmonic signal with an amplitude of I_2m (Fig. 2, a), followed by recording as a series:

$$i_2 = \frac{4I_{2m}}{\pi}\sum_{k=0,1\ldots}^{\infty}\frac{c}{c^2-(2k+1)^2}\cos\frac{\pi}{2c}(2k+1)\times\cos[(2k+1)\omega_2 t+\theta_2]. \quad (11)$$

Then, having found the effective value of this signal in the usual way (Fig. 2, c) and knowing its first harmonic from (11), one can easily determine the harmonic coefficient.

$$K_{\Gamma(i_2)} = \frac{1}{I_{20m}}\sqrt{\frac{1}{c} - I_{20m}^2}, \quad (12)$$

where

$$c = \frac{T_2}{T_2 - 2\Delta t}, \quad (13)$$

$$I_{20m} = \frac{4I_{2m}c}{\pi(c^2-1)}\cos\frac{\pi}{2c}. \quad (14)$$

For small sps, the dependence (12) is shown in Fig. 2, in a graph from which it can be seen, for example, that at f_2= 400 Hz, Δt=100 microseconds, c=1,087, the distortion from the pause can be ignored. For large values of c, which is typical for high frequencies of f_2 or elevated values of Δt, an approximate formula can be used

$$K_{\Gamma(i_2)} = \frac{1}{I_{20m}}\sqrt{\sum_{k=1}^{\infty}(I_2^2\text{km} + I_2\ \text{km}) + \frac{1}{c} - I_{20m}^2}, \quad (15)$$

In this case, the values will be slightly overestimated.

To compare the distortions of the analyzed frequency conversion method with others, Fig. 3,b shows the dependence for an inverter(S) with a 180° conduction angle of its switches (Ilves,2012).

As can be seen from Fig. 3, b, even the simplest AMFC (m_1=2) at $\frac{\omega_1}{\omega_2} \geq 5{,}5$ and $\varphi_{21} \geq 20^{\circ}$ provides less distortion than and(Multi,2020) shows the dependences of load current distortions on the parameters $\frac{\omega_1}{\omega_2}, \varphi_{21}, m_1$ for three-phase frequency converters with artificial switching (FCDCAS) controlled by cyclically connecting the phases of the grid to the load (Orlov,2017)at regular intervals. The $\frac{I_2}{I_{21}}$ (I_2, I_{21}- the effective values of the total load current and its fundamental harmonic, respectively) indicator associated with the $K_{\Gamma(i_2)}$ dependence was used to evaluate the distortions.

$$K_{\Gamma(i_2)} = \sqrt{\frac{I_2}{I_{21}} - 1}. \quad (16)$$

A comparative analysis under equal conditions for $m_1, \frac{\omega_1}{\omega_2}, \varphi_{21}$ shows that AMFC provides significantly lower distortion, especially harmonic distortion, and also minimizes impacts that may occur in the ecosystem compared to FCDCAS

Conclusions

1. The problem of increasing the environmental sustainability of gas turbine installations, reducing emissions, noise and thermal pollution is solved with the help of AMFC in GTI.

2. A method is proposed for determining the distortion of the load current for frequency converters with direct amplitude modulation to control the GTI and minimize their noise pollution.

3. Results of calculations of load current distortions for AMFC and some other types of converters.

4. The results obtained, as well as the method for determining primary currents, can be used in the design of energy-efficient and environmentally friendly GM.

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