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ASYNCHRONOUS ELECTRIC MOTOR WITH SINGLE-PHASE STATOR WINDING

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Abstract: *The current standard considers the efficiency of electric motors only in terms of power efficiency and does not pay attention to the so-called economic efficiency - the power factor that affects the loss of electricity in the motor supply network and depends on its energy excellence. This ill-considered approach to establishing the energy efficiency class is a significant shortcoming of the European standard and requires its refinement. The single-phase power supply network in housing and communal services has led to the fact that modern motor compressor units of refrigerators, air conditioners, etc. are equipped with single-phase asynchronous electric motors. An innovative single-phase asynchronous AC motor for motor-compressor units of household appliances is considered in the paper. The stator winding of it is composed of two identical series-connected coils enclosed in half-slots of the stator with a spacious offset of* 90^0*. The phase shift of the currents in the coils is provided by a capacitor connected in parallel to one of the coils. The proposed motor is technological in production, has higher specific power and energy efficiency than existing models and meets the IE-3 class energy efficiency. Equivalent electrical circuit and vector diagram of currents for this motor have been developed and shown. They are intended for its mathematical simulation, calculation of static operating characteristics, analysis of dynamic properties at operation in the electric drive system, and also at the level of design work.*

Анотація. *Розглянуто однофазний асинхронний двигун змінного струму мотор-компресорних агрегатів побутової техніки, обмотку статора якого складено двома однаковими послідовно увімкненими котушками, укладеними у пів пазів статора із просторовим зсувом* 90^0*. Фазовий зсув струмів в котушках забезпечується конденсатором, приєднаним паралельно до однієї з котушок. Такий двигун є технологічним у виробництві, має вищі питому потужність і показник енергетичної ефективності та відповідає класу енергетичної ефективності IE-3. Розроблено його заступну електричну схему і векторну діаграму струмів, які призначені для побудови його математичної моделі, розрахунку статичних робочих характеристик, аналізу динамічних властивостей при роботі в системі електроприводу, а також на рівні проектно-конструкторських робіт.*

Ключові слова: *Однофазний асинхронний двигун, ефективність, обмотка статора, заступна схема, векторна діаграма, ємність фазо зсувного конденсатора*

Keywords: *Single-phase asynchronous motor, efficiency, stator, winding, equivalent electrical circuit, vector diagram.*

1. Introduction

The recession in electrical power production in the public sector of developed countries, due to the rising cost of fuel or other energy resource by 12.3%, demands the reduction in the number of energy-intensive consumers which are not related to industry, namely in housing/utilities sector and agricultural one [1-5]. The 20 per cent planned increase in the cost of electricity until 2040 may lead to the reduction in electricity consumption and to the cost rise of tie-in merchandise with the included value of electricity [6]. It is possible to balance these consequences in the first approximation by increasing the efficiency of the used electrical equipment and mainly of electric motors. According to IEA (International Energy Agency) reports, up to 46% of global electricity consumption is accounted for by electric motor driven systems, almost 12% of which is accounted in housing/utilities and agricultural sectors [7]. It is globally recognized that the average efficiency of electric motors is 70%, and therefore increasing the share of their energy-efficient models, as well as the development and implementation of their new designs will help save energy resource [8-10]. The current standard considers the efficiency of electric motors only in terms of energy efficiency and does not pay attention to the so-called economic efficiency - the power factor that affects the loss of electricity in the motor supply network and depends on its energy excellence. This ill-considered approach to establishing the energy efficiency class is a significant shortcoming of the European standard and requires its refinement. The concept of energy efficiency development in different countries [11,12] takes into consideration not only the consumer's interest in having an energy-efficient electric motor, but also the interest of the electricity producer to produce it with low energy costs, and as for electricity suppliers - to provide electrical resource to the consumer with low power losses. The last two conditions are inextricably linked with the economic performance - the power factor.

The single-phase power supply network in housing and communal services has led to the fact that modern motor compressor units of refrigerators, air conditioners, etc. are equipped with single-phase asynchronous electric motors [13-15]. The first single-phase asynchronous motor was theoretically grounded and built by Galileo Ferraris in 1888, and only in 1890 Maurice Hutin and Maurice Leblanc proposed the use of capacitor to shift the phases of the stator winding currents [16,17]. Since then, the motor has not been fundamentally changed – it has two phases in the stator winding and a short-circuited rotor.

Single-phase by the name of the power supply source, they are two-phase devices. Their stator has two separate windings - working and auxiliary (two phases), which are orthogonally placed in the stator, designed to be independently powered by a single-phase network and magnetically connected. The time shift of currents in them is provided by artificially different electrical phase resistances, namely: active - due to unequal wire cross-section and reactive inductive - due to different number of turns or reactive capacitive – by connection of capacitor. Despite the existing types of compressors, their electric drive includes one of two types of single-phase motors that have the same operating winding and as the auxiliary one - starting winding (one-phase asynchronous motor - OAM), or as auxiliary one - additional winding with capacitor (asynchronous condenser motor - ACM). The general view of the motors is shown in Fig.1.

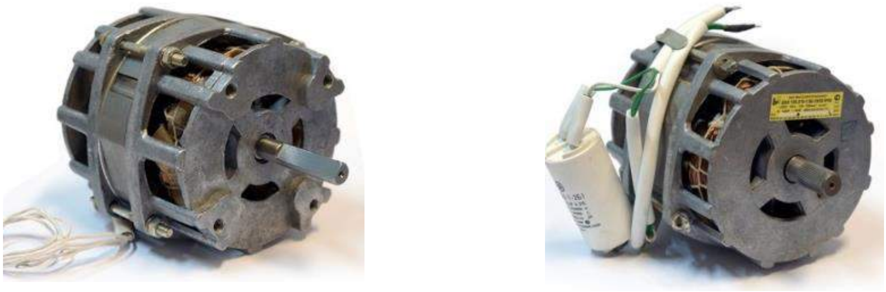
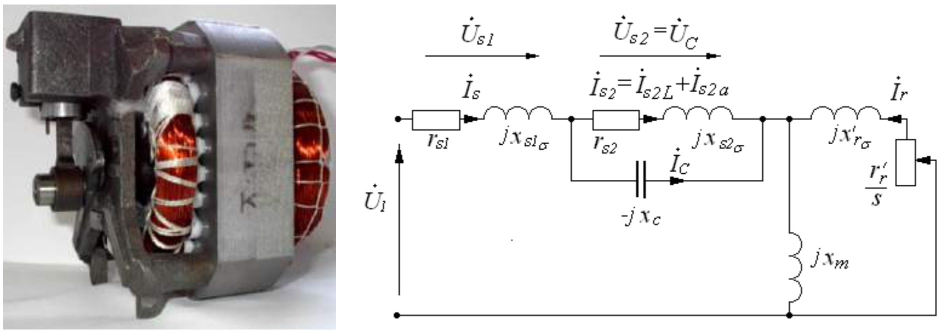

a) b)

Fig.1. Appearance of a single-phase asynchronous motor with starting (a) and additional capacitor (b) windings

The motors differ by the time of auxiliary winding switching on: it is short term of time for the starting winding, and it is continuous for the additional one. OAM is significantly inferior to ACM in terms of energy efficiency η and power factor $Cos\varphi$. If we consider their joint assessment as energetic one - in the form of composition $\beta = \eta \cdot Cos\varphi$, that is natural, and, according to the catalog data it is equal to $0{,}24 \le \beta \le 0{,}45$ for OAM and $0{,}45 \le \beta \le 0{,}65$ for ACM. Based on this, ACMs have an advantage when used as a drive of compressors [18, 19]. To promote new models of compressor equipment on the world market today, stricter requirements are set for the energy efficiency indicator at a level not lower than $\beta \ge 0.8$, so the work on OAM and ACM further improvement remains relevant.

2. Asynchronous motor single-phase stator and its equivalent circuit

Further improvement of the ACM energy efficiency was made in [20] The ACM was considered as the motor that had two phases on the stator - working and auxiliary one. The phases were made of winding wire of different cross-section and they were designed for their independent electrical supply. It was proved that the manufacture of the stator winding with a winding wire of the same cross section with one working phase, which was cloven into two identical sequentially turned on coils enclosed in the same number of stator slots with a clear offset of 90^0, makes the motor single-phase, simplifies its manufacture and rises energy efficiency (W/kg) up to the level $\beta \ge 0.8$.



a) b)

Fig.2. (a) - General view of the motor of the NKV-10-3-K compressor equipped with SACM;
(b) - its equivalent circuit without taking into consideration power losses in the magnetic circuit

The time shift of currents in the coils is provided by connecting a capacitor at the time of motor starting in parallel to one of the two coils of the stator winding to the phase shift one. In this case the need to have the capacitance of the capacitor four or more times higher, but with an operating voltage twice less, is not a critical obstacle and makes the proposed engine competitive with existing OAM and ACM. By the way, instead of an AC starting capacitor, the developer uses bipolar electrolytic capacitors, which turn off after starting the motor and then the motor operates on a pulsating magnetic field formed by series-connected operating and phase-shifting coils of the stator winding.

Therefore, such motor is a single-phase asynchronous capacitor motor (SACM) by design, but this motor is schematically converted to two-phase at start-up time. The general view of SACM, made on the basis of standard compressor unit motor, is shown in Fig.2 (a).

The equivalent scheme of any engine is the basis for building its mathematical model for static performance calculating, to compare them with similar prototypes of the motor, to calculate and analyze the dynamic characteristics of the electric drive system where it will work, as well as at the beginning of the design process. Even today, it is impossible to find in scientific sources any adequate alternative schemes of OAM and ACM by which it would be possible to study them and, especially, in dynamics. The explanation of this state of affairs can be found in the inherent significant difference between two phases of the stator winding. In any case, it is believed that the motor operates only on a pulsating magnetic field formed by the working phase, and the starting or additional phases in the equivalent circuit are absent. This approach corresponds to the alternate circuit of a three-phase asynchronous motor with symmetrical phases. However, since the SACM proposed in [13,18] has only one phase and its halves are symmetrical and are sequentially turned on to the power supply, it becomes possible to create an adequate equivalent circuit for it, Fig. 2 (b).

3. The capacitance of the phase shifter coil of the sacm stator winding and vector diagram of its currents

To the effective starting and operating conditions of the SACM must correspond the time angle of the current shift I_S and I_{S2} - between the operating and phase shift sections of the stator winding. It is achieved by turning on the capacitor C in parallel to any half of the stator winding, Fig.2 (b). The best angle of current shift is equal to a quarter of the period in time or 90º on the currents diagram, Fig.3 (a). This is due to the orthogonal location of the winding halves in the stator bore. In the vector diagram of currents, shown in Fig.3 (a), it corresponds to the identity

$$90^0 = \varphi_{s2} + \alpha = \varphi_{s2} + arctg\left(\frac{I_C - I_{s2L}}{I_{s2a}}\right), \tag{1}$$

In which I_{s2a}, $I_{s2\sigma}$ - active and reactive inductive components of full current I_{s2} in the phase shifting part of the stator winding, φ_{s2} - total current shift angle I_{s2} relative to the voltage $U_{s2} = U_C$, applied to the phase shifting part of the winding. Transforming equation, (1) we obtain

$$tg\left(90^0 - \varphi_{s2}\right) = \frac{I_C - I_{s2L}}{I_{s2a}}, \tag{2}$$

where the reactive capacitive current in the branch with a capacitor is

$$I_C = \frac{U_{s2}}{x_c},$$

active and reactive inductive components of full current I_{s2} are

$$I_{s2a} = \frac{r_{s2}}{Z_{s2}^2} U_{s2}, \text{ and } I_{s2L} = \frac{x_{s2\sigma}}{Z_{s2}^2} U_{s2},$$

in which r_{s2}, $x_{s2\sigma}$ - active and reactive inductive resistances of the phase-shifting part of the stator winding. Making their substitutions in (2), we obtain:

$$\frac{I_C - I_{s2L}}{I_{s2a}} = \frac{\left(r_{s2}^2 + x_{s2\sigma}^2 - x_{s2\sigma} x_c\right)}{x_c r_{s2}} = tg\left(90^0 - arctg\frac{x_{s2\sigma}}{r_{s2}}\right), \tag{3}$$

whence the capacitive resistance of the branch with the capacitor is

$$x_c = \frac{r_{s2}^2 + x_{s2\sigma}^2}{x_{s2\sigma} + r_{s2} \cdot tg\left(90^0 - arctg\frac{x_{s2\sigma}}{r_{s2}}\right)}. \tag{4}$$

The capacitance of the capacitor, which will correspond to the rotating magnetic field when starting SACM, will be

$$C = \frac{10^6}{2\pi f \cdot x_c}, (\mu F). \tag{5}$$

Equations (1) and (2), used at the beginning of the calculation of the capacitive resistance of the capacitor, correspond to the vector diagram of currents and voltages shown in Fig.3 (a). The vector diagram is constructed under the condition that the capacitive current I_C is opposite to the reactive inductive current I_{s2L} of the phase-shifting part of the winding, and its active resistance r_{s2} does not depend on the capacitance

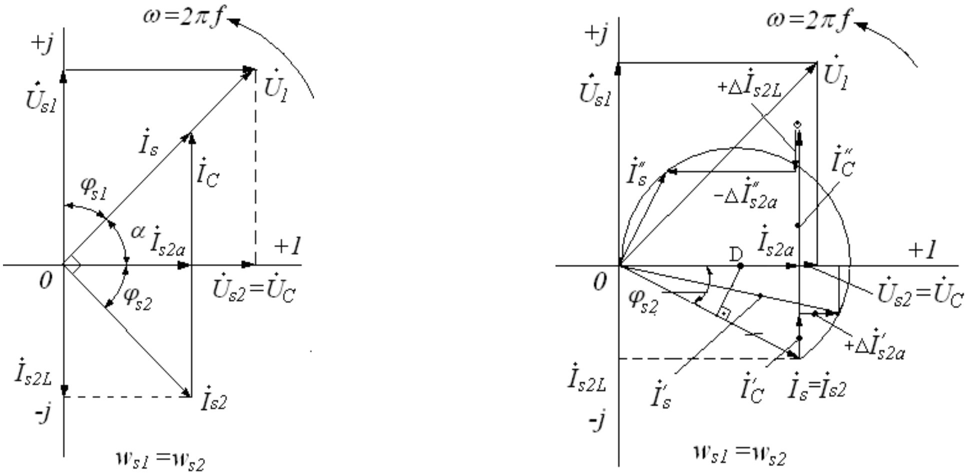
of the capacitor, i.e. $I_{s2a} = idem$ But, if we numerically investigate the equation of impedance of the phase-shifting part of the stator winding (6)

$$\underline{Z}_n = \frac{-r_{s2} \cdot jx_c + x_{s2\sigma} \cdot x_c}{r_{s2} + j(x_{s2\sigma} - x_c)} = \frac{r_{s2} + jx_{s2\sigma}}{j\dfrac{r_{s2}}{x_c} - \left(\dfrac{x_{s2\sigma}}{x_c} - 1\right)} = r_n \pm jx_n, \tag{6}$$

in which r_n - active and jx_n - reactive components of full resistance $\underline{Z}_n$, it is easy to determine the existence of a link between the resistances of the phase-shifting part of the stator winding and the condenser capacitance.

Establishing of such connection and confirming the adequacy of the initiated vector current diagram as it is shown in Fig.3 (a), was performed through the construction of the resistances diagram and phase shift winding full resistance numerical calculations performance and its component resistances for SACM sample with single-phase stator winding, that was made on the basis of ACM motor of the refrigeration compressor unit, which was installed in the household refrigerator.

According to the tests of idling and short circuit of the manufactured SACM sample, and in accordance with the substitution scheme in Fig.2, the resistances in Ohms were: $x_m = 614.1$, $x_{s1\sigma} = x_{s2\sigma} = 6$, $r_{s1} = r_{s2} = 9.7$, $x'_{r\sigma} = 23.8$, $r'_r = 9.9$. At the beginning of the increase in the capacitance of the condenser, when its capacitive resistance $x_C = \infty$ (the branch is separated), the modulus of full resistance of the stator winding phase-shifting part was $Z_n = \sqrt{9.7^2 + 6^2} = 11.4\Omega$, and its phase was $\varphi_{s2} = arctg\dfrac{6}{9.7} = 31{,}74^0$. The graphically constructed diagram of the resistances of the SACM stator winding, with increasing capacitance of the phase shifting condenser C, is shown in Fig.4.



a) b)

Fig.3. Vector diagram of currents and voltages of (a) - two-phase ACM, and (b)- SACM

The diagram shows: the full resistance of the stator winding phase-shifting part $\underline{Z}_n, \underline{Z}'_n, \underline{Z}''_n ... = f(x_C)$ for several values of the condenser capacitance; full resistance components of the stator winding phase shifting part $r_{s2}, r'_{s2}, ..., (-jx_C), (-jx'_C), ..., = f(x_C)$; phase shift angle $\varphi_{s2}, \varphi'_{s2}, ... = f(x_C)$, etc., from which follows the character of the change of active $r_n = f(x_C)$ and reactive $x_n = f(x_C)$ resistances of the stator winding phase shift part. The results of the calculation are shown in Fig.5.

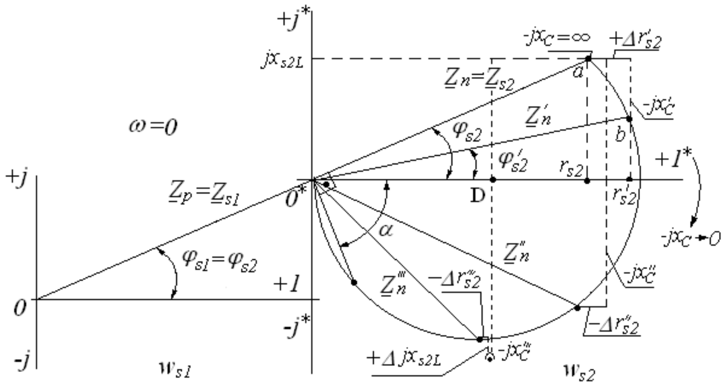


Fig.4. The diagram of SACM resistances with the phase shifting part of the stator winding, where the coordinates of the center of the resistance circuit – (point D) are $\left[\frac{Z_n}{2}Cos\varphi_{s2};\,j0\right]$

As follows from the dependence $x_n(n)$, when the capacitance of the condenser increases from zero to infinity, which corresponds to the segment $(-jx_C)$ in Fig.4, there is a phenomenon of the stator winding phase-shifting part active resistance increasing within the phase angle $31{,}74^0 > \varphi_{s2} > 0$ with a simultaneous decrease in reactive inductive resistance.

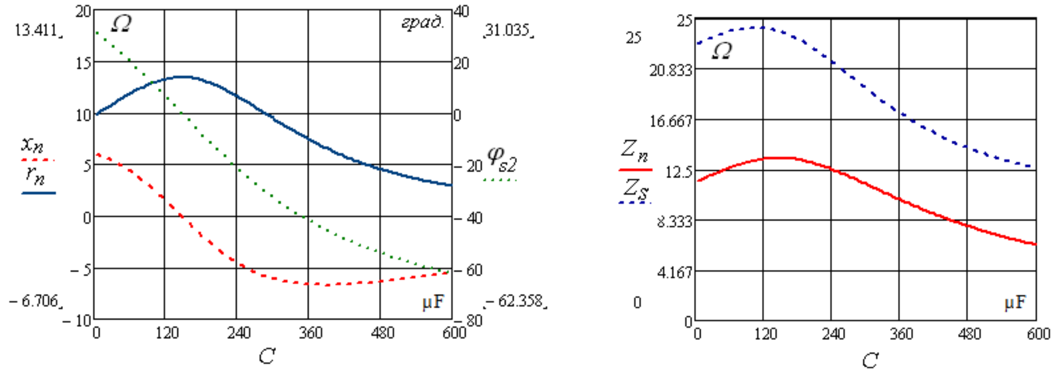


Fig.5. Dependences of the resistance modules of the stator winding phase shifting part R_n, X_n, Z_n, its argument φ_{s2} and the full resistance of the stator winding $Z_s = Z_{s1} + Z_{s2}$ depending on the capacitance C of the condenser branch

Further increase in the condenser capacitance is accompanied by an asymptotic decrease in the active component of the resistance of the stator winding phase-shifting part to zero.

As for the full resistance reactive component of the winding phase-shifting coil, after the active resistance reaches the value $r_{s2} = \frac{Z_n}{2}Cos\varphi_{s2}$ at point D, the growth of the capacitive component of the reactance is compensated by the growth of the reactive inductive resistance.

In view of the foregoing, the vector diagram of currents and voltage of the developed motor with stator winding in which the starting part is provided, differs from one shown in Fig.3 (a) and will look like Fig.3 (b), which should be taken into consideration when developing SACM mathematical model. Capacitance of the starting condenser of the investigated motor model is $C_n = 530\mu F$, of industrial motor $C_p = 140\mu F$ at 200 V amplitude of supply voltage.

4. Conclusions

1. The reduction of electricity consumption in the housing/utilities and agro-industrial sectors of the economy at the current level is associated with the use of adjustable electric drive with the use of frequency converters, three-phase asynchronous and synchronous motors with permanent magnets. This choice is based on the assumption that OAM and ACM have reached energy efficiency parameters limits. But from the “Electric machines” general course it is known that three-phase low-power asynchronous motors are inferior to their single-phase counterparts in terms of energy efficiency. Moreover, in case of frequency converter damage, the use of the electric drive becomes impossible for a long time. Therefore, it is desirable to use the motor, which could operate both from the frequency converter and by direct connection to the mains. To make it possible, the motor winding must be symmetrical, which corresponds to SACM.

2. Performed by comparison, testing of SACM, made on the basis of ACM and installed into the NKV 10-3-K motor compressor unit, proved that at the boiling point of freon -20^{0}C refrigeration capacity of compressors was the same and amounted to 183.2 W, the active power consumption of the motors is almost the same - 123.1 W in the industrial sample and 120.6 W in the new one, and the current consumed from electrical grid is 0.63 A in the industrial sample and 0.55 A in the new one.

The given figures indicate that the advantage is on the side of the new motor model. The conducted testing indicates on higher power efficiency of the new motor, lower losses and higher power factor, and, consequently, its power efficiency class is higher than IE3.

3. The developed circuit diagram and vector diagram of currents will be useful in compiling the equations of SACM electrical equilibrium to build its mathematical model for performance characteristics calculating both in statics and dynamics.

Abbreviations

OAM - one-phase asynchronous motor
ACM - asynchronous condenser motor
SACM - single-phase asynchronous capacitor motor

Nomenclature

I_{s2} - full current in the phase shifting part of the stator winding

C - capacitor

I_{s2a} - active inductive components of full current

$I_{s2\sigma}$ - reactive inductive components of full current

φ_{s2} - total current shift angle I_{s2} relative to the voltage $U_{s2} = U_C$

r_{s2} - active inductive resistance of the phase-shifting part of the stator winding

$x_{s2\sigma}$ - reactive inductive resistance of the phase-shifting part of the stator winding

$Cos\varphi$ - power factor

η - energy efficiency

I_C - capacitive current in the branch with a capacitor

I_{s2L} - reactive inductive current

r_n - active components of full resistance

jx_n - reactive components of full resistance

$\underline{Z}_n$ - full resistance

x_c - capacitive resistance

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ОГЛЯД СУЧАСНИХ СХЕМ РЕГУЛЮВАННЯ КОНТУРАМИ ПИЛОВУГІЛЬНИХ КОТЛОАГРЕГАТІВ ТЕС ПРИ НЕСТАЦІОНАРНОСТІ ЇХ ДИНАМІЧНИХ ХАРАКТЕРИСТИК

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Анотація: *В структурі генеруючих потужностей Об’єднаної енергосистеми України енергоблоки теплоелектростанцій (ТЕС) потужністю 200 і 300 МВт несуть основне навантаження для забезпечення балансу добового графіка електронавантаження в напівпіковому режимі. В 2022 році ці енергоблоки були однією з основних цілей ракетних атак з метою розбалансування енергосистеми. Аварійне відключення одних енергоблоків має компенсуватися потужністю інших, в протилежному випадку впроваджуються аварійні відключення електропостачання споживачів. Питання підвищення маневрових можливостей існуючих енергоблоків сьогодні стоїть вкрай гостро. Котлоагрегатам ТЕС притаманні зміни динамічних характеристик при зміні режиму їх роботи. Тому до систем регулювання висуваються підвищені вимоги до якості функціонування і запасів стійкості. Стаття містить аналіз сучасних розробок в області синтезу робастних і адаптивних систем регулювання інерційними контурами котлоагрегатів ТЕС. Розглянуті схеми регулювання з*