Selection of Asynchronized Turbogenerators Parameters Taking into Account the Operating Mode

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Abstract. The purpose of the work is to develop an algorithm for calculating currents in the asynchronized turbogenerator rotor windings when it operates at a power system with a variable load. Typically, synchronous turbogenerators of thermal power plants are used to maintain the balance of active and reactive power in the power system. But they cannot fully ensure the maintenance of balance by switching to non-nominal modes: during periods of power consumption dips, reduce power to 50-70% and switch to under-excitation mode to compensate for reactive power. Therefore, it is promising to install asynchronized turbogenerators at power plants in parallel with synchronous turbogenerators, which remain stable over a wide range of changes in active and reactive power. The work analyzed data from the operation of asynchronous turbogenerators in different countries. The subject of the study was an ASTG-200-2U3 asynchronized turbogenerator with two identical field windings. The goal of the work was achieved by calculating the field windings currents using the finite element method and modeling in the FEMM program when the load magnitude and nature changes. The most important results of the work are the proposed algorithm for calculating the asynchronized turbogenerators field currents depending on the load size and nature in order to maintain the frequency and voltage nominal values. The significance of the results obtained lies in the fact that practical recommendations have been obtained for choosing the asynchronized generator load angle depending on the load size and nature, including in the modes of consumption of reactive energy.
***Keywords*:** asynchronized turbogenerator, synchronous turbogenerator, the load nature, rotor winding, magnetic field modeling.

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Selectarea parametrilor turbogeneratoarelor asynchronizați ținând cont de modul de funcționare

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Rezumat. Scopul lucrării este de a elabora un algoritm de calcul al curenților în înfășurările rotorului unui turbogeneratorului asinhron atunci când acesta funcționează la un sistem de alimentare cu sarcină variabilă. În mod obișnuit, turbogeneratoarele sincrone ale centralelor termice sunt utilizate pentru a menține echilibrul puterii active și reactive în sistemul energetic. Dar nu pot asigura pe deplin menținerea echilibrului prin trecerea la moduri non-nominale: în perioadele de scădere a consumului de energie, reduceți puterea la 50-70% și treceți la modul de subexcitare pentru a compensa puterea reactivă. Prin urmare, se promite instalarea turbogeneratoarelor asincrone la centralele electrice în paralel cu turbogeneratoarele sincrone, care rămân stabile pe o gamă largă de modificări ale puterii active și reactive. Lucrarea a analizat date din funcționarea turbogeneratoarelor asincrone în diferite țări. Subiectul studiului a fost un turbogenerator asincron ASTG-200-2U3 cu două înfășurări de câmp identice. Scopul lucrării a fost atins prin calcularea curenților înfășurărilor de câmp folosind metoda elementelor finite și modelarea în programul FEMM atunci când magnitudinea și natura sarcinii se modifică. Cele mai importante rezultate ale lucrării sunt algoritmul propus pentru calcularea curenților de câmp a turbogeneratoarelor asincrone în funcție de mărimea și natura sarcinii pentru a menține valorile nominale de frecvență și tensiune. Semnificația rezultatelor obținute constă în faptul că s-au obținut recomandări practice pentru alegerea unghiului de sarcină a generatorului asincron în funcție de mărimea și natura sarcinii, inclusiv în modurile de consum de energie reactivă.
Cuvinte-cheie: turbogenerator asinhron, turbogenerator sincron, natura sarcinii, înfășurarea rotorului, modelarea câmpului magnetic.

Выбор параметров асинхронизированных турбогенераторов с учетом режима эксплуатации

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Аннотация. Целью работы является разработка алгоритма расчета токов в обмотках ротора асинхронизированного турбогенератора при его работе на энергосистему с переменной нагрузкой. Обычно для поддержания баланса активной и реактивной мощности в энергосистеме используются синхронные турбогенераторы тепловых электростанций, которые не могут в полной мере обеспечить поддержание баланса за счет перехода в неноминальные режимы: в период провалов энергопотребления снижать мощность до 50-70% и переходить в режим недовозбуждения для компенсации реактивной мощности. Поэтому перспективно на электростанциях параллельно с синхронными турбогенераторами устанавливать асинхронизированные турбогенераторы, которые сохраняют устойчивость в широком диапазоне изменения активной и реактивной мощности. При проведении работы были проанализированы данные эксплуатации асинхронизированных турбогенераторов на электростанциях разных стран. Как предмет исследования, был рассмотрен асинхронизированный турбогенератор АСТГ-200-2У3 с двумя одинаковыми, автономными, взаимно-перпендикулярными обмотками возбуждения. Поставленная в работе цель достигается расчетом токов в обмотках возбуждения при изменении величины и характера нагрузки с использованием метода конечных элементов и моделирования в программе FEMM. Наиболее важными результатами работы является предложенный алгоритм расчета токов возбуждения асинхронизированных турбогенераторов в зависимости от величины и характера нагрузки с целью поддержания номинальных значений частоты и напряжения. Значимость полученных результатов состоит в том, что получены практические рекомендации по выбору угла нагрузки асинхронизированного генератора в зависимости от величины и характера нагрузки, в том числе в режимах выдачи и глубокого потребления реактивной энергии. Показано, что установка асинхронизированных турбогенераторов параллельно с синхронными турбогенераторами исключает необходимость перевода синхронных турбогенераторов в неноминальные режимы, для которых они не предназначены и которые являются причиной ускоренного износа.

Ключевые слова: асинхронизированный турбогенератор, синхронный турбогенератор, характер нагрузки, обмотка ротора, моделирование магнитного поля.

INTRODUCTION

The operation of modern energy networks has significant features: there are large "dips" and pronounced "peaks" in electricity consumption; the power plants electrical equipment is worn out, but the global economic crisis and, especially, war, do not make it possible to replace it in a timely manner; the contribution to the overall energy system from generators powered by renewable energy sources has increased significantly.

Therefore, in order to maintain the frequency and voltage nominal values in the network, it is necessary to constantly regulate the active and reactive power balance in the power system and ensure compensation for excess reactive energy [1-3].

The amount of reactive power that goes to the consumer affects the design parameters of electricity transmission lines, since it leads to an increase in the total network current and, accordingly, to the need to increase the wires cross-section.

This increases the cost of overhead power transmission line (OHPL) supports and requires increasing the power of transformers [2, 4].

For power lines that are already in operation, the current magnitude I, which is transmitted through wires of a certain cross-section, is known. Compensation (reduction) of reactive power allows you to increase the amount of active power that is transmitted through the same wires without changing the cross-section:

$$I = \frac{\sqrt{P^2 + Q^2}}{3 \cdot U_f}, \text{A}.$$

where P and Q – active (W) and reactive (var) power, respectively;

U_f – phase voltage of three-phase network, V.

Sufficient compensation of reactive power through the installation of compensating devices (shunt reactors, autotransformers, transformers with voltage regulation and other systems) allows to reduce active power losses, W:

$$\Delta P = \frac{P^2 + Q^2}{U^2} \cdot R.$$

Network voltage is related to the reactive power balance and determines the voltage across the load U_{load}:

$$U_{load}^2 = \left(E - \frac{Q_{load} + \Delta Q}{E} \cdot X_\Sigma\right)^2 - \\ - \left(\frac{(P_W + \Delta P) \cdot X_\Sigma}{E}\right)^2$$

where E – electric field strength, V/m;

Q_{load}– reactive power in the network, var;

ΔQ – total reactive power losses in the network and generator, var;

X_{Σ} – total reactance in the network, Ohm;

P_w – active load power, W;

ΔP – sum of active power losses in the network and generator, W.

To solve the issue of maintaining the energy balance in the system, it is not enough to use only the specified compensation installations. It is also possible to disconnect overhead power lines that are lightly loaded, but this reduces the reliability of the power system and worsens the power supply to consumers.

The most effective way to reduce network voltage, which has increased due to excess reactive energy, is to switch synchronous turbogenerators (TG) to reactive power consumption mode. This solution is only possible for thermal power station generators. Changing the operating mode of turbogenerators at nuclear power plants is unacceptable [2, 5].

However, the operational characteristics of TG of thermal stations that operate in a state of physical wear and tear do not correspond to such operating conditions. They are not maneuverable enough and are significantly limited in the consumption of reactive power from the network; their parameters are determined by the capabilities of the cooling systems and the resulting excess mechanical forces in the stator core end packages [6, 7].

These efforts increase in the reactive power consumption mode (in the under-excitation mode). At the same time, the density of the stator core packages decreases, the teeth of the end packages bend, deformation of the stator winding frontal parts occurs, and ruptures of bands and insulation are possible. The vibration of the generator, the number and duration of repairs increases significantly [3-6].

Therefore, it can be argued that the problem of normalizing the voltage and frequency in the power system cannot be solved only by changing the operating mode of synchronous generators.

It is necessary to additionally install static or electrical machine devices for regulating reactive power, or install new types of TG at power plants that can operate stably in the modes of supply and deep consumption of reactive energy [9-11].

METHODS, RESULTS AND DISCUSSION

Domestic and world experience shows that for this purpose it is advisable to use asynchronized turbogenerators (ASTG), which are installed in parallel with synchronous TGs at thermal power plant units [9, 12-17].

They generate active energy, maintain a balance of active and reactive energy in the network, which ensures normalization of voltage and frequency, and increases the reliability of synchronous TGs that operate nearby [17-20].

The issue of using ASTG arose in the 90s of the twentieth century. During this period, due to the decline in industrial production, the active power transmitted through overhead power lines decreased [10, 20, 21].

This causes an increase in voltage in high-voltage networks (220-750 kV) due to the ground-line capacitor effect, which significantly increases the reactive energy in the lines. There have been cases of an increase in voltage in 500 kV lines to 540 kV with an acceptable value of 525 kV. Increased voltage accelerates wear of electrical equipment, shortens the service life of transformers insulation, switches, disconnectors, autotransformers [22-24].

In 1985, in Ukraine, at the Burshtyn TPP, for the first time in world practice, was put into operation ASTG with a capacity of 200 MW (ASTG-200-2U3), created on the TGV-200-2U3 generator basis at the plant “Elektrotyazhmash” (Kharkov, Ukraine). In 1991, the second ASTG was put into operation at the Burshtyn TPP. On March 22, 2024, these blocks were destroyed by Russian missiles.

ASTG is a complex that included a synchronous machine with a symmetrical two-phase rotor winding and an excitation control system. In this work, to obtain practical results, ASTG-200-2U3 is considered. The excitation system consists of two reversible controlled rectifiers (according to the number of rotor windings) and an automatic excitation regulator. The rectifiers are connected to the power system through a transformer.

The automatic excitation regulator receives signals about the generator stator winding voltage and current values, about the rotor current, and about the rotor angular position (the value of the angle δ). The automatic excitation regulator contains voltage and electromagnetic torque regulators and a rotor position coordinate converter.

ASTG can operate synchronously and with slight slip, in which the magnetic field of the field winding currents can move relative to the rotor surface. The rotor is massive, so the permissible slip S_{acc} can be very small, within the range of $S_{acc} \leq 0.001$. This slip value is set to limit additional heating from eddy currents in the rotor array. The position coordinate converter in the automatic excitation regulator block regulates the angle δ – the angle that determines the position of the rotor geometric axis relative to the stator voltage vector.

The angle setter block in the automatic excitation regulator determines the value of the angle δ. Such feedback on the angle δ is introduced to limit the range of slip changes in operating mode. In steady-state conditions, such a connection ensures a synchronous rotor speed (without slipping), and also serves to automatically equalize the currents in the two excitation windings, which ensures uniform heating of the rotor, [18].

Two windings with autonomous regulation, the ability to work with slight slip, information and the ability to regulate the angular position of the rotor in the ASTG allows you to simultaneously adjust its electromagnetic torque M_{elm} and the amount of reactive power Q_{ASTG}.

This is the main difference between ASTG and synchronous TG, [5, 6]:

$$M_{elm} = -U_s \cdot \frac{X_{af} \cdot I_{fy}}{X_s};$$
$$Q_{ASTG} = U_s \cdot \frac{X_{af} \cdot I_{fx} - U_s}{X_s},$$

where U_s is the ASTG stator winding voltage;

X_{af} – mutual inductance resistance of the stator and rotor windings;

X_s – the stator winding inductive reactance;

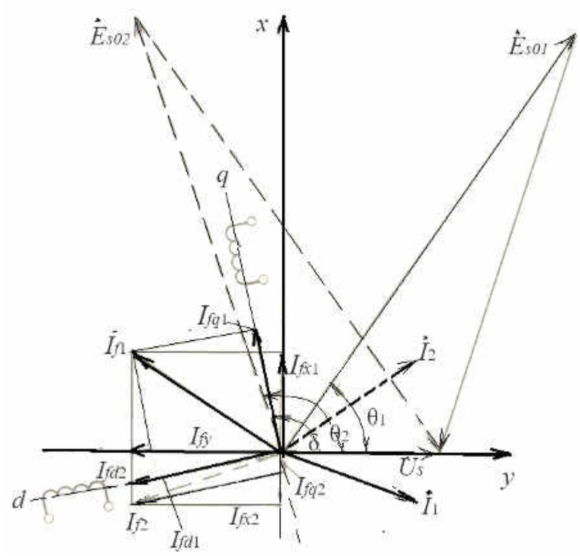
I_{fx} and I_{fy} are projections of the excitation current I_f on the x and y axes, which are rotated relative to the d and q axes by an angle δ, Fig. 1.

The use of an asynchronized control principle makes it possible to separately control the electromagnetic torque and reactive power of the ASTG, regardless of the rotor speed and its angular position.

As follows from the vector diagram (Fig. 1), to change the reactive power compensation mode (consumption or generation) it is enough to redistribute the currents in the rotor windings.

Also, the angular position of the rotor δ can be adjusted regardless of changes in the operating mode and load angle θ due to the ability to autonomously redistribute currents in the field windings. Such capabilities allow ASTG to operate stably under variable load schedules, provide broad regulation of active and reactive power in the power system, and maintain their necessary balance.

ASTGs free synchronous TGs that operate nearby from the tasks of regulating the power balance in the network, which is necessary to extend their service life. Therefore, the creation of an algorithm for calculating the ASTG parameters, in particular its field current, is of practical importance.



θ_1 – ASTG load angle in the mode of delivering reactive power to the power system simultaneously with active power; θ_2 – ASTG load angle in the mode of consuming reactive power from the power system simultaneously with the output of active power

Fig. 1. ASTG vector diagram: mode of reactive power output to the power system (solid lines) and mode of consumption of reactive power from the power system (dashed lines)

It is necessary to know the rules for changing currents in the field windings when regulating the balance of active and reactive power when the nature and magnitude of the load in the power system changes.

The subject of our study was ASTG-200-2U3 with two identical windings on the rotor, which are shifted by 90°, Fig. 2.

The phase zones $A{-}A', B{-}B'$ and $C{-}C'$ of the stator winding show in Fig. 2; two symmetrical rotor windings $RA{-}RA', RB{-}RB'$, in which direct currents i_{rA} and i_{rB} flow, are indicated. They correspond to the instantaneous values of the stator phase currents (i_{sA}, i_{sB}, i_{sC}).

ASTG has the following parameters: nominal power $P_N = 200$ MW, phase voltage $U_N = 9095$ V, rated stator current $I_{sN} = 8625$ A; power factor $\cos\varphi_{sN} = 0.85$ (leading); network frequency $f_s = 50$ Hz; the stator core outer diameter $d_{se} = 2.43$ m; active length of the stator core and rotor "barrel" $l_s = 2.7$ m; air gap $\delta = 77.5$ mm; stator slots number $Q_s = 30$, rotor slots number $Q_r = 44$, outer rotor diameter $d_{re} = 0.56$ m,

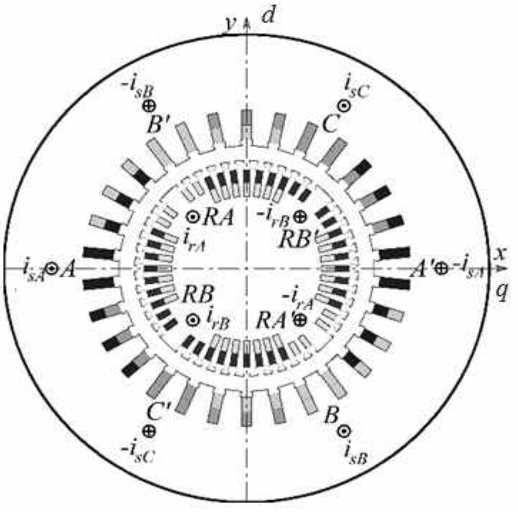


Fig. 2. Calculation model of the electromagnetic system ASTG (cross section)

Direct current is supplied to both excitation windings from autonomous sources; in steady state, the currents in both windings are equal. To excite ASTG, a static thyristor self-excitation system is usually used, which consists of two identical reversible thyristor exciters, the current into which is supplied from the ASTG terminals through a converter transformer.

In transient modes, the automatic excitation control system simultaneously and independently controls the currents in the two rotor windings. Such regulation ensures stable operation of the ASTG when the balance of active and reactive power changes, including when there is significant consumption of reactive power.

During the research, the stator winding voltage and the generator power factor cosφ were considered constant [17, 19].

Usually, the calculation of the total magnetic field, taking into account the rotating ASTG rotor magnetic field, is based on multi-position numerical calculations of a quasi-stationary magnetic field. At the same time, we believe that the contribution from eddy currents in the rotor core to the overall picture of magnetic fields is negligible and can be ignored [6, 11. 19].

A quasi-stationary magnetic field is described by the differential equation [6]:

$$\mathrm{rot}\left[\frac{1}{\mu} \cdot \mathrm{rot}(\vec{k}A_z)\right] = \vec{k}J_z$$

where μ is the absolute magnetic permeability;

A_z and J_z – axial components of the vector magnetic potential and current density, respectively; $\vec{k}$ – ort of the axis z.

The magnetic field was calculated using the finite element method using the FEMM program [20, 25]. The specific operating mode of the ASTG is determined by the ratio of the rotor winding current I_f and the symmetrical system of phase currents of the stator winding (load).

The magnetomotive force (MMF) F_f and F_s are directed along the d axis at the moment $t = 0$. We consider the mode when the direction of the d axis is formed by identical symmetrical currents in both rotor windings [6, 16].

When modeling on the outer surface of the stator core (at the boundary of the calculation area), we use the Dirichlet boundary condition A_z=0.

As the beginning of the phases in any of the design modes, we use the direction of the MMF vector of the phase winding $A - A'$ (base winding), which is oriented along the longitudinal axis of the rotor d.

The phase values of the stator winding currents can be written, A:

$$I_A = I_m \cdot \cos(\omega t + \beta);$$
$$I_B = I_m \cdot \cos(\omega t - \frac{2\pi}{3} + \beta);$$
$$I_C = I_m \cdot \cos(\omega t + \frac{2\pi}{3} + \beta),$$

where $I_m = \sqrt{2}I_s$ – stator current amplitude, A;

t – time, s;

$\omega = 2\pi f$ – angular frequency,

$\beta = \varphi + \theta$ – angle between the stator winding phase current vector I_s and the idling mode electromotive force (EMF) vector E_{s0}, el. degr.;

φ – shift angle between current and voltage vectors, el. degr.;

θ – the angle between the vectors E_{s0} and U_s, which depends on the load nature (load angle), el. degr.

For the considered model, the distribution of magnetic fields in the ACTG was obtained (Fig. 3).

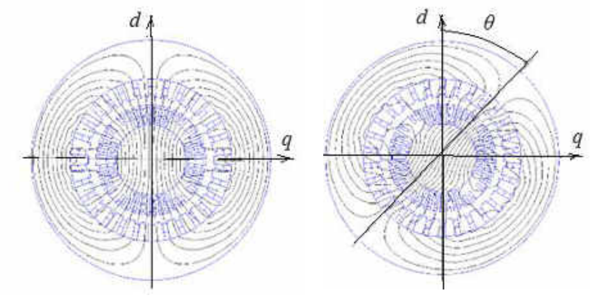
Based on the methodology outlined in the current values in the field windings ($I_{f0} = 946.6\ A$) were determined, which determine the value of the phase EMF in idling mode [17, 18].

$$E_l = \sqrt{E_{la}^2 + E_{lr}^2} = \sqrt{7750^2 + 5256^2} = 9364\ \mathrm{V},$$

where:

$$E_{la} = U_s \cdot \cos\varphi + U_R = 9093 \cdot 0{,}85 + 21 = \\ = 7750 \text{ V}$$
$$E_{lr} = U_s \cdot \sin\varphi = 9093 \cdot 0{,}56 = 5656 \text{ V};$$
$$U_R = I_s \cdot R_s = 8625 \cdot 0{,}00247 = 21 \text{ V};$$

where R_s= 0,00247 Ohm – the stator winding active resistance (per phase).



a *b*

Fig. 3. Distribution of magnetic fields in ASTG
***a* – in idling mode;**
***b* – in nominal mode**

The multiplicity of the ASTG excitation current, in comparison with the current of a synchronous TG of similar power (912 A), providing the rated voltage in idling mode, is equal to:

$$k_f = \frac{949{,}6}{912{,}0} = 1{,}04.$$

If in the mode of 50% of the rated load (I_s= $= 0.5 \cdot I_{sN}= 4312\ A$) the current in the field winding is not changed, then an EMF:

$$E_{f0} = E_l = 9364 \text{ V}.$$

In this case, the EMF from the armature reaction flux will be equal to:

$$E_a = E_{a0} \cdot \frac{I_s}{I_{s0}} = 9364 \cdot \frac{8625}{4324} = 18678 \text{ V}.$$

Similarly, at a rated load ($I_{sN} = 8625\ A$), the total EMF will be equal to 25157 V.

In this mode, the ACTG parameters are determined by the rated stator current and angle β, el. degr.:

$$\beta = -\varphi l + \theta + 90 - \xi_f = \\ = -(\varphi_l - \theta - 90 + \xi_f) = -162;$$

where $\xi_f = 0{,}11$ – flux linkage initial phase.
In this case, the total EMF will be equal to:

$$E_{fl} = \sqrt{E_{la}^2 + (E_a + E_{lr})^2} = \\ = \sqrt{7750^2 + (18678 + 5256)^2} = 25157 \text{ V}.$$

This mode corresponds to the load angle θ and the current in the rotor windings I_f:

$$\theta = \operatorname{arctg}\frac{E_a + E_{lr}}{E_{la}} - \varphi_l = 77 - 34 = \\ = 43 \text{ el. degr};$$
$$I_f = I_{f0} \cdot \frac{E_{fl}}{E_{f0}} = 949{,}6 \cdot \frac{25157}{9364} = 2551 \text{ A};$$
$$E_v = I_s \cdot X_v = 8625 \cdot 0{,}054 = 466\ V;$$

where $X_v = 0{,}054$ Ohm – is the inductive resistance of the stator winding frontal parts.

The values of the angle β and currents in the rotor windings, which are necessary to ensure the nominal parameters of the ASTG, are calculated:

$$\beta = -59{,}5 \text{ el. degr. and } I_f = 2471 \text{ A}.$$

With these values in the rated load mode, the ASTG parameters will be nominal:

$$\cos\varphi_N = 0{,}85;\ P_N = 200 \text{ MW};$$
$$U_{sN} = 9093{,}2 \text{ V}.$$

Calculation data using the proposed algorithm for different load values are presented in Table. 1 and shown in Fig. 4 (regulating characteristic of ASTG) and in Fig. 5 (recommended changes in angles β and θ ASTG depending on changes in load).

Table 1

Recommended values of ACTG parameters at different loads (I_s), provided that the values $U_{sN} = 9093\ V$ and $\cos\varphi_N = 0.85$ are maintained constant

I_s, A	8625	8000	7000	6000	5000	4000	3000	2000	1000	0
I_f, A	2471	2342,4	2139,8	1932,1	1733,8	1543,8	1360,7	1192,5	1041,1	912,0
$-\beta$, el. degr	159,5	158,6	157,12	154,9	152,3	149,1	144,8	139,2	131,8	121,7
θ, el. degr.	35,4	34,6	33,4	31,4	29,1	26,2	22,1	16,9	9,7	0
P_a, MW	200,0	185,7	161,6	139,3	116,0	92,6	69,5	46,4	23,2	0

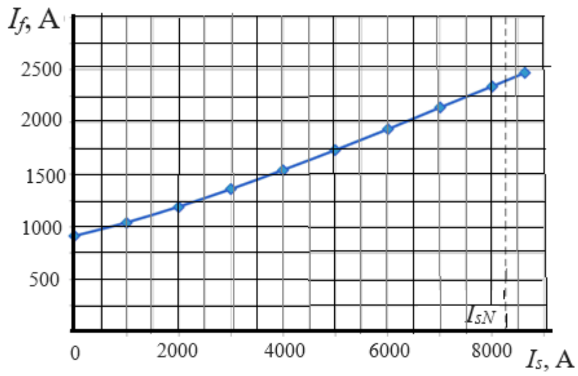


Fig. 4 – Recommended changes in ASTG excitation current depending on load changes I_f=f(I_s)

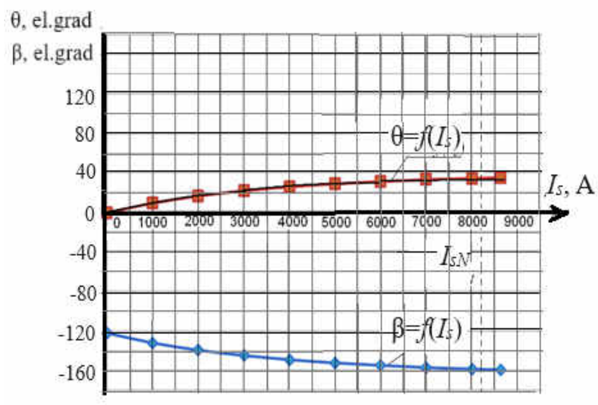


Fig. 5 – Recommended changes in angles β and θ ASTG depending on changes in load (stator current I_s) β = f(I_s) and θ = f(I_s)

Conclusions

1. It is shown that the problem of regulating voltage and frequency levels in the power system cannot be solved only by changing the operating modes of synchronous turbogenerators TPPs. For example, by reducing their power to 50-70% of P_N during "gaps" in energy consumption. It is necessary to additionally install static or electrical machine reactive power control devices, or which is more expedient and promising, to install asynchronized turbogenerators at power plants in parallel with synchronous turbogenerators.

2. Asynchronized turbogenerators can operate stably in the modes of supply and deep consumption of reactive energy, and maintain the parameters of the electrical network. This also eliminates the need to transfer synchronous TGs to non-rated modes for which they are not intended.

3. An algorithm was obtained for calculating the asynchronized turbogenerator excitation currents, angles θ and β depending on the stator current (from the load), which are necessary to ensure the nominal balance of active and reactive power in the power system when the load changes, including with deep consumption of reactive power. At the same time, the ASTG operation stability is maintained. During the research, the stator winding voltage and the generator power coefficient cosφ_N were considered constan.

4. The use of the proposed algorithm eliminates the need to re-simulate magnetic fields with each load change in the power system and will allow one to abandon the selection of current values in the field windings (I_f) depending on the load (load angles θ).

5. The proposed calculation algorithm was tested for ASTG-200-2U3 (cosφ_N=0.85; P_N=200 MW; U_{sN}=9093.2 V).

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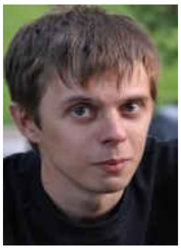

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