Bases of calculation and design of asynchronous diesel generators for autonomous system of power supply

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Abstract. The article discusses the characteristics of diesel generator sets currently used in autonomous power supply systems. The modes of operation of synchronous generators and their overload capacity are analyzed. The overloading capacity of diesel generator sets (DGS) can be significantly increased when used as an electromechanical energy converter of asynchronous generators (AG). The initial algorithm for their selection involves calculating the optimal value of the rotor speed and choosing the range of rotation frequency. The value of the optimal value of the rotational speed is determined depending on the method of maintaining the constancy of the current frequency when calculating the parameters of an autonomous asynchronous semiconductor cascade, which is understood as an AG together with its excitation and control system. The dependences of individual terms of electrical power losses on the operating mode of an autonomous asynchronous semiconductor stage are considered. After determining the optimal speed, the possible AG power is selected. Then, from a number of powers, its nominal power is selected. After determining the rated power, the minimum and maximum values of the rotational speed, it is possible to determine the optimal operating modes of the diesel generator set with the AG. As a criterion of optimality, the specific effective fuel consumption of the diesel generator set is taken. This approach to the choice of the type of diesel generator set when designing autonomous power supply systems requires a detailed consideration of the technical and economic characteristics of the units. The proposed design principles can ensure the most complete use of the positive properties of a diesel engine and an electromechanical energy conversion system, as a result of which to improve the technical and economic characteristics of autonomous power supply systems.

1. Introduction

Introduction. The success of the operation of commercial and municipal facilities (CMO) largely depends on the uninterrupted operation of technical life support systems, the most important of which is the guaranteed power supply system (GES).

SGEP is designed to ensure uninterrupted supply of all consumers of KMO with electricity in accordance with established standards that determine the requirements for the quality of electricity in case of emergency outages from main sources.

As the most reliable and economical in such systems, diesel generator sets (DGU) with aggregate power from 5 to 4000 kW have become widespread. Synchronous machines (SM) [3] are used as...
converters of mechanical energy into electrical energy in DGS [3], which sometimes perceive uneven and unstable load, which are harmful modes for the operation of the generator.

The article proposes a method for adjusting the SGEP generator to a sharply variable characteristic of the network using an asynchronized generator with a variable speed. The reliability and efficiency of the autonomous power supply systems depend significantly on the type and operating modes of the drive motor of the power source. The choice of the motor for the drive of synchronous (SG) and asynchronous (AG) generators should be made on the basis of the characteristic features of their operation. For any type of generator, the correct choice of the engine provides for a detailed analysis of its limiting and external characteristics together with the energy characteristics of the generator [1, 2].

2. Materials and methods
Currently, autonomous power supply systems use, as a rule, diesel engines developed for transport installations. Such diesel engines have all-mode speed controllers \( n \), which ensure stable operation in a wide range of \( n \) from \( n_{\text{min}} \) to \( n_{\text{max}} \). The characteristics of such motors can be as shown in Figure 1, where the \( ef \) curve represents the full external characteristic, the \( ab \) and \( dc \) curves are the upper and lower limiting characteristics. In accordance with the definitions of these characteristics, the figure of the \( abcd \) determines the field of possible modes that do not have any restrictions on the duration of work. The operation of the engine according to the external characteristic is possible only during the limitations on the duration of operation (up to 1-2 hours). In this regard, the shaded areas of the figure \( ef3de \) should be understood here as a field of modes in which the duration of continuous operation and the total operating time during operation are limited. All modes falling into this shaded field can be considered as overload modes; knowing this, you can choose the power and speed of the drive generator[3,4]. And in Figure 2 shows a universal characteristic and the field of possible modes of operation of a diesel engine with an asynchronous generator (AG).

![Figure 1. Field of possible operating modes of a diesel engine and DG with a synchronous generator.](image1)

![Figure 2. Universal characteristic and field of possible modes of AG operation.](image2)

When using a synchronous generator, its rotation frequency \( n_c \) is selected depending on the number of pairs of generator poles and the frequency of the generated current \( f \). So, at \( f = 50 \text{ Hz} \), the synchronous rotation frequency \( n_c \) can take one of the following values: 3000, 1500, 1000, 750, 500, 375, 300, 250, 200 rpm, etc. Based on the mass requirements - the overall parameters of the power
plant, the value of \( n_e \) is selected (it is obvious that \( n_{\text{min}} < n_e < n_{\text{max}} \)) and then the possible rated power of the generator \( P_{\text{nom}} \) is determined [5].

Figure 1 it is clearly seen that at \( n_e \) the rated power of the generator can be equal to

\[
P'_{\text{nom}} = N_{e2} \eta_g
\]  

(1)

where \( N_{e2} \) - engine power according to the limiting characteristic at \( n = n_e; \eta_g \) - generator efficiency.

After determining \( P'_{\text{nom}} \), the nearest \( P_{\text{nom}} \) is selected from the range determined by GOST 12139-84, subject to the condition \( P_{\text{nom}} \leq P'_{\text{nom}} \). In the case of using SG, diesel engines must operate according to the regulatory characteristic with a slope of 2-6%. Moreover, the regulator is usually adjusted so that \( n = n_e \) at \( N_e \approx 0,5 N_{\text{e_nom}} \) where \( N_{\text{e_nom}} = P_{\text{nom}}/\eta_g \). Thus, the field of possible modes of operation of a diesel generator (DG) is narrowed to a narrow band, indicated in Fig. 1 hatched line 51'23'4'. It can also be seen here that, due to the slope of the regulatory characteristic, the overload capacity of the DG slightly decreases (the power at points 2' and 4' is less than at points 2 and 4). The maximum power of the DG at overload \( N_n \) is determined from the condition

\[
N_{e \text{ nom}} < N_e < N_{e \text{ max}}
\]  

(2)

The overload capacity of diesel generator sets (DGU) can be significantly increased when used as an electromechanical energy converter AG [6-10]. The peculiarity of such diesel generators is the ability to operate with variable speed and the algorithm for their selection is as follows. At the beginning, the optimal value of \( n_{\text{opt}} \) is calculated and the range of change in the rotational speed \( \Delta n \) is selected. The value of \( n_{\text{opt}} \) is determined depending on the method of maintaining the constant frequency of the current \( f \) at \( n=\text{var} \) when calculating the parameters of an autonomous asynchronous semiconductor stage (AAPC), which is understood as an AG together with its system of excitation and control. Energy is supplied to the AG stator in two ways: electromechanically from the internal combustion engine shaft and electromagnetic through the rotor circuit from the excitation system. Generator electromagnetic power[10-12]

\[
P_{el} = N_e + P_{el},
\]  

(3)

where \( P_{el} \) - is the effective power of the diesel engine (mechanical power); \( P_{el} \) - electrical power of the excitation system.

The components of the electromagnetic power are:

\[
N_e = P_{el} (1 - s); \quad P_{el} = P_{el}^*.
\]  

(4)

(5)

where \( s \) - the AG rotor slip \( [s = (n_e - n)/n_e] \)

At a synchronous rotation frequency \( (n=n_e) \), \( s=0 \) and \( N_e=P_e \). If \( s \neq 0 \), then the change in the mechanical energy supplied to the AG rotor should be compensated by the change in the power supplied from the excitation system. Since in AAPK the excitation energy of the AG is also obtained due to the effective power of the engine, then

\[
N_e = P_e + \sum \Delta P,
\]  

(6)

where \( P_e \) - generator power

\( \Delta P \) - the sum of all losses in the AAPC.

Let us consider the dependences of the individual terms \( \sum \Delta P \) on the AAPC operating mode.

Additional and mechanical losses in the AG \( \Delta P_{a,m,AG} \) depend on the AG power and its rotor speed. This dependence can be represented as

\[
\Delta P_{a,m,AG} = \Delta P_{a,m,AG(0)} + \Delta P_{a,m,AG(0)} (1-s) k
\]  

(7)

where \( \Delta P_{a,m,AG(0)} \) - additional and mechanical losses of AG at \( s = 0 \); \( k \) - coefficient of proportionality.

Additional and mechanical losses in the pathogen \( \Delta P_{a,m,p} \) depend on the power of the pathogen in the about the same way as in the AG. If we also take into account the fact that the power of the pathogen depends on \( \Delta n \), then

\[
\Delta P_{a,m,p} = \Delta P_{a,m,p(0)} \alpha (1+\Delta s) + \Delta P_{a,m,p(0)} (1-s) k
\]  

(8)

where \( \alpha \) - a value showing a change in the additional and mechanical losses of the synchronous exciter as a result of a change in the rotation frequency, causing a change in the slip of the rotor by the value of \( \Delta s \); \( \Delta P_{a,m,p(0)} \) - additional and mechanical losses in the exciter at \( s = 0 \); \( \alpha \) - the proportionality coefficient.
Losses in the excitation system of the exciter $\Delta P_{e,e}$ in the general case, the greater, the lower the rotor speed $n_r$ of the exciter, since with a decrease in $n_r$ it is necessary to increase the excitation current. They can be represented as

$$\Delta P_{e,e} = \Delta P_{e,e(0)} (1+s)\gamma,$$

where $\Delta P_{e,e(0)}$ - losses in the excitation system of the exciter at $s = 0$;

$\gamma$ - coefficient of proportionality.

The losses in the exciter can also be represented as

$$\Delta P_{exc} = \Delta P_{exc(0)} (1+|s|),$$

where $\Delta P_{exc(0)}$ - losses in the exciter at $s = 0$; $\beta$ - proportionality coefficient, taking into account the scheme and operating mode of the exciter at the current sliding module $|s|$ [10-13].

Stator copper loss $\Delta P_{c,s}$, rotor $\Delta P_{r,s}$, losses in the stator steel $\Delta P_{s,s}$ are practically independent of slip. Losses in rotor steel $\Delta P_{s,r}$ proportional to the rotor current frequency $f$, and can be represented as:

$$\Delta P_{s,r} = \Delta P_{s,r(0)} q |s|^2$$

where $\Delta P_{s,r(0)}$ is the loss in the rotor steel at $s = 1$; $q$ - proportionality coefficient.

Considering equations (7) - (11) and neglecting the relatively small value of the part of the components $\sum \Delta P_{i}\approx 0$, the total losses $\sum \Delta P$ in the AAPC can be brought to mind where $\Delta P_{inv}$ - power losses in the frequency converter [12 - 14].

These losses can be represented as the sum of all losses in AG

$$\sum \Delta P_{AG} = \Delta P_{a.m.AG(0)} (1+k) + \Delta P_{c.s.} + \Delta P_{c.r} + \Delta P_{s.s}$$

and losses in the AG excitation system

$$\sum \Delta P_{exc} = \Delta P_{a.m.p(0)} (k+\alpha s + \alpha) + \Delta P_{e.e(0)} + \Delta P_{inv} + \Delta P_{exc(0)} \beta, (14)$$

In accordance with the accepted designations of efficiency: AG $\eta_{AG}$, excitation systems AG $\eta_{exc}$ and AAPC $\eta_{AAPC}$ can be expressed by the equations:

$$\eta_{AG} = \frac{P_s}{P_g + \sum \Delta P_{AG}}; \eta_{exc} = \frac{|P_s|}{|P_{ref}| + \sum \Delta P_{exc}}; \eta_{AAPC} = \frac{P_s}{N_p + \sum \Delta P_{AG} + \sum \Delta P_{exc}}$$

where $|P_s|$ - active power module of the AG rotor, as a sum

$$P_s = P_{ref} + P_{e.g}$$

In the formula (16) $P_{ref}$ - the active power of the rotor at $s = 0$.

The formula for $\eta_{AAPC}$ taking into account (15) and (16) can be represented as

$$\eta_{AAPC} = \frac{1}{\eta_{AG}} + \frac{(P_{ref})}{P_g + |s|} + \frac{1}{\eta_{exc}}$$

The active power of the rotor $P_t$ together with the reactive power $Q_p$ determine the total power $H = \sqrt{P_t^2 + Q_p^2}$ of the synchronous exciter, which in turn determines the mass, dimensions and efficiency of the AG excitation system. The synchronous exciter is selected so that its rated apparent power $H_{nom}$ is not less than the required $H_{max}(H_{nom} > H_{max})$ at $s = s_{max}$.

In this case, at $s 
neq s_{max}$, a decrease in $s_{min}$ will take place. and the more, the greater the difference $|s|$ from $|s_{max}|$. Thus, it can be shown that

$$\eta_{exc} = f(\Delta s).$$

Considering that the synchronous exciter and the inverter are series-connected elements of the excitation system

$$\eta_{exc} = \eta_{s.exc} \eta_{inv},$$

where $\eta_{inv}$ - the efficiency of the inverter, which depends on $s$, i.e., $\eta_{inv} = f_i(s)$. 

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Since \( \eta_{\text{exc}} = f(\Delta s) \) and \( \eta_{\text{inv}} = f(s) \), then \( \eta_{\text{exc}} = f(s, \Delta s) \). The complex nature of the dependence \( \eta_{\text{AAPC}} = f(s, \Delta s) \) does not allow to unambiguously determine the optimal slip values \( s_{\text{opt}} \) and the range of its change \( \Delta s \). Therefore, first of all, in DGS with AG, the synchronous rotation frequency \( n_c \) is selected.

Then, according to equation (17), taking into account dependence (18), they are determined by the values of \( \eta_{\text{AAPC}} \) for different \( s \). The optimal value is taken as \( s = s_{\text{opt}} \), at which \( \eta_{\text{AAPC}} \) reaches a maximum, and from \( s_{\text{opt}} \) it is determined

\[
n_{\text{opt}} = n_c (1 + s_{\text{opt}})
\]  

(19)

Then, knowing \( \Delta s \) or setting its values in relation to \( s_{\text{opt}} \), we find \( s_{\text{opt}} \), at which the average value of \( \eta_{\text{AAPC}} \Delta s \) reaches a maximum. The values of \( s \) and \( \Delta s \) are chosen optimal if the product \( A = \eta_{\text{AAPC}} \eta_{\text{AAPC}} \Delta s \) reaches its maximum \( (A = A_{\text{max}}) \). After determining \( n_{\text{opt}} \), the possible power of the AG is

\[
P'_{\text{2}} = N_{\text{e}2} \eta_{\text{AAPC}}
\]  

(20)

where \( N_{\text{e}2} \) - the effective engine power in terms of the limiting characteristic at \( n = n_{\text{opt}} \) (ordinate of point 2 in Figure 2).

Then the rated power of AG \( P_{\text{nom}} \) is selected from a range of capacities. Here it is only necessary to fulfill the following condition:

\[
\frac{P_{\text{nom}}}{\eta_{\text{AAPC}}} \leq N'_{\text{enom}}
\]  

(21)

where \( N'_{\text{enom}} \) - the engine power according to the limiting characteristic;

\( \eta_{\text{AAPC}} \) - efficiency at \( n = n_{\text{max}} (s = s_{\text{max}}) \).

Suppose that the selected nominal power of the AG corresponds to the engine power \( N_{\text{enom}} \), determined by the ordinate of point 1 in Fig. 2. According to the value of this power, \( n_{\text{min}} \) is determined based on the need to ensure stable operation of the diesel engine in the event of a surge in the rated load on the engine operating at \( N_e = 0 \) and \( n = n_{\text{min}} \). This condition can be fulfilled if, at \( n = n_{\text{min}} \), the engine power according to the external characteristic is \( N_{\text{e ext}} \geq N_{\text{enom}} \). Then

\[
n = \frac{n_{\text{min}}}{1 - \Delta n_{\text{rec}}}
\]  

(22)

where \( n'_{\text{min}} \) – the speed at which the engine power according to the external characteristic corresponds to the rated power of the installation;

\( \Delta n_{\text{rec}} \) – surge frequency /

\[
\Delta n = \frac{n_{\text{min}} - n_{\text{min}}}{1 - \Delta n_{\text{rec}}} \text{ Maximum relative change in rotational speed with a sharp change in load from 0 to } N_{\text{enom}}
\]

It is known that if the stability of the current frequency \( f \) in a diesel generator set with an AG is ensured in the zone of variation of the rotational speed \( 0.5 n_c \leq n \leq 1.5 n_c \), then at \( n'_{\text{min}} < 0.5 n_c \) the value

\[
n_{\text{min}} = \frac{0.5n_c}{1 - \Delta n_{\text{rec}}}
\]  

(23)

The upper speed limit is determined by the ratio

\[
n_{\text{max}} = \frac{n_{\text{min}}}{1 + \Delta n_{\text{sh}}} \text{ at } n_{\text{max}} < 1.5 n_c \text{ and } n_{\text{max}} = \frac{1.5n_c}{1 + \Delta n_{\text{sh}}}
\]

where \( \Delta n_{\text{sh}} \) – the change in \( n \) during load shedding;

\( n'_{\text{max}} \) – the maximum allowable speed.
3. Results and discussion

After determining $P_{nom}$, $n_{min}$ and $n_{max}$, it is possible to determine the optimal operating modes of the diesel generator set with AG. As a criterion of optimality, it is advisable to take the specific effective fuel consumption of diesel generators. Knowing the economic characteristics of a diesel engine and AAPC, it is possible by calculations to estimate the effective efficiency or specific effective fuel consumption of the diesel generator set $b_i$ at various speed and load modes and build lines of equal specific costs (isolines) in coordinates $N_e - n$. Typically, such isolines have the form shown in Fig. 2 by thin lines, where $b_1 < b_2 < b_3 < ... < b_n$. With the known dependences $b = f(N_e, n)$, it is graphically or analytically easy to determine the law of optimal regulation in Figure 2, which is represented by the BB line passing in the zone of minimum specific fuel consumption. Taking into account the limitations of the limits of the change in the speed of rotation, the regulation of $n$ in the entire range of variation of $N_e$ will be optimal along the ABCD line, where the AB and CD lines are regular characteristics at the setting $n_{min}$ and $n_{max}$, respectively. A narrow strip in the vicinity of the shaded line ABCD represents the field of optimal operating modes of the DGS and AG.

When operating a diesel generator set with optimal speed control, not only high efficiency is achieved, but also its overload capacity is significantly increased. This is clearly seen when considering Figure 2. Here, the part of the field of possible modes of operation of DGS with AG, limited by the figure 15D31, differs in that $N_e > N_{nom}$ and can be considered as a field of overload modes. At the same time, some part of the field of overload modes of the diesel generator set lies below the limiting characteristic of the engine. In connection with these overloads of DGS with AG, it is advisable to divide into two areas - allowing long-term operation and short-term. The magnitude of the short-term overload can be determined by the formula

$$\frac{\delta P_{short}}{P_{nom}} \leq \frac{P_{max}}{P_{nom}} = \frac{N_{e_{max}}}{N_{enom}} \cdot \frac{\eta_{AAPC(n=n_{max})}}{\eta_{AAPC_{nom}}},$$

(24)

Here $N_{e_{max}}$ - the diesel power according to the external characteristic at $n = n_{max}$; $\eta_{AAPC(n=n_{max})}$ and $\eta_{AAPC_{nom}}$ - efficiency of AAPK at $N_{e_{max}}$ and $N_{e_{nom}}$, respectively.

The value of the long-term overload is determined similarly

$$\frac{\delta P_{long}}{P_{nom}} = \frac{N_{e_{max}}}{N_{enom}} \cdot \frac{\eta_{AAPC(n=n_{max})}}{\eta_{AAPC_{nom}}},$$

(25)

Calculations show that for a diesel generator set with AG $\frac{\delta P_{short}}{P_{nom}} = 1.2 \div 1.3$, while a diesel generator set with synchronous generators at the same levels of diesel boost could allow $\frac{\delta P}{P} = 1.1 \div 1.25$. This is explained by the fact that at high load powers, diesel generators with AG operate at $n = n_e$.

The installed capacity of all diesel generators in an autonomous power supply system should, in addition to providing consumers, allow maintenance of individual diesel generators without interrupting the power supply to consumers. Therefore, the total rated power of the DGS \(\sum_{i=1}^{n_{max}} P_{nom} \) is chosen so that when the most powerful DG is stopped, the remaining operating power will provide reliable power supply to consumers. For this purpose, the following conditions must be met:

$$\sum_{i=1}^{n_{max}} P_{nom_i} - P_{nom}^{max} \geq P_{base}$$

(26)

$$\sum_{i=1}^{n_{max}} P_{long_i} P_{nom_i} - \delta P_{long} P_{nom}^{max} \geq P_{30min}^{max}$$

where $n_{ycr}$ - the number of installed diesel generators; $P_{nom}^{max}$ - the rated power of the most powerful DG. $P_{base}$ - base generator power.
4. Summary
This approach to the choice of the type of diesel generator set when designing autonomous power supply system’s requires a detailed consideration of the technical and economic characteristics of the units. The proposed design principles can ensure the most complete use of the positive properties of a diesel engine and an electromechanical energy conversion system, as a result of improving the technical and economic characteristics of autonomous power supply systems as a whole in the following indicators: mass-dimensional - by reducing Rust and reducing the required fuel reserves; operating consumption of fuel, lubricating oil and other operating materials; to the resource of the DGU.

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