UDC 681.5; 004.5

Self-contained drilling rig automatic control system efficiency improvement by means of assuring compatibility and integration methods development

Sergei Chernyi

Ph.D (Eng), Associate Professor,
Department of Electrical and Automation,
Kerch State Marine Technological University

Anton Zhilenkov

Senior Lecturer
Department of Electrical and Automation,
Kerch State Marine Technological University

Sergey Sokolov

Ph.D, Associate Professor
Department of "Complex provision of information security",
Admiral Makarov State University of Maritime and Inland Shipping,
Saint Petersburg, Russian Federation

Ivan Titov

Graduate student
Kerch State Marine Technological University,
electromechanical LLC 'Black Sea Ferry Investments'
Saint-Petersburg Branch, Russia

Abstract
The stabilization problem of two or three parallel operating diesel gas generators as part of autonomous electric energy system is considered in the article. This system working conditions are considered as a part of mountainous self-contained platform where ship electric mains load sharp changes are unsuitable for existing diesel gas generators automatic control systems because the latter are characterized by rotating speed high instability. Rotating depends on generator loads (torque), hence the diesel gas generator frequency controller adjustment must be improved depending on its operational conditions. The drilling rig autonomous electric energy system operation analysis allowed establishing that commutation processes based on loads loss and connection cause mains voltage and frequency fluctuations. Their spectrum is of the same frequency range as DGGS rotating oscillation spectrum, this conduce to power oscillations onset between parallel-working generators.

On the conducted experiments basis the diesel gas generator speed controller adjustment factors values, which provide the best transient process with specified power, were obtained. It is seen from conducted analysis that the controller adjustment should be conducted under minimum power rather than normal power. It was demonstrated that however the load increment will cause stability margin increase. On the decibel-log frequency characteristic (DLFC) method basis, the analytical dependence between diesel engine and controller parameters was established. This dependence allows system oscillation acceptable degree establishing.
Key words: OFFSHORE PLATFORM, SYSTEM, OSCILLATIONS

Introduction

The use of diesel gas generator sets (DGGS) as primary energy sources driving motors in autonomous electric energy systems (AEES) of gas-diesel engines offshore drilling platforms (DP) allows providing the following: using of casinghead gas, which is taken without processing from an oil, as DGGS fuel that in turn will reduce the DP operating prime cost, the possibility of primary energy sources of DP AEES operating on diesel and gas diesel fuel. It increases DP AEES reliability and improves the environmental production performance. The gas diesel fuel combustion gases are up to 80% less toxic in comparison with diesel gas generator sets exhausts. There are no solid constituents (sulphur dioxide and soot particles) in DGGS exhausts; this allows engine components wear reducing. The engine sludge does not arise, oil is not polluted therefore the engine lifetime is increased 1.5-2 times [1,2] due to the absence of sulphur dioxide and soot in combustion gases. The fuel feeding automatic control system of DGGS on DP is their main using problem. The automatic control system main types are mechanical and electronic systems.

The DGGS control mechanical systems applying is possible only under load individual performance. The electronic control systems do not have disadvantages mentioned above and provide the possibility of DGGS integrated control with emergency situation automatic control. However, existing electronic control systems [6] are designed as a rule for transport vehicles objects, where there is no need for parallel DGGS operating on general tires.

The DGGS stabilization problem in DP AEES. The offshore drilling platform autonomous electric energy system is electrical sources and consumers complex electrotechnical aggregate operating in various and time-controlled working conditions. The main of them are continuous, short-time and intermittent working conditions. At that, each consumer is characterized by loading, which does not depend on other electrical consumers working conditions. It is impossible to construct a general graph of AEES loads considering the loading of each consumer. Moreover, it is necessary to consider the drilling platform electric driver operating specificity.

The self-contained drilling rig power consumption data are shown in Table 1, from which we can see that tripping operation modes, especially drilling, are the hardest for AEES. The drilling practice is characterized by abrupt change in loading on main drive shaft; this change is associated with varying lithological drilling conditions and other factors [3].

In general, the drilling platform AEES may be characterized by the following features:

- The autonomic network load commutation is of impulse nature with random intensities and durations distribution. Switching loads intensities may be from several dozens to hundreds of kilowatts.
- When random loads application of DBU sections, intercommutation intervals may be from several seconds to several minutes.
- The DBU loads commutation periodicity is close to GGS time constant.
- If any generating sets oscillating properties, the commutation load conduce to swaying of the latter and occurring of amplitude oscillation tension and active power between generating sets; and they in turn cause the frequency fluctuations occurring.
- Considering that loads loss and connection commutation processes are of random nature and cause the amplitude random mains voltage and frequency fluctuations, the latter to some extent may be the

loads commutation process evaluation in autonomic network.

DGGS (DG) gas diesel control device parameters optimization. DG dynamic model parameters are classically determined by identification methods with subsequent adjustment by condition of optimal parameters achieving in transient modes, which are typical for load loss and rise situations, and by control [4, 5].

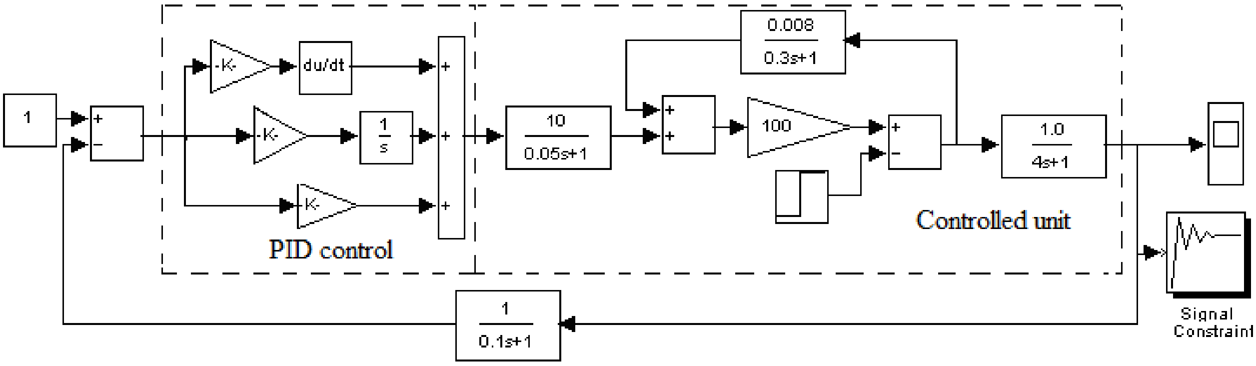

Figure 1. DG dynamic model

DG dynamic model implemented in Matlab-Simulink with pre-set values, which are close to physical with the load of 80% from normal, is shown in Fig. 1. From the Fig. 1 we can see that DG may be presented by three series-connected segments. Each segment is characterized by high amplification coefficient. The positive feedback segment considers the turbo compressor impact. The turbo compressor and diesel engine transmission factors are changed depending on load. DG is the controlled unit in relation to PID control. The controlled unit dynamic properties by control and perturbation action are characterized by transient process curve obtained by modeling and shown in Fig. 2. This process reflects the oscillating nature of processes with certain eigenfrequency ω_0 and oscillability index m_0.

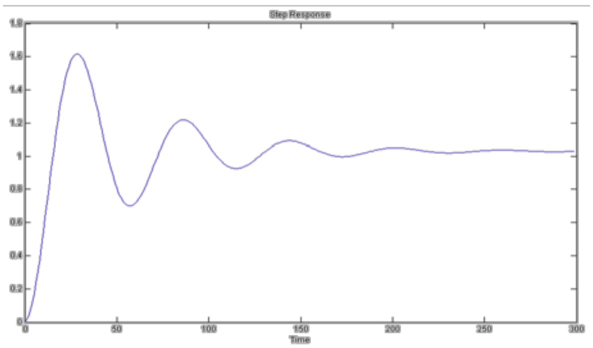

Fig. 2. DG transient process curve.

When perturbation action on the system, PID control parameters should be selected in such a manner as to provide the system damping degree excluding the oscillating process in output shaft. For this purpose, let us analyze the possible system m_c oscillation index reduction for various controller parameters and its possible numerical values. Evaluation of possible m_c reduction comparing with m_0 if there is proportional plus reset (PPR) controller with transfer function:

$$W_{PPR}(c) = k_c \frac{(T_i c + 1)}{T_i c} = k_c\left(1 + \frac{1}{T_i c}\right),$$

where k_c – controller acceleration factor; T_i - integration constant.

Transfer function of closed-circuit system with PPR controller when $W_{oc} = 1$:

$$W = \frac{W_{PPR}(c)W_0(c)}{1 + W_{PPR}(c)W_0(c)}$$

We obtain characteristic equation $c = m_c\omega \pm j\omega$:

$$1 + W_{PPR}(m_c, j\omega)W_0(m_c, j\omega) = 0:$$

From obtained complex equation, the following calculating formulas may be obtained:

$$k_c = \frac{1}{A_0}\left(\omega T_i\left(m_c^2 + 1\right)\sin\varphi_0\right) = \frac{1}{A_0}\left(m_c \sin\varphi_0 - \cos\varphi_0\right)$$

,

from which considering the data represented in [3] we find out:

$$m_c = \frac{k_c A_0 + \cos\phi_0}{\sin\phi_0} = \sqrt{\frac{A_0 k_c}{\omega T_i \sin\phi_0} - 1}$$

where

$$A_0 = \sqrt{[\mathrm{Im}_0(m_0\omega)_0]^2 + [\mathrm{Re}_0(m_0,\omega)]^2} - \frac{k_0}{(1-\omega^2 T_0)^2 + (2\xi\omega T_0)^2}$$

– object amplitude-frequency characteristic;

$\varphi_0 = \operatorname{arctg}(\operatorname{Im}_0(m_0\omega))^2 / \operatorname{Re}_0(m_0\omega)$ – its phase-frequency characteristic.

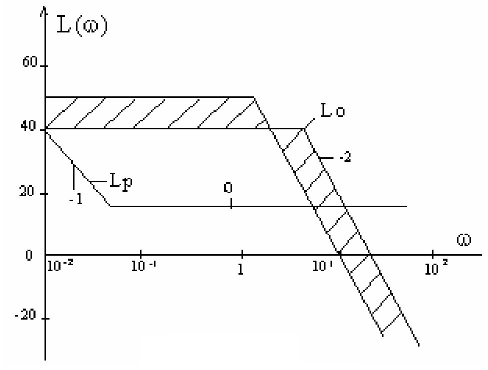

Figure 3. Bode magnitude diagram (DLFC) of open-circuit system

The obtained formulas [1, 5] analysis shows that the oscillation index m_c value cannot be reduced comparing with m_0. This also follows from open-circuit system DLFC analysis (Fig. 3):

$$W_c = W_c W_0 = \frac{k_c T_i c + 1}{T_i c} \cdot \frac{k_0}{T_0^2 c^2 + 2\xi T_0 c + 1}$$

From this formula, it follows that the desirable DLFC with the 20 dB/dec area basically cannot be provided in such composition. Consequently, nature of process will be determined by the object only.

It is evident that same picture will be observed for proportional controller with $W_c = k_c$.

In this case, the system characteristic equation is of the form:

$$T_0^2 c^2 + 2\xi T_0 c + (k_c k_0 + 1) = 0$$

From the last formula, we can easy find a connection between system m_c and object m_0 oscillation indexes:

$$m_c = m_0 \sqrt{k_0 k_c (1 + m_0^2)} + 1$$

Thus, oscillating processes $m_c < m_0$ can always increase only. At that, the fluctuation frequency:

$$\omega_0 = \frac{1}{T_0}\sqrt{1 + k_0 k_c - \xi^2}$$

when $k_0 k_c > 1$ also is increased.

Now let us consider the possibility of system oscillating degree reduction for the case of ideal PPR controller with transfer function:

$$W_{PPR}(c) = k_c (1 + T_d c)$$

where T_d - differentiator time constant.

In this case, the characteristic equation is of the form:

$$T_0^2 c^2 + (2\xi T_0 + k_0 k_c T_d)\, c + k_0 k_c + 1 = 0$$

From this equation we can find the connection between adjustment parameters $T_Д, k_p$ and m_c, m_0.

$$m_c = \frac{\frac{T_д}{2\xi T_0} k_0 k_c + 1}{\left(\frac{m_0^2 + 1}{m_0^2} (k_0 k_c + 1) - \left(\frac{T_d}{2\xi T_0} k_0 k_c + 1 \right)^2 \right)^{1/2}} \quad (1)$$

From the last equation, as follows from the analysis, we can notice that parameter m_c can be increased so system oscillating process will decay. The relation between parameters can be established from obtained formula or from DLFC composition considering DG parameters change (Fig. 4).

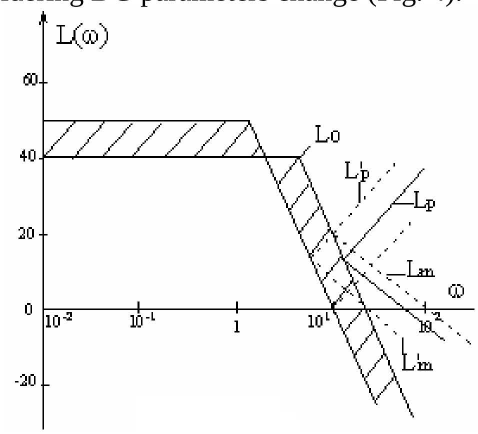

Figure 4. Desirable system DLFC

From the DLFC analysis, it follows that controller adjustment should be conducted under minimum DG power rather than normal power. In this case, the load increment will cause stability margin increase due to acceleration factor fall. For aperiodic transient process providing, i.e. when $m_c = \infty$, we find out the equation from (1): $\frac{m_0^2 + 1}{m_0^2}(k_0 k_c + 1) = \frac{T_d}{2\xi T_0} k_0 k_c + 1$, which allows finding of necessary connection between controller and object parameters. Thus, for transfer process aperiodic nature providing when DGGS load perturbation, its controller must contain the differentiate component. For this reason, we select PID control settings for similarity of task solving.

PID control optimal parameters calculation is carried out automatically by formula method depending on controlled unit and selected optimum test. When optimal parameters search, the user is offered to select one of the following optimum tests: aperiodic control, control with 20% of overcontrolling, mean-square error minimization. For PID control coefficients selection, various non-linear systems theory methods or mathematical modeling may be used. From engineering point of view, the second method is easier. It allows selecting of suitable coefficients value through trial and error in interactive mode. For this purpose, the Signal Constraint package of MATLAB environment may be used.

In Fig. 1, the DG closed-cycle control system main elements are the following: controlled unit, PID control, feedback objective and comparative node. Controller coefficients Kp, Ki and Kd values must be found when prescribed controlled object structure and its parameters known indeterminacy. Controller coefficients Kp, Ki and Kd values are selected in accordance with Ziegler-Nichols method designed for PID control optimal adjustment. The adjustable parameters initial value 0,8P_n, и Kp=1,5.10-2; Ki=1,3.10-4; Kd=4,2.10-3. Obtained result is shown in Fig. 5. In this figure, two curves conform to transient processes in system when initial values and coefficients Kp=1,7.10-2; Ki=1,5.10-4; Kd=4,4.10-3 values were found after PID control optimization.

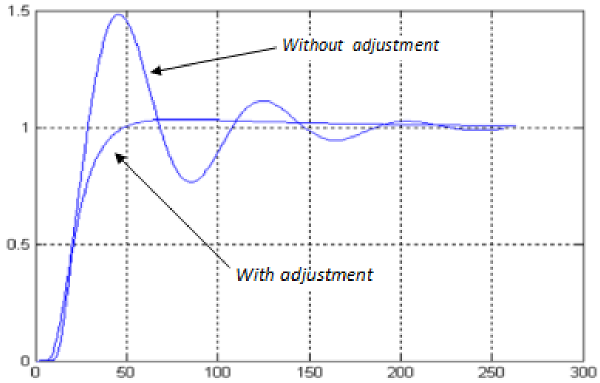

Figure 5. Controller adjustments results

DGGS controller parameters change automation. Under the PID control, the control signal depends on the difference between measured parameter and given value, also on integral, differential and the rate of parameters change. As a result PID control provides the executive unit condition (intermediate state between on or off) where measured parameter is equal to given value. Considering that executive unit condition is stabilized, the parameter maintaining in system accuracy is increased in tens of times. Consequently, the control mode provides the accuracy.

The control signal, which is generated by controller, is determined by error ratio (proportional component), error time length (integrated component) and finally the error change rate (differential component). The optimization problem definition is the following: to find out the controller coefficients Kp, Ki and Kd values, where the transient process will have default parameters in closed structure, at the prescribed controlled object structure and its parameters known indeterminacy.

The control quality provided by PID control depends significantly on how the selected control parameters conform to the system properties. It means that the PID control must be adjusted before starting.

Considering that DGGS are characterized by rotating speed high instability, which in turn depends on generator load (torque), the regulator coefficients must be controlled depending on DGGS operating condition. In the conducted experiment basis, the generator coefficients values, which provide the best transient process with specified power, were obtained. Coefficients values are given in Table 2.

Table 2. DGGS generator optimal coefficients values

P	Kp	Ki	Kd
0	0	0	0
0,2	$0,61.10^{-2}$	$0,46.10^{-4}$	$2,5.10^{-3}$
0,4	$1,24.10^{-2}$	$0,98.10^{-4}$	$3,9.10^{-3}$
0,6	$1,7.10^{-2}$	$1,5.10^{-4}$	$4,4.10^{-3}$
0,8	$1,84.10^{-2}$	2.10^{-4}	$4,6.10^{-3}$
1	$1,85.10^{-2}$	$2,4.10^{-4}$	$4,8.10^{-3}$

DG rotating speed stabilization efficacy evaluation. The real-word functional DGGS may be considered as ideal machine affected by normal-mode signal, which physical nature and parameters are determined in the second chapter. However, in real PID control system, the regulator was adjusted in only one operative range point, there is every reason to believe that suggested control algorithm will allow significant increasing of DG rotating stability in the whole load power range.

In DG structural diagram, the normal-mode signal in the form of destabilizing function

f_ω in accordance with accepted measuring technique is attached to the conclusion (Fig. 6).

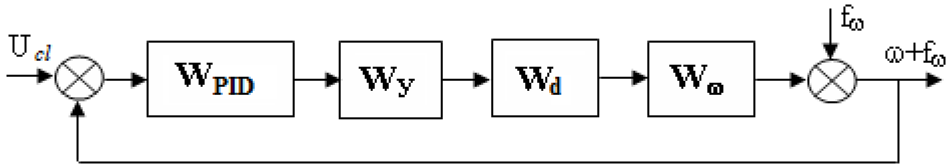

Figure 6. DG structural diagram

where

$$W_{\text{PID}}=\frac{T_{\text{п}}T_g c^2+K_{\text{п}}T_{\text{i}}c+1}{T_{\text{i}}c};W_y=\frac{K_y}{T_y c+1};$$

$$W_{\text{d}}=\frac{(T_{TH}c+1)}{\frac{T_{TH}}{1-K_dK_{TH}}c+1}\cdot\frac{K_d}{1-K_dK_{TH}};W_\omega=\frac{1/D}{\frac{T_e}{D}c+1}$$

Accepted, we find out the level of closed system $f_{\omega\text{cl}}$ $W_{\text{c}}=W_{\text{PID}}W_yW_{\text{d}}W_\omega$ disturbance in output:

$$f_{\omega cl}=\frac{f_\omega}{1+W_c}=f_\omega\frac{1}{1+W_c}=f_\omega W_{cl}$$

Noise spectral density in closed system output

$$S_{\omega\text{cl}}(\omega)=S_\omega.\left|W_{cl}(j\omega)\right|^2=S_\omega.\left|\frac{1}{1+W_c(j\omega)}\right|^2$$

From presented formula, considering DLFC nature of stable system for region effective noise rejection, where $|W_C|>>1$:

$$S_{\omega\text{cl}}(\omega)\approx S_\omega.\frac{1}{\left|W_C(j\omega)\right|^2}$$

It can be represented

$$W_C=\frac{T_{\text{i}}T_g c+K_{\text{п}}T_{\text{i}}c+1}{T_{\text{i}}c}\cdot\frac{K_y}{T_y c+1}\cdot\frac{K_g.(\text{T}_{\text{тн}}\text{c}+1)}{\frac{\text{T}_{\text{тн}}}{1\text{-}\text{K}_{\text{y}}\text{K}_{\text{тн}}}p+1}\cdot\frac{1/D}{\frac{T_e}{D}c+1}=$$

$$\frac{K_y}{D}\cdot\frac{K_{\text{d}}}{1\text{-}\text{K}_{\text{d}}\text{K}_{\text{TH}}}\cdot\frac{a_3c^3+a_2c^2+a_1c+1}{(b_3c^3+b_2c^2+b_1c+1)c}\cdot\frac{1}{T_{\text{i}}c}$$

where $a_3=T_{\text{i}}T_{\text{d}}T_{TH}$ $\quad a_2=T_{\text{i}}T_{\text{g}}+K_{\text{п}}T_{\text{i}}T_{TH}$

$$a_1=K_{\text{п}}T_{\text{i}}+T_{TH}\;\; b_3=\frac{T_{\text{y}}T_eT_{TH}}{D(1-K_{TH}K_{\text{d}})}$$

$$b_2=T_{\text{y}}\frac{T_e}{D}+\frac{T_yT_{TH}}{1-K_{TH}K_{\text{d}}}+\frac{T_eT_{TH}}{D(1-K_{TH}K_{\text{d}})}$$

$$b_1=T_y+\frac{T_e}{D}+\frac{T_{TH}}{1-K_{TH}K_d}$$

Computing a_i and b_i coefficients values for the whole DGGS load range are shown in Table 3.

Table 3. Computing and coefficients values

P / a_i,b_i	0	0.2	0.4	0.6	0.8	**1.0**
a_3	0	16,3	12,1	8,8	6,9	**5,5**
a_2	0	54,6	41	27,76	23,5	**18,9**
a_1	0	1,1	1,86	2,22	2,0	**1,7**
b_3	0	0,1	0,19	0,4	0,5	**0,3**
b_2	0	2,2	4,0	7,8	10,3	**6,3**
b_1	**0**	**4,5**	**5,0**	**6,4**	**6,6**	**5,6**

It comes out of the polynomials $A(a_i, p)$ and $B(b_i, p)$ coefficients calculating results that in practice they compensate each other. At that, the error is not above 10 dB in narrow frequency range. For this reason, for f_ω noise rejection efficiency evaluation in diesel rotating, we can use the W_k approximation in the form of:

$$W_K\approx\frac{K_yK_d}{D(1-K_dT_{TH})}\cdot\frac{1}{T_{\text{i}}p}=\frac{K_{\text{e}}}{T_{\text{i}}p}$$

The transfer function of the closed system is of the form

$$W_{cl}(c)=\frac{1}{1+W_k(c)}=\frac{T_i p}{T_i p+K_e}=\frac{\left(T_i/K_e\right)}{\frac{T_i}{K_e}c+1}$$

Engine output speed noise spectral density:

$$S_{\omega cl}(\omega)=S(\omega)\frac{\left(\frac{T_i}{K_e}j\omega\right)^2}{1+\left(\frac{T_i}{K_e}\right)^2\omega^2}$$

Output signal dispersion is determined from known formula, which is used for correlation function determination:

$$R_{out}(\tau)=\int_{-\infty}^{+\infty}S_{\omega cl}(\omega)e^{-j\omega\tau}d\omega$$

which for $\tau=0$ is worked out to

$$R_{out}(0)=\sigma^2_{out}=\int_{-\infty}^{+\infty}S_{\omega cl}(\omega)d\omega$$

Because of ω_i values where $\left(\frac{T_i}{K_e}\right)^2\omega^2>>1$, $W_{cl}(j\omega)=1$, the low-frequency range only affects the output parameters spectrum; for this range

$$W_{cl}(j\omega)=\left(\frac{T_i}{K_e}\right)^2\omega^2$$

For the foregoing reasons, the output parameter dispersion considering value $S(\omega)$ may be determined by the formula

$$R_{out}(0)=\sigma^2_{out}=\frac{1}{2\pi}\left(\frac{T_i}{K_e}\right)^2\int_{-\infty}^{+\infty}\frac{\sigma^2_{in}\alpha}{\omega^2+\alpha^2}\cdot\frac{d\omega}{\omega^2}=\left(\frac{T_i\,\sigma_{in}}{\sqrt{2K_e\alpha}}\right)^2$$

It is theoretically possible to reduce the gas diesel engine speed fluctuation range by 25-39 times under PID control optimal adjustment for the whole power range.

The DGGS efficient structure and load chart development and analysis. DGGS parameters controllers optimization when its single-step operation allowed practically increasing of DG rotating stability to normal DG rotating stability. It offers opportunities for their parallel operating providing under effective control of each generator active power.

In accordance with the conclusions drawn before, it is necessary to ensure the equality (proportionality under unequal installed capacities) of GD torque and their rotating equality up to rotor angular positions for providing of equality of powers generated by each generator. Torque sensors or active power can control both actual active component of power and torque directly on the shaft (angular sensors position that are based on Hall Effect).The general scheme of parallel DGGS is shown in Figure 7.

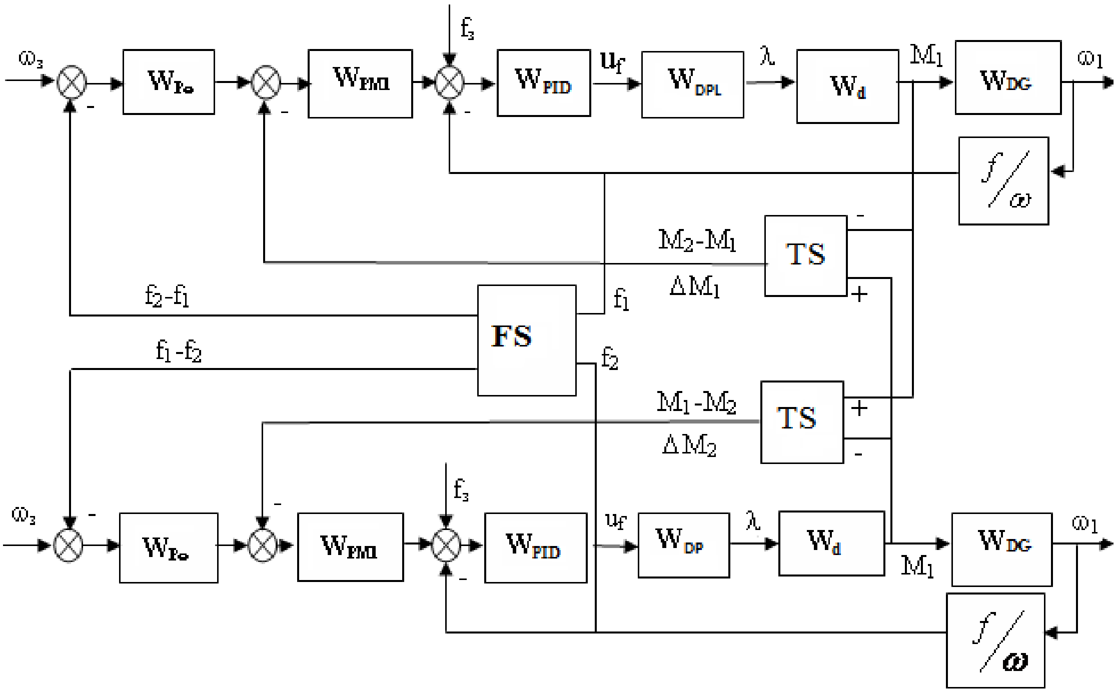

Figure 7. The parallel DGGS scheme

In proposed scheme, the reversible counter fulfils functions of integrated type low-frequency filter for frequency signals. If the frequency difference varies within zero level, the rapid fluctuations are averaged by counters and do not pass to the output. Indeed, if the sign of the difference is changed, it takes some time before the counter will drop into the new state, and only then the pulses can pass to the output. The counter capacity can be increased and the range of number variation of pulses between the extreme values can be assigned; this is equivalent to an increase of the integrators time constant.

Conclusions

The AEES operating analysis allowed establishing that commutation processes based on loads loss and connection cause mains voltage and frequency fluctuations. On the DLFC method basis, the necessity of differentiate component use in diesel regulation has been proved and the analytical dependence between diesel engine and controller parameters has been established. This dependence allows system oscillation acceptable degree establishing.

On the PID control DGGS parameters optimization basis, the nonlinear dependence on DGGS shaft load rate is determined for each type of loads.

References

1. Chernyi S., Zhilenkov A. (2015) Analysis of complex structures of marine systems with attraction methods of neural systems. *Metallurgical and Mining Industry*, No. 1, p.p. 37–44
2. Vasil'yev Yu.N., Zolotarevskiy L.S., Ksenofontov S.I. *Gazovye i gazodizel'nye dvigateli*. [Gas and gas-diesel engines]. Moscow, VNIIEGazprom, 1992.
3. Lukas V.A. *Teoriya avtomaticheskogo upravleniya*.[Automatic control theory]. Moscow, Nedra, 1990, 416 p.
4. Zhilenkov A., Chernyi S. (2015) Investigation performance of marine equipment with specialized information technology. *Procedia Engineering*. Vol. 100, p.p. 1247–1252
5. Chernyi S., Zhilenkov A. (2015) Modeling of complex structures for the ship’s power complex using XILINX system. *Transport and Telecommunication*. Vol. 16 (1), p.p. 73–82
6. Shchokin V., Tkachuk V. (2014). Automation agglomeration production on based application neuro-fuzzy regulation of lower level. *Metallurgical and Mining Industry*. No 6, p.p. 32-39