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Naval Power System Dynamics with Proportional Type Regulators

This work analyzes the dynamic behavior of naval power system using proportional type controllers, system which provides energy for consumers on the vessel so that the voltage and frequency is always in nominal value limits. Essential problems of the work relates to the tuning of controllers, because the system is nonlinear and we can't apply known criteria. Analyzing type P controllers we found that oscillations known to occur in proportional type controller can put out the naval power system.

Keywords: *naval power system, regulators, generator.*

1. Introduction

It is to analyzing the naval power system at the maximum power point. This type of synchronous generator is one which has permanent magnets; the excitation is accomplished using those permanent magnets.

Diesel engine operation at the maximum power point (P_{max}) requires the following torque:

$M_{MD} = 14.574\,[N \cdot m]$ and speed (pulsation: $\omega = 252\,[rad/s]$)

Catalog data and characteristics of Diesel engine and synchronous generator with permanent magnets are [5]:

Diesel engine:

nominal mechanical characteristic of Diesel engine is:

$$M_{MD} = -1.5 \cdot 10^{-3}\omega^2 + 0.7\omega - 66.57$$

the coordinates for the maximum power point are:

$$M_{MD}^{*} = 14.6\,[N \cdot m] \;,\; \omega^{*} = 252\,[rad/s]$$

Synchronous generator with permanent magnets:

$L_d = 0.07\ [H]$ - synchronous reactance from 'd' axis; $L_q = 0.08\ [H]$ - synchronous reactance from 'q' axis; $\Psi_{MP} = 1.3\ [Wb]$ - permanent magnet flux.

Power factor of synchronous generator with permanent magnets:

$\cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}}$ (P-active power; Q-reactive power).

Knowing the equations of synchronous generator with permanent magnets [2,3,4]**:**

$$\begin{cases} U_d = 1.6 I_d - \omega 0.08 I_q \\ U_q = 1.6 I_q + \omega 0.07 I_d + \Psi_{MP}, \\ M = -0.01 I_q I_d + \Psi_{MP} I_q \end{cases}$$

and the values for Diesel engine torque, $M_{MD} = 14.574\ [N \cdot m]$, speed / pulsation is $\omega = 252\ [rad/s]$, the following system is obtained:

$$\begin{cases} U_d = 1.6 I_d - \omega 0.08 I_q \\ U_q = 1.6 I_q + \omega 0.07 I_d + \omega \Psi_{MP} \\ -14.574 = -0.01 I_q I_d + \Psi_{MP} I_q \\ U_d = -R I_d; \quad U_q = -R I_q \\ P = U_d I_d + U_q I_q \\ Q = -U_d I_q + U_q I_d \\ \cos\varphi = \frac{P}{\sqrt{P^2 + Q^2}} \\ \omega = 252; \Psi_{MP} = 1.6 \\ I_R = \frac{\sqrt{I_d^2 + I_q^2}}{\sqrt{3}}; U_R = \frac{\sqrt{U_d^2 + U_q^2}}{\sqrt{3}} \\ \Psi_S^2 = (0.08 I_q)^2 + (\Psi_{MP} + 0.07 I_d)^2 \end{cases} \qquad (1)$$

This system, which solving leads us to two sets of solutions one for static stability area and the other for unstable area.

For the unstable area, matching to the P1 point:

$Q = 0\ [VAR]$; $\cos\varphi = 1$; $\Psi_{MP} = 1.6\ [Wb]$; $I_d = -18.825\ [A]$;

$I_q = -8.1499\ [A]$;

$I_R = 11.843\ [A]$; $\Psi_S = 0.71047\ [Wb]$; $U_q = 58.092\ [V]$;

$U_d = 134.18\ [V]$;

$R = 7.1289\ [\Omega]$; $U_R = 84.419\ [V]$; $P = -2999.4\ [W]$.

The stable operation takes place P2 point and the solutions for this area are:

$Q = 0\,[VAR]$; $\cos\varphi = 1$; $\Psi_{MP} = 1.6\,[Wb]$;

$I_d = -4.9912\,[A]$; $I_q = -8.8332\,[A]$; $I_R = 5.8577\,[A]$; $\Psi_S = 1.4365\,[Wb]$;

$U_q = 301.02\,[V]$; $U_d = 170.09\,[V]$; $R = 34.079\,[\Omega]$; $U_R = 199.62\,[V]$;

$P = -3507.9\,[W]$

The stable operation takes place in P2 point at Rcharge=34.079[Ω], as demonstrated by the mathematical model of synchronous generator with permanent magnets.

The operating points P1 and P2 are represented in Figure 1:

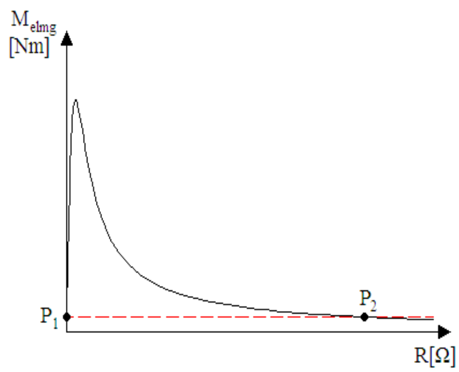

Figure 1. The torque dependence of charge resistance

At given torque and speed results voltage and current at synchronous generator with permanent magnets**:**

The management system requires knowing the optimal speed $n^*(\omega^* = 252 = 2\pi n^*)$ at torque $M^*_{MD} = 14.574\,[Nm]$, the rectifier controller interposed between the synchronous generator with permanent magnets and electric battery must be made as to achieve the coordinates of maximum power point: n^*, M^*_{MD}.

At a Diesel engine operating on maximum power point, synchronous generator with permanent magnets will charge the electric storage battery an active power:

$$P^* = 3507.9\,[W]$$

and the current, voltage and frequency, in three-phase, have values:

$$I^*_R = 5.8577\,[A],\ U^*_R = 199.62\,[V],\ f^* = \frac{252}{2\pi} = 40.127\,[Hz]$$

The adjustments in Diesel engine-synchronous generator with permanent magnets system are made only to the synchronous generator with permanent magnets, which will have the torque $M_{GSMP} = M^{*}_{MD}$, the flow of diesel in Diesel engine being the nominal qN (Figure 2),[3] .

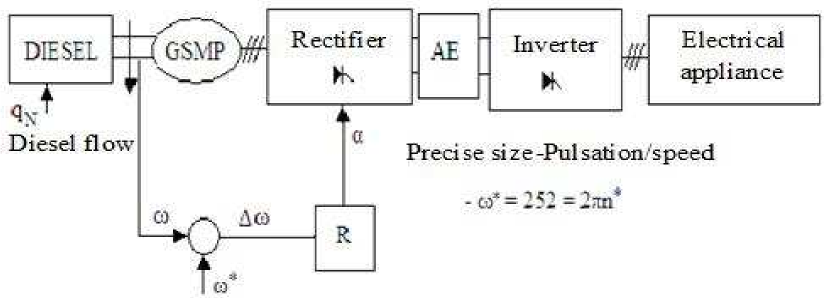

Figure2. Naval power system block diagram

In conclusion if we know the value of the torque of Diesel engine we can calculate the maximum power point specific values: U, I, f.

2. Naval power system dynamics with p type regulators

The regulator-R, P type, has for mechanical angular velocity ω, the equation [1,2]:

$$\Delta R = k\Delta\omega$$

where: ΔR is the variation of resistance; Δω is the variation of mechanical angular speed; k is the regulator constant.

Next, we analyze naval power system dynamics with P type regulators during pulsation changing ω, using the value

$$\Delta\omega = 10\,[rad/s]$$

For a certain value of diesel flow (q=5[g/s]), the mechanical characteristic for Diesel engine is:

$$M_{MD} = -1.5 \cdot 10^{-3}\omega^2 + 0.7\omega - 66.57$$

In the working area the linear mechanical characteristic is:

$$M_{MD} = -0.5\omega - 28.686$$

because the derivate of the function $M_{MD}(\omega)$ for $\omega = 252\,[rad/s]$ has the value 0.056 and the straight line $M_{MD}(\omega) = a\omega + b$ which goes through coordinate point $M_{MD} = 14.574$ şi $\omega = 252$.

At an electrical charge which has the value R, voltages U_d and U_q are written:

$$\underline{U} = U_d + jU_q = -R(I_d + jI_q)$$

where:

$$U_d = -RI_d,\ U_q = -RI_q$$

Is resulting system of algebraic equations (2), which defines naval power system operation in stationary power system:

$$\begin{cases} U_d = 1.6I_d - \omega 0.08I_q \\ U_q = 1.6I_q + \omega 0.07I_d + \omega\Psi_{MP} \\ 0 = -0.01I_qI_d + \Psi_{MP}I_q - 0.056\omega + 28.686 \\ U_d = -RI_d; \quad U_q = -RI_q \\ P = U_dI_d + U_qI_q \\ Q = -U_dI_q + U_qI_d \\ \cos\varphi = \dfrac{P}{\sqrt{P^2 + Q^2}} \\ \omega = 262; \Psi_{MP} = 1.6 \\ I_R = \dfrac{\sqrt{I_d^2 + I_q^2}}{\sqrt{3}}; U_R = \dfrac{\sqrt{U_d^2 + U_q^2}}{\sqrt{3}} \\ \Psi_S^2 = (0.08I_q)^2 + (\Psi_{MP} + 0.07I_d)^2 \end{cases} \tag{2}$$

$Q = 0\,[VAR]$; $\cos\varphi = 1$; $\Psi_{MP} = 1.6\,[Wb]$; $I_d = -4.5227\,[A]$; $I_q = -8.5180\,[A]$; $I_R = 5.5681\,[A]$; $\Psi_S = 1.4531\,[Wb]$; $U_q = 322.63\,[V]$; $U_d = 171.3\,[V]$; $R = 37.876\,[\Omega]$; $U_R = 210.90\,[V]$; $P = -3522.9\,[W]$.

The electrical charge connected to synchronous generator's terminals has the value $R = 37.876\,[\Omega]$.

This values constitute the initial conditions from the differential equation system which defines the transient power system from $\omega = 262\,[rad/s]$, to $\omega = 252\,[rad/s]$, knowing that the regulators are P type .

Determining the constant of proportionality K of the regulator helps pulse/frequency of the system to come back to the initial values, resulting $\omega = 252\,[rad/s]$.

In conclusion the values are to be obtained from the next system:

$$\begin{cases} U_d = 1.6I_d - \omega 0.08 I_q \\ U_q = 1.6I_q + \omega 0.07 I_d + \omega \Psi_{MP} \\ -14.574 = -0.01 I_q I_d + \Psi_{MP} I_q \\ U_d = -RI_d \\ U_q = -RI_q \\ P = U_d I_d + U_q I_q \\ Q = -U_d I_q + U_q I_d \\ \cos\varphi = \dfrac{P}{\sqrt{P^2 + Q^2}} \\ \omega = 252 \\ \Psi_{MP} = 1.6 \end{cases} \quad (3)$$

which has the further solutions:

$Q = 0\,[VAR]$; $\cos\varphi = 1$; $\Psi_{MP} = 1.6\,[Wb]$; $I_d = -4.9912\,[A]$; $I_q = -8.8332\,[A]$; $\Psi_S = 1.4365\,[Wb]$; $U_q = 301.02\,[V]$; $U_d = 170.09\,[V]$; $P = -3507.9\,[W]$; ω=252 [rad/s]; R=34.079[Ω]

The determining the initial and final values

P type regulator, has for mechanical angular speed ω the next equation: $\Delta R = k\Delta\omega$

or

$$\Delta R = k\Delta\omega = k(252 - 262) \quad (4)$$

and with $\Delta R = 34.079 - 37.876$ results:

$$K = \frac{\Delta R}{\Delta\omega} = \frac{34.079 - 37.876}{252 - 262} = 0.3797$$

From $\Delta R = 0.3797(\omega - 262)$ and is to be obtained:

$$U_d = (37.876 - 0.3797(\omega - 252))I_d ; U_q = (37.876 - 0.3797(\omega - 252))I_q$$

Together with the values U_d and U_q as being determined the next system of differential equations is obtained, on which the next simulations are based on.

$$
\begin{cases}
0 = (37.876 - 0.3797(\omega - 252) + 1.6)I_d + 0.07\dfrac{dI_d}{dt} - \omega 0.08 I_q \\
0 = (37.876 - 0.3797(\omega - 252) + 1.6)I_q + \omega(0.07 I_d + 1.6) + 0.08\dfrac{dI_q}{dt} \\
5\dfrac{d\omega}{dt} = -0.01 I_q I_d + 1.6 I_q - 0.056\omega + 28.686 \\
I_d(0) = -4.5227 \\
I_q(0) = -8.518 \\
\omega(0) = 262
\end{cases}
\tag{5}
$$

The time evolution of sizes U, ω, M_{GSMP}, M_{MD}, I; for P type regulator are presented in Figures 3; 4; 5; 6; 7 [6].

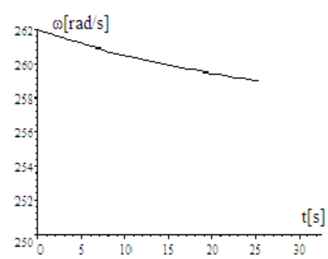

Figure 3. Variation in time of ω

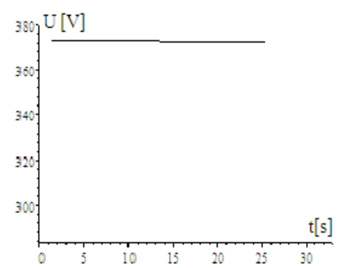

Figure 4. Time variation of stator voltage

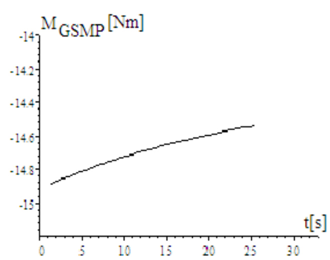

Figure 5. Time variation of GSMP torque

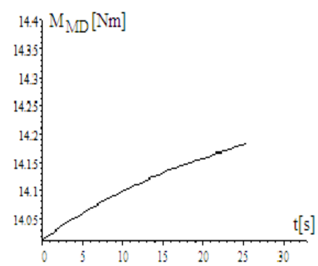

Figure 6. Time variation of MD torque

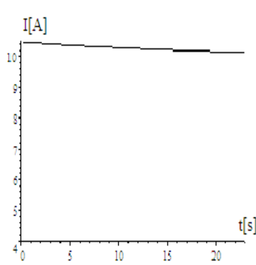

Figure 7. Time variation of electric current

3. Conclusions

In the transient processes of the naval power system the regulators have an essential role. P type regulator, fine-tunned, made a very good stability without oscillations at ω and at I_E. Proportionality constant is determined simply from final and initial values, both for the excitation regulator and for the flow regulator.

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