# THE EXCITATION CONTROL AND STABILITY OF SMALL HYDROELECTRIC POWER STATIONS SYNCHRONOUS GENERATORS WHEN OPERATION IN POWER SYSTEM

**R.I. Mustafayev[1], L.H. Hasanova[1], Q.M. Aliyev[2], M.M. Musayev[1]**

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[1]Azerbaijan Scientific-Research and Disigned-Prospecting Institute of Energetics, Baku, Azerbaijan AZ1012, Aven. H.Zardabi-94
[2]"Azerenergy" JSC, Baku, Azerbaijan, 17 A. Maharramov St.

E-mail: mustafyevri@mail.ru, gasanovalg@mai..ru, , qaliyev@azerenerji.gov.az, musahil@gmail.com

## ABSTRACT

The article discusses the minimization of active power losses depending on the mode of operation of the generator and the load profile. The optimal law of control of synchronous generator excitation in small hydroelectric power plants, at which the energy losses are minimized due to the optimal reactive power interchange, was determined.

In addition to solar and wind power the power of micro and small hydroelectric power stations (SHPS), as an unconventional renewable power sources, is widely used.

These, as a rule, are the diversion hydro power stations, using the enery of mountain rivers and channels. Small HPS are also used in Azerbaijan; their installed capacity is 10-13 MW. Power supply circuits of load nodes with small HPSs availability are various, however when broad electrification the electrical networks cover practically all any significant human settlements (in any case in Azerbaijan), therefore, the circuit, shown in Fig.1, can be taken as the most frequently used one of power supply.

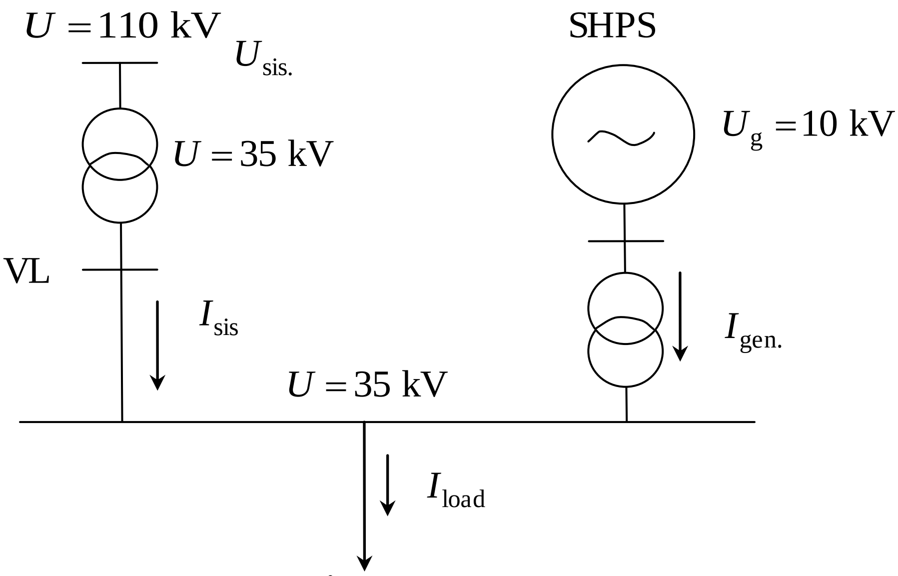


**Figure 1.**

In this case the load (it could be small settlement with some production, etc.), is supplied simultaneously from the generator of small HPS and the system on VL line. As for the active power, the strategy of its control is evident: the consumer's load-curve on active power must be first of all met by the generation of active power by small HPS, and in case of shortage by power interchange from the system on VL line. In this simple power supply circuit the electricity (power) losses from active power interchange are entirely determined by consumer's load curve on active power and by the curve of active power output by small HPS.

As for the reactive power, so far as there is a source of controlled reactive power in the circuit, and it is the synchronous generator of small HPS, it is possible to determine the optimal control law of small HPS's synchronous generator excitation, where the minimum power losses in mentioned circuit is achieved only at the expense of optimal reactive power interchange.

Control of synchronous machines' excitation current at a constant shaft load results in a change of power losses in stator copper and excitation system.

The total losses are shown in [1] and presented in the form of:

$$\Delta p_{\mathrm{g}} = \frac{\left(\beta^2 \cdot P_n^2 + \alpha^2 \cdot Q_n^2\right) \cdot R}{U^2} + \frac{R_f}{x_{ad}^2}\left[\frac{x_d \cdot x_q}{U^2}\left(\beta^2 \cdot P_n^2 + \alpha^2 Q_n^2\right) + \alpha\left(x_d + x_q\right) \cdot Q_n + U^2\right] \cdot \left[1 + R(Q)\right] \qquad (1),$$

where $\alpha = \dfrac{Q}{Q_n}$ – load factor on reactive power; $\beta = \dfrac{P}{P_n}$ – load factor on active power; $P_n, Q_n$ – rated active and reactive power of generator; $U$ – phase-to-phase voltage of generator; $x_d, x_{ad}$ – synchronous inductive impedance and mutual induction reactance along the direct axis *d*; $x_q$ – synchronous inductive impedance along the quadrature axis *q*; $R, R_f$ - accordingly active resistances of armature winding and excitation winding reduced to stator; $R(Q)$ – a factor, taking into account a saliency of synchronous machine. The value $R(Q)$ is determined by the correlation:

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$$R(Q) = \frac{\left(x_d - x_q\right) \cdot \left(\dfrac{\beta^2 \cdot P_n^2 + \alpha^2 \cdot Q_n^2}{U^2} \cdot x_q + \alpha \cdot Q_n\right)}{\dfrac{x_q^2}{U^2} \cdot \left(\beta^2 \cdot P_n^2 + \alpha^2 \cdot Q_n^2\right) + 2\alpha \cdot x_q \cdot Q_n + U^2} \qquad (2)$$

The last expression is linearized by [1] authors, and determined that, it can be replaced with 10% accuracy by the expression of following view:

$$R(Q) = R_0 + \left(R_i - R_0\right)\frac{Q}{S_{baz}} \qquad (3)$$

where, $R_0$ – is a value of (2) function with $Q = 0$, and $R_i$ – is a value of (2) function with $Q = S_{baz}$; $S_{baz}$ – is a base power equal to apparent power of synchronous machine.

The (1) expression with consideration for (3) expression can be reduced to the form of:

$$\Delta p_{\text{g}} = a \cdot Q^3 + b \cdot Q^2 + c \cdot Q + d \qquad (4)$$

where, $a = \dfrac{(R_i - R_o) \cdot R_f \cdot x_d \cdot x_q}{S_{baz} \cdot x_{ad}^2 \cdot U^2}$; $b = \dfrac{R}{U^2} + (1 + R_0)\dfrac{x_d \cdot x_q \cdot R_f}{x_{ad}^2 \cdot U^2} + \dfrac{R_f \cdot (R_i - R_0)}{S_{baz} \cdot x_{ad}^2} \cdot (x_d + x_q)$

$$c = \frac{R_f}{x_{ad}^2} \cdot (x_d + x_q) \cdot (1 + R_0) + \frac{(R_i - R_0) \cdot R_f}{S_{baz} \cdot x_{ad}^2}\left(\frac{x_d \cdot x_q}{U^2} \cdot \beta^2 \cdot P_i^2 + U^2\right);$$

$$d = \frac{R}{U^2} \cdot \beta^2 \cdot Đ_n^2 + \frac{R_f}{x_{ad}^2}\left(\frac{x_d \cdot x_q}{U^2} \cdot \beta^2 \cdot P_n^2 + U^2\right) \cdot (1 + R_0).$$

In (4) expression the first term is by some orders less than the rest ones, so they can be neglected. Then the dependence of $\Delta p$ losses on reactive power of small HPS's generator will be expressed in the form of:

$$\Delta p_{\text{g}} = b \cdot Q_{\text{gen}}^2 + ñ \cdot Q_{\text{gen}} + d \qquad (5)$$

When supplying according to the circuit in fig. 1, the load or part of it can also be supplied from the system on VL line, loss in which will be:

$$\Delta p_L = I_L^2 \cdot R_L = \left(\frac{P_L^2}{U^2} + \frac{Q_L^2}{U^2}\right) \cdot R_L = \frac{P_L^2}{U^2} \cdot R_L + \frac{R_L}{U^2} \cdot Q_L^2 = m + n \cdot Q_L^2 \qquad (6)$$

where $m = \dfrac{P_L^2}{U^2} \cdot R_L$, $n = \dfrac{R_L}{U^2}$, $Đ_L$, $Q_L$ – are the active and reactive powers, transmitted via VL. $R_L$ – active resistance of VL, $U$ – phase-to-phase voltage of VL.

Thus, the reactive power of load in general case is equal to:

$$Q_{load} = Q_{\text{gen}} + Q_L \qquad (7)$$

The total power losses in line and generator are equal to:

$$\Sigma\Delta p = \Delta p_L + \Delta p_{\text{gen}} = m + n \cdot Q_L^2 + b \cdot Q_{\text{gen}}^2 + ñ \cdot Q_{\text{gen}} + d \qquad (8)$$

Determining $Q_L$ from (7) and substituting into (8) we will obtain:

$$\Sigma\Delta p = m + n \cdot (Q_{\text{load}}^2 - 2 \cdot Q_{\text{load}} \cdot Q_{\text{g}} + Q_{\text{g}}^2) + b \cdot Q_{\text{g}}^2 + ñ \cdot Q_{\text{ã}} + d \qquad (9)$$

Taking the derivative of $\Sigma\Delta p$ with respect to $Q_{\text{g}}$ and equating it to zero we will get:

$$-2 \cdot Q_{\text{load}} \cdot n + 2 \cdot n \cdot Q_{\text{g}} + 2 \cdot b \cdot Q_{\text{g}} + c = 0 \qquad (10)$$

And, finally, solving (10) relative to $Q_{\text{g}}$ will find:

$$Q_{\text{g}} = \frac{2 \cdot Q_{\text{load}} \cdot n - c}{2 \cdot (n + b)} = \frac{n}{n + b} \cdot Q_{\text{load}} - \frac{c}{2(n + b)} \qquad (11)$$

If to minimize the losses only in the generator itself, the (11) expression is transformed into the form of:

$$Q_{\text{g}} = -\frac{c}{2 \cdot b} \qquad (12)$$

This expression is given in [1]. It should be noted that for cylindrical rotor synchronous machines $b$ and $c$ factors do not depend on active power, i.e., when changing the motive torque on the generator's shaft, the minimum losses are achieved at a constant reactive power.

In that way, it follows from the expression (11) that, the reactive power of generator (and consequently the excitation current) needs to be controlled in proportion to value of load's reactive power with taking into account the parameters of transmission line and generator.

Let's illustrate the above algorithm in a specific example.

Generator's parameters: $S_{rat}$ = 11,8 MVA; $P_{rat}$ = 10 MW; $Q_{rat}$ = 5,15MVAr; $U_{rat}$ = 10KV; $x_d$ = 0,987(relative unit); $R_{G\text{-}T}$ = 0,02(relative unit) (a resistance of generator's stator winding is combined with active resistance of transformer $T_R$. 10/35), $R_f$ = 0,045 (relative unit); $x_f$ = 1,1 (relative unit); $x_q$ = 0,633 (relative unit); $x_{ad}$ = 0,787 (relative unit); $x_{aq}$ = 0,433 (relative unit). The calculated factors of (5) equation are: $b = 5{,}3\cdot10^{-10}$; $c = 3{,}7\cdot10^{-3}$; $d = 37\cdot10^{3}$; $R_0 = 0$; $R_i = 0{,}16$.

The daily load curve (Fig.1) of 35 kV section according to the readings of Indigo counters is adopted from [2] and presented in Fig.2. Let's take the length of 35 kV transmission line (Fig.1) equal to 15 km, the specific resistance and inductance, of which, are accordingly equal to $r_0 = 0{,}3$ ohm/km; $x_0$ = 0,4 ohm/km).

Then $r_0 = 4{,}5$ ohm and the factor $n$ in (11) formula will be equal to:

$$n = \frac{4{,}5}{35^2\cdot10^6} = 3{,}69\cdot10^{-9} = 36{,}7\cdot10^{-10}$$

In accordance with (11) formula:

$$Q_g = \frac{36{,}7\cdot10^{-10}}{36{,}7\cdot10^{-10}+5{,}3\cdot10^{-10}}\cdot Q_{load} - \frac{36{,}7\cdot10^{-10}}{2\cdot\left(36{,}7\cdot10^{-10}+5{,}3\cdot10^{-10}\right)} = 0{,}87\cdot Q_{load} - 0{,}44 \text{ (MVAr)} \quad (13)$$

The maximum value of reactive load on load curve is equal to $Q_{load\,max} = 4$ MVAr = 4000 kVAr; the average value of $Q_{load\,md} = 3{,}5$ MVAr and the minimum value of $Q_{load\,min} = 3{,}0$ MVAr=3000 kVAr. Let's calculate the losses in line and generator for these values $Q_g$, $Q_L$, as well as the total losses $\Sigma\Delta p = \Delta p_g + \Delta p_L$.

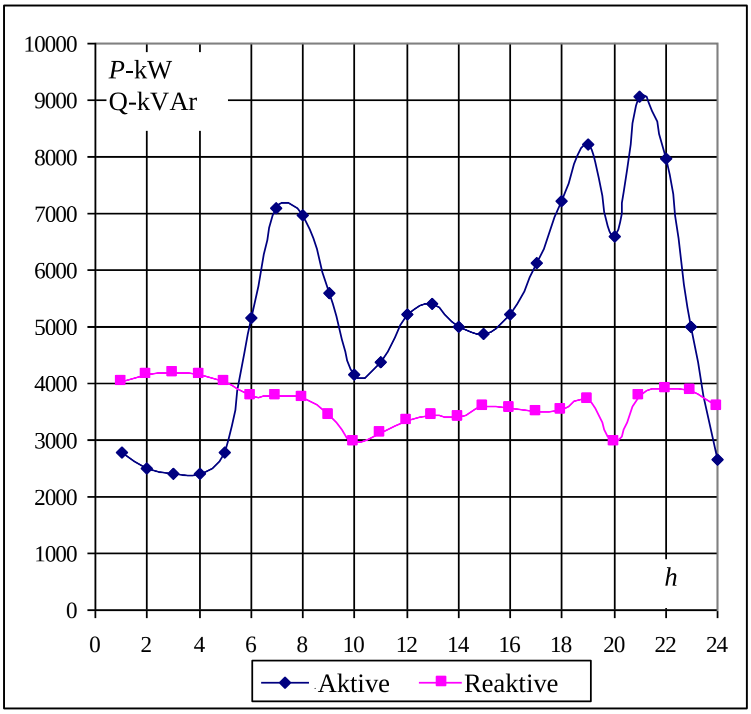


***Figure 2.***

For $Q_{load.max}$=4000 kVAr $Q_g = 3040$ kVAr (according to formula 12); $Q_L = 960$ kVAr; $\Delta p_L = 3{,}38$ kW; $\Delta p_g = b\cdot Q_g^2 + c\cdot Q_g + d = 53{,}14$ kW; $\Sigma\Delta p = 56{,}52$ kW

For $Q_{load.av.}$=3500 kVAr $Q_g = 2605$ kVAr, $Q_L = 895$ kVAr, $\Delta p_L = 2{,}94$ kW, $\Delta p_g = 50{,}23$ kW; $\Sigma\Delta p = 53{,}17$ kW

For $Q_{load\ min}$=3000 kVAr $Q_g = 2170$ kVAr, $Q_L = 830$ kVAr, $\Delta p_L = 2{,}53$ kW, $\Delta p_g = 47{,}52$ kW, $\Sigma\Delta p = 50{,}05$ kW

Thus, the obtained expressions for total power losses are the most minimal for indicated consumer's loads.

It is not difficult to convince in this, carrying out a check. Let for $Q_{load.max}$=4000 kVAr, $Q_g$=2000 kVAr and $Q_L$ =2000 kVAr. Then $\Sigma\Delta p$=61,2 kW, for $Q_g$=4000 kVAr $Q_L$=0, $\Sigma\Delta p$=60,28kW and finally for $Q_g$=0 and $Q_L$=4000 kVAr $\Sigma\Delta p$=95 kW.

With such relatively small turndowns of load's reactive power it is reasonable not to control the reactive power of generator as a functions of load's reactive power, but to find such value of generator's reactive power, which remaining changeless, for maximum and minimum values of load's reactive power would give, the total power losses not more than 5 %, for example. Naturally such mode is quasi-optimal.

For given calculating example such value of generator's reactive power is equal to $Q_g$=2800kVAr=const. In this case the error in comparison with the optimal diagram when determining the total losses at maximum load ($Q$=4000 kVAr) constitutes Δ=0,46 %, and at minimal load it is Δ=3,2 %. That is quite acceptable for engineering calculations.

Thus, with a relatively small fluctuations values of load's reactive power about the average value, it is possible to restrict to quasi-optimal mode, at which the reactive power of generator remains changeless, the errors are minimal in this mode and do not exceed 5 %.

When reducing the output reactive power of generator, its value becomes smaller than the rated one, and is determined by a minimum of electric power losses, it is necessary to check a generator's operation from stability point of view. As for static stability without excitation control, it will, naturally, be for smaller excitation current (reactive power) value less than for the rated one. It is known that to ensure a dynamic stability, each generator is supplied with relay field forcing when short-circuits in generator's external circuit or a sharp increase of motive torque on a generator's shaft. To check this it needs to use the full mathematical model of generator, which, for reduced generator parameters is presented in [3] form:

$$\left.\begin{aligned}
&\rho\psi_{ds} = -U_s \cdot sin\theta + \Psi_{qs} \cdot (1-s) - 0{,}02 \cdot i_{ds} \\
&\rho\psi_{qs} = U_s \cdot cos\theta - \Psi_{ds} \cdot (1-s) - 0{,}02 \cdot i_{qs} \\
&\rho\psi_{dr} = -0{,}028 \cdot \Psi_{dr} + 0{,}022 \cdot i_{ds} + 0{,}022 \cdot i_{df} \\
&\rho\psi_{qr} = -0{,}027 \cdot \Psi_{qr} + 0{,}0117 \cdot i_{qr} \\
&\rho\psi_{qr} = -0{,}057 \cdot U^{*}_{df} - 0{,}045 \cdot i_{df} \\
&\rho s = 0{,}001 \cdot m_{HT} - 0{,}001 \cdot m_{EM} \\
&\rho\theta = s \\
&m_{EM} = \Psi_{ds} \cdot i_{qs} - \Psi_{qs} \cdot i_{ds} \\
&i_{ds} = 3{,}23 \cdot \psi_{ds} - 1{,}12 \cdot \psi_{df} - 1{,}65 \cdot \psi_{dr} \\
&i_{qs} = 2{,}745 \cdot \psi_{qs} - 1{,}7 \cdot \psi_{qr} \\
&i_{df} = 2{,}47 \cdot \psi_{df} - 1{,}12 \cdot \psi_{ds} \cdot 1{,}07 \cdot \psi_{dr}
\end{aligned}\right\} \quad (14)$$

For $cos\varphi = -0{,}94$ of rated active power of generator equal in relative units to $p$ = 0,784, the reactive power will be equal to $q$ = 0,373, this mode is corresponded to the excitation voltage equal to $U^{*}_{f} = 1{,}58$. These and other operation parameters are presented on fluktogrammas in Fig. 3 (*a*, *b*, *c*), where the images of torque and powers are the functions of time $m_{EM} = f(\tau)$, $p = f(\tau)$, and $q = f(\tau)$, and up to 500 radian the motive torque $m_{HT} = 0$ and $U_f^* = 0$. From 500 up to 12000 radian when $m_{HT} = 0$, $U_f^* = 1$ (generator locked in synchronism), further from 12000 radian up to 20000 radian the motive torque of generator became equal to $m = -0{,}8$ (Fig.3,*a*) and excitation voltage $U_f^* = 1{,}58$, corresponding to that the active power value is equal to $p = -0{,}784$ (рис.3,b), and the reactive one $q = -0{,}373$ (Fig. 3c), thus, the mode equal to $\cos\varphi = -0{,}9$ (leading) was reproduced. From 20000 up to 20157 radian a motive torque jump on generator's shaft is formed up to the value of $2{,}4 \cdot m_{st.}$, i.e. $m_{HÒ} = -1{,}9$, with duration of action $\tau = 157$ radian. (t = 0,5 sec.). In Fig. 3 (*d*, *e*, *f*, *g*) are accordingly shown the slip, angle *θ*, excitation current and electromagnetic torque in the range of $2 \cdot 10^4$ up to $2{,}08 \cdot 10^4$ radian (i.e., in the range of 800 radian). It is seen from the fluktogrammas, that the generator is dynamically stable. For example, load angle *θ* varies from 0,363 radian (20,7°) for $m = -0{,}8$ by 2,1 radian (119,7°), i.e., the total angle leading constitutes 140,4°.

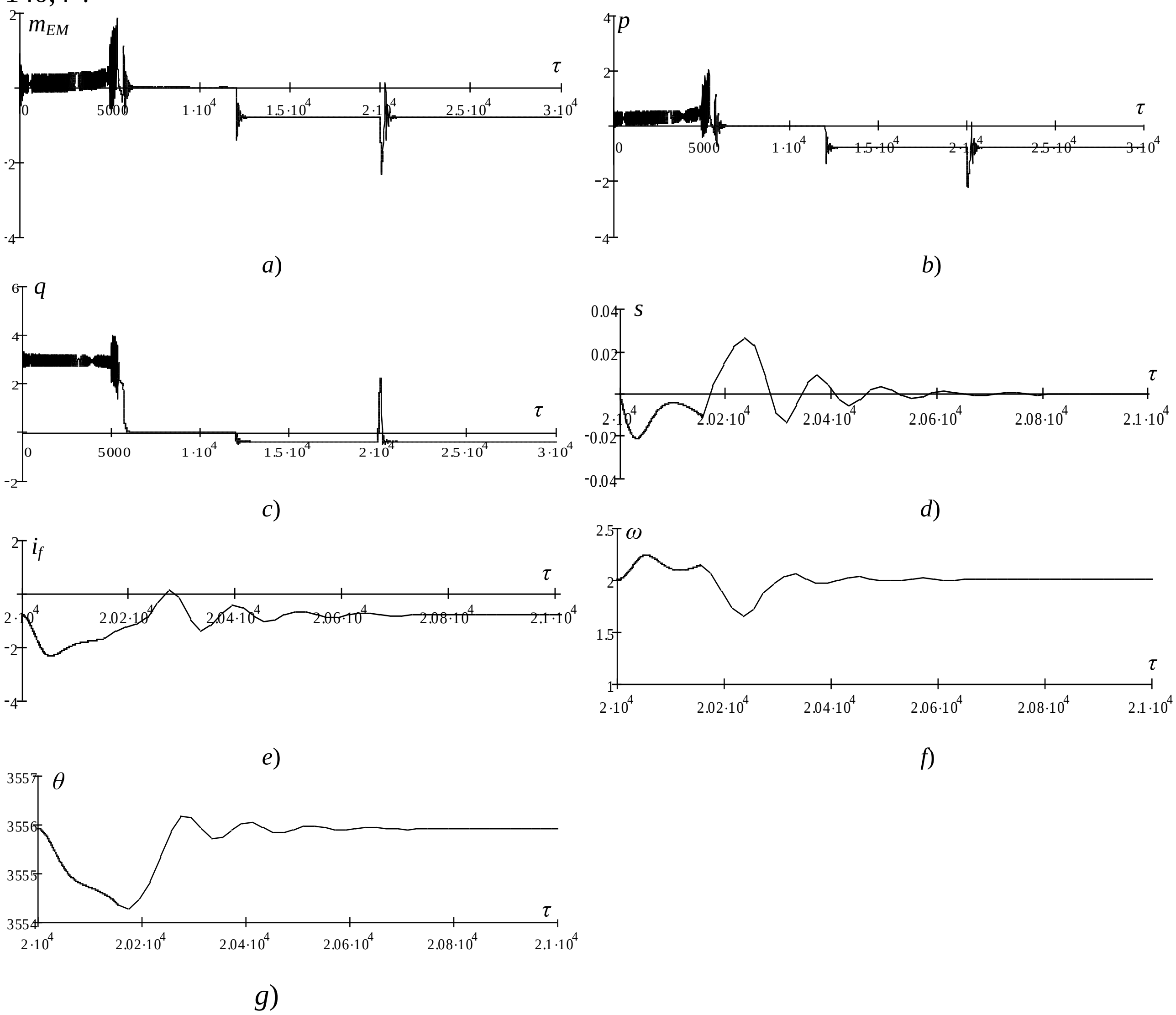


***Figure 3.***

In fig.4 ( *a* ,*b*, *c*) the fluktogrammas of generator's $m_{EM}$ , $p$ and $q$ mode parameters changes are presented when $q = -0{,}207$, which corresponds to the optimal value of reactive power for ensuring the minimal losses in electric power supply system, Fig.1. As it is seen from the fluktogrammas, when attempting to jump a torque up to $m_{HT} = -1{,}9$ value the system from 2 $\cdot 10^4$ radian falls out of step.

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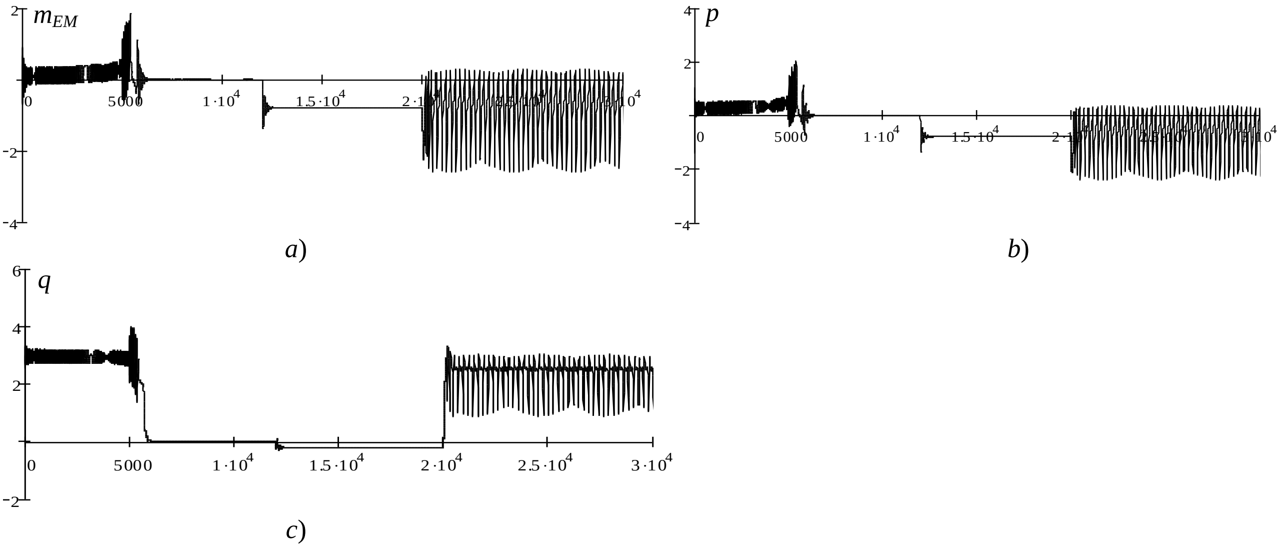
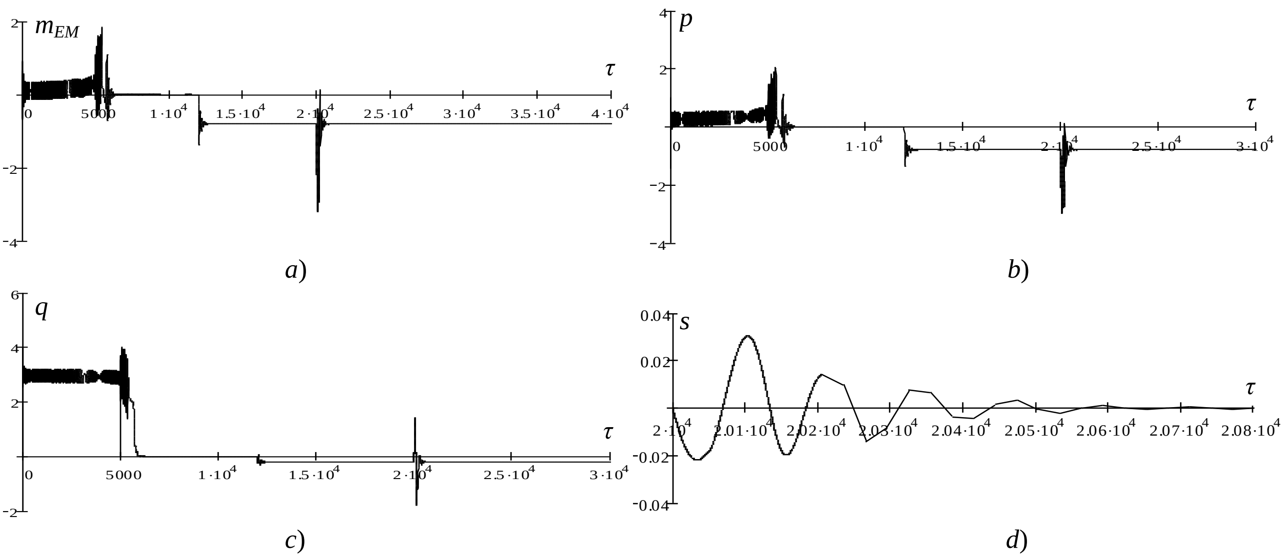
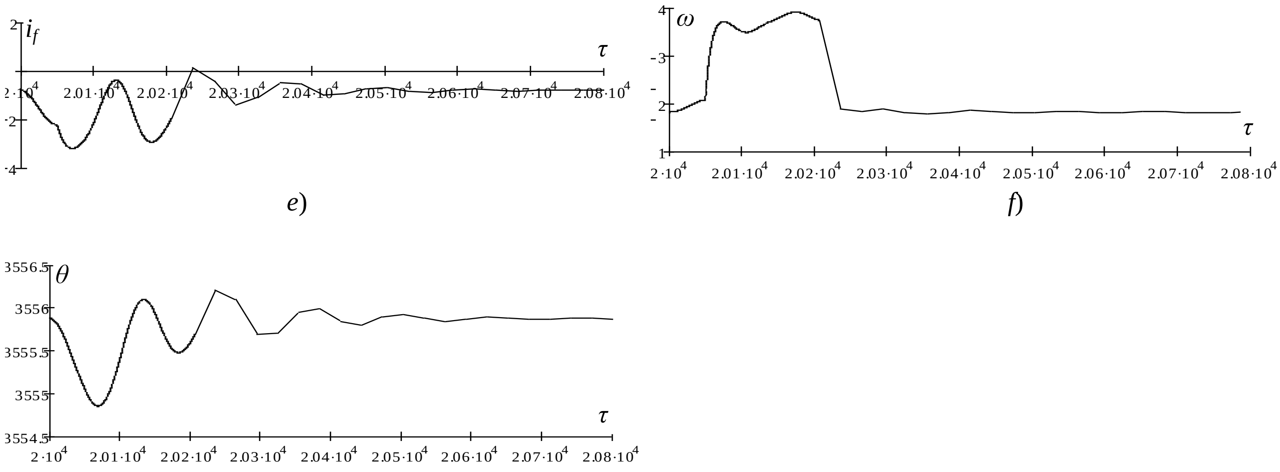


***Figure 4.***

As it has been noted, the generators are equipped with field enhancing system. In Fig.5 the fluktogrammas of generator's $m_{EM}$ , $p$ and $q$ (Fig.5, *a* , *b* ,*c*) and *s*, *θ*, $i_f$ and $m_{EM}$ mode parameters changing are presented in the time range from 2 $10^4$ up to 2,08·$10^4$ radian (Fig.5, *d*, *e*, *f*, *g*) for the same conditions, that in Fig.3.4, but with turning on the relay field forcing. Twofold field forcing $U_{fd} \approx 3$ (from $U_{fd_{nom}} = 1{,}58$) with 50 radian delay (0,16 sec.) turned on after giving $m_{H\grave{O}} = -1{,}9$. As it is seen from the fluktogrammas the system has remained dynamically stable.






g)

***Figure 5.***

Thus, the generator can successfully operate from dynamic stability point of view with excitation less than the rated one, returning in this process to the network the optimal reactive power, which in Fig.1 circuit is approximately 40 % less than the rated one.

## CONCLUSION

For generator of small power HPS, supplying the load simultaneously with the system power transmission line, the optimal value of generated reactive power is determined, at which the minimization of electric power losses from reactive power interchange is achieved in considered load node.

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