Modernization of Control Systems of Primary and Secondary Hydroenergetic Sources of Electricity from the Point of View of their Fulfillment of Important Functions in Operation of a Power Engineering System in the Slovak Republic

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A. Introduction

Shortly after putting the first more important hydroelectric power plant in the Slovak Republic into operation in 1936 (VE Ladce) and subsequent construction of other VEs on this river, requirements for these sources of electricity have increased not only for the amount of electricity produced but also the use of some specificities, which can be offered by these sources (peak loads coverage, load coverage in replacement of faulty sources, participation in ES frequency control, participation in ES voltage control, etc.) in operation of a power engineering system (ES), has started. Finally, requirements for electricity, produced from primary energetic sources (hydroelectric power plants - VE) not only as for the amount but also for fulfillment of qualitative functions in operation of ES SR resulted in a faster construction of new VEs but an emphasis on qualitative functions of VEs has also supported development and construction of pumped storage plants (PVE) whereas the fulfillment of qualitative functions by hydroelectric power plants and PVEs in operation of ES has also required introduction of automatic systems on a level of actual hydroalternators (turbine - generator), their automatic starting, controlling their operation and shutting down an automatic control system of VE and PVE as a single unit with an optimum selection of a number of operational units, distribution of active and reactive loads, etc., automatic system of optimal control of cascades of hydroelectric power plants built on one and more rivers with both tough and looser hydraulic relationships and also an automatic control system of a group of VEs on one river from the point of view of optimum operation of two independent international ESs. Construction and introduction of these automatic systems has started from the second half of 50s (1956) and they were on a level of knowledge and technical means available at that time (from 1956 until now). Solution of problems of these automatic systems related to operation of VEs, PVEs and complete control system of VE and PVE is shown e.g. in [6], [7], [8].

Many of these solutions have been upgraded, these upgrades were mostly represented by advanced automatic elements in a range from an automatic element, represented by a relay, up to a microcomputer element.

However, at present, I expect that in upgrading and construction of new VEs and PVEs it is time to pay attention, from the point of view of a design of control systems of all levels, first of all to the actual system which we want to be automatically controlled. Thus it is necessary to pay attention to an actual description of a system weather for instance its mathematical description sufficiently corresponds to a behavior of the system in real operation, weather in the past, with an insufficient quality and price availability of technical means it was not required to describe some functions of the controlled system in a very simplified form, e.g. weather linearity of processes was not accepted in cases in which the processes were with a rough non-linearity, etc. New requirements for theoretical reevaluation of models of ES elements can also require new knowledge in the area of operation of growing electrification systems covering several international ESs.

Referring to the ideas on upgrading of control systems of VE and PVE mentioned above, I want to discuss an automated control system of a hydroelectric generating set (turbine - generator) in the following.

B. Automatic Control System of a Hydroelectric Generating Set

An automatic control system of a hydroelectric generating set covers a control of all of the modes of operation of a hydroelectric generating set - a turbine, a generator and their accessories - so that the required criteria for quality of control were met while keeping stability of control processes.

A hydroelectric generating set control is a fundamental section of this control system.

Modernization of the existing hydroelectric generating sets and their accessories, design and construction of new hydroelectric generating sets, new theoretical knowledge on production equipment of VEs and PVEs, new knowledge in the area of theory of control, modern technical means for automated control systems and new requirements for fulfillment of production functions of hydroelectric generating sets in complicated ESs require to use the knowledge and requirements mentioned above also in modernization of the existing and construction of new control systems of hydroelectric generating sets to a maximum extent.

First of all, the following is required to meet this goal:

- to reevaluate a mathematical description of water turbines and generators from the point of view of control of their operational processes
- to reevaluate main control circuits of a hydroelectric generating set from the point of view of fulfillment of production functions of both present and future periods
- to reevaluate an affect of non-linearities, occurring in control circuits of a hydroelectric generating set, which have been replaced with linear relationships so far
- to reevaluate possibilities of a stability evaluation of control circuits of a hydroelectric generating set using exact methods, simulation means or their combination, respectively.

1. Description of a Hydraulic Circuit and a Water Turbine from the Point of View of a Main Control Circuit - Speed Control

A water turbine operation is strongly affected by its hydraulic circuit and a generator. It is a very complicated non-linear system requiring to do some simplification from the point of view of a speed control.

Head (H), flow (Q), a control element position (Y) and a second control element position (Y_0), if applicable, will be considered as input variables to this system.

Turbine speed (n), (velocity (Ω)) and moment of force (M_T) which give a turbine power output (P_T) will be of our interest as output variables.

In a normal operation, a hydroelectric generating set is operating into a large capacity ES, speed (ES frequency) is changed slightly whereas both power output and moment can be changed in a full control range. So, turbine power output depends on a position of a turbine flow control element. The relationship of a control element and a turbine power output is non-linear as a rule and depends on a turbine type, too.

With respect to simplification, we will not differentiate turbines from different points of view and we will not discuss different turbine designs either, however, we will consider their classification into two groups, equal-pressure and over-pressure ones.

1.1. Equal-Pressure Turbine Static Characteristics

Water pressure at both the turbine wheel input and output of an equal-pressure turbine (e.g. Pelton turbine) is the same thus water flow through a turbine does not depend on a turbine speed and a total pressure energy of water given by a water head is changed in a control element into a kinetic energy, i.e. water speed, a theoretical value of which is as follows:

$$v = (2gH)^{0,5} \qquad (1)$$

whereas its actual value v_s is reduced, compared to the theoretical value, by the loss in a control element.

Water flow through an equal-pressure turbine depends only on an effective opening of a control system.

$$Q = f(Y) \qquad (2)$$

Equal-pressure turbine moment is given by:

$$M = kQ(v_s - v_o) \tag{3}$$

k ... turbine constant; Q ... flow through a turbine; v_s ... velocity of water flowing out of a control element; v_o ... circumferential velocity of a turbine.

It results from the equation (3) that, at a constant turbine speed, an equal-pressure turbine moment is proportional to the water flow through a turbine, whereas, at a constant flow at the given head, the moment is the largest one if a circumferential speed of a turbine $v_o = 0$.

$$M_{max} = k.Q.v_s \tag{4}$$

The following can be derived for the value of a proposed moment for the given power output P_{max}, nominal water flow through a turbine Q_n and the given head:

$$M_n = k.Q_n.v_s/2 \tag{5}$$

The following equation can be obtained by dividing equations (3) and (5):

$$\frac{M}{M_n} = \frac{Q}{Q_n} \cdot \frac{v_s - v_o}{v_s/2}$$

$$m = q\ (2 - v_o^*);\ v_o^* = v_o/(v_s/2) \tag{6}$$

m ... a relative moment; q ... a relative flow; v_o^* ... a relative circumferential velocity.

With relative variables, v_o^* can be replaced with a relative speed n^*, and then we can obtain the following:

$$m = q\ (2-n^*) \tag{7}$$

As a relative flow depends on a relative opening of a turbine control element, the following can be written for the moment:

$$m = f(y)\ (2-n^*). \tag{8}$$

1.2. Over-Pressure Turbine Static Characteristics

A turbine wheel with over-pressure turbines (Kaplan, Francis, ...) operates at an overpressure, whereas only a part of a water head is consumed for creation of a kinetic energy being output from the distribution mechanism, the other part is changed into a kinetic energy in a turbine wheel (when neglecting the part of energy consumed to overcome a centrifugal force, surge loss, ...). Thus the expressions shown for equal-pressure turbines can be used for over-pressure turbines only with some limitations.

Flow in over-pressure turbines depends on two variables and it is not easy to determine the relationships. Thus it seems to be convenient to measure a set of curves $q = f(y, n^*)$ on a model turbine wheel and save it into a turbine model memory. A point of intersection of all lines $q = f(y)$ can be determined by approximation from the measured curves and equations for a set of curves can be written for respective n^*.

$$q = k_1(y-y_c)+q_c;\ k_1=f(n^*);\ A(y_c,q_c). \tag{9}$$

$A\ (y_c,\ q_c)$ ... point of intersection coordinates.

The moment is proportional to flow, however a value of the moment changes with speed. In a similar way as it was done with the flow lines, a set of moment lines can be led into a common point of intersection B (q_B, m_B). A general equation for the moment determination is as follows:

$$m = k_2(q - q_B) + m_B;\ k_2 = f(n^*) \qquad (10)$$

1.3. Equal-Pressure Turbine Dynamic Characteristics

As for its dynamic aspect, the flow q of an equal-pressure turbine at its changes due to changes in an opening of a turbine control mechanism is affected by a water mass in a penstock. Certain time (T_w) is required to set the water in the piping to motion.

$$T_w = \frac{v_w}{a};$$

T_w... time constant "water rise"
v_w... water velocity in a piping with a cross section S; (11)
a ... water acceleration

The energy required for acceleration of the water in the piping is covered from the head. The following can be derived for a specific change in flow.

$$q = \frac{Q}{Q_{max}} = y - y_A.0,5\ T_w \frac{d_q}{dt} \qquad (12)$$

or after carrying out Laplace transformation respectively, the following can be written:

$$q(s) = \frac{1}{1+0,5y_A T_w s} \cdot y(s) \qquad (13)$$

whereas, the transfer function q(s)/y(s) is given as follows:

$$\frac{q(s)}{y(s)} = \frac{1}{1+0,5y_A T_w s} \qquad (14)$$

y_A... a specific opening of a distribution mechanism in the investigated area $(y_A=Q/Q_{max})$.
The equations (13), (14) show a delayed relationship of a water flow on a change in the opening of a distribution mechanism, a time constant of which depends on a specific opening y_A and the time of water rise T_w.

As, during a change in the opening of a turbine distribution mechanism, a change in a water flow occurs only after some time, it is obvious that in a transient process, a water outlet velocity from the turbine distribution mechanism v_w must also change and thus a moment of the turbine must also change in a transient process.

The following can be proved for a specific outlet velocity:

$$v^*(s) = 1 - \frac{0,5\ T_w s}{1+0,5y_A T_w . s}\ y(s) \qquad (15)$$

Taking into account the equations (13) a (15) for a specific value of a turbine moment in a transient process, the following can be written:

$$\frac{m(s)}{y(s)} = \frac{2-n^* - y_A T_w s}{1+0,5 y_A T_w s} \qquad (16)$$

A change in a turbine speed does not occur immediately if a turbine moment is changed, which is prevented by an influence of mass of rotating parts, whereas the following applies:

$$\frac{n^*(s)}{m(s)} = \frac{1}{T_a s} \qquad (17)$$

T_a... time constant of the set (start time of the set)

The equation (17) represents a transfer with an integration action. However, with the real systems, this transfer is usually proportional to a first order delay which is usually caused by a self-regulating capability of the set e_{str} and a self-regulating capability of ES (e_{ES}). Then, for a summary coefficient of self-regulation $e_c = e_{str.} + e_{ES}$ the following can be written instead of the equation (17):

$$\frac{n^*(s)}{m\ (s)} = \frac{1}{T_a s + e_c} \qquad (18)$$

For a speed change at an opening change of the control mechanism of equal-pressure turbines, the following can be derived:

$$\frac{m(s)}{y(s)} = \frac{2-n^* - 0,5\ T_w y_A 2s}{1 + 0,5 y_A T_w s} = \frac{1 - y_A T_w s}{1 + 0,5 T_w y_A s} \qquad (n^*=1)$$

The following can be set when taking the equation (17) into account:

$$\frac{n^*(s)}{y(s)} = \frac{1 - y_A T_w s}{s\ T_a(1 + 0,5\ T_w y_A s)} = \frac{1 - y_A T_w s}{0,5\ T_w y_A T_a s^2 + T_a s} \qquad (19)$$

When taking the equation (18) into account:

$$\frac{n^*(s)}{y(s)} = \frac{1 - y_A T_w s}{0,5\ y_A T_w T_a s^2 + (T_a + 0,5\ y_A e_c T_w)s + e_c} \qquad (20)$$

1.4. Over-Pressure Turbine Dynamic Characteristics

A water head change into a kinetic energy or velocity v_{w1}, respectively in a turbine distribution mechanism and an increase in a specific velocity of the water in a turbine wheel with an over-pressure turbine is done according to the following equation:

$$H = \frac{v_{w1}^2}{2g} + \frac{v_{02}^2 - v_{01}^2}{2g} = kQ^2 + \omega^2\ (R_2^2 - R_1^2) \qquad (21)$$

v_{w1}... water velocity at an intake into a turbine wheel

v_{01}, v_{02}... relative velocity of water at the beginning or end of a turbine wheel channel, respectively

R_1, R_2... a turbine wheel radius at the intake or outlet from a turbine wheel, respectively

ω... turbine angular velocity
k... constant

The following can be stated for small changes of specific variables, taking the equation (21) into account:

$$\frac{H}{H_{max}} = \alpha \frac{Q^2}{Q_n^2} + (1-\alpha) \frac{n^2}{n_n^2} \tag{22}$$

If a specific small change in a head acts on a specific change in a flow and a specific change in speed, the following can be obtained after derivation of the equation (22):

$$h = \frac{d}{dt} (\alpha(q - q_y)^2 + (1 - \alpha)n^{*2}) \tag{23}$$

If we apply a general expression for a hydraulic impedance for the piping:

$$\frac{h(s)}{q(s)} = z(s) \tag{24}$$

$m_t(s) = q(s) + h(s)$

$z(s) = - y_A T_w s$ can be considered for a non-flexible piping.

Solution is as follows:

$$q(s) = \frac{\alpha y(s)}{\alpha + 0,5T_w y_A s} - (1-\alpha) \frac{n^*(s)}{\alpha + 0,5T_w y_A s} \tag{25}$$

$$h(s) = - \frac{\alpha T_w y_A s}{\alpha + 0,5T_w y_A s} y(s) + \frac{(1-\alpha) T_w y_A s}{\alpha + 0,5T_w y_A s} n^*(s) \tag{26}$$

$m_t(s) = h(s) + q(s)$

$$m_t(s) = \alpha \frac{1 - T_w y_A s}{\alpha + 0,5 y_A T_w s} y(s) + (1-\alpha) \frac{T_w y_A s - 1}{\alpha + 0,5 y_A T_w s} n^*(s) \tag{28}$$

It is obvious from the equation (28) that an over-pressure turbine moment depends on 2 components, on a control mechanism opening and a speed change.

As the following applies:

$$m_t(s) = sT_a n^*(s) \tag{29}$$

$$\text{resp.}\, m_t(s) = (sT_a + e_C)n^*(s) \tag{30}$$

When taking the equation (29) into account, the following can be obtained:

$$\frac{n^*(s)}{y(s)} = \frac{\alpha\,(1 - T_w y_A s\,)}{0{,}5 T_a T_w y_A s^2 + [\alpha T_a - T_w y_A(1-\alpha)]s + 1 - \alpha} \tag{31}$$

For the case of control, the most unfavorable case occurs if $y_A = 1$. Then the equation (31) can be obtained in the following form:

$$\frac{n^*(s)}{y(s)} = \frac{\alpha\,(1 - T_w s)}{0{,}5 T_a T_w s^2 + [\alpha T_a - T_w(1-\alpha)]s + 1 - \alpha} \tag{31a}$$

When taking the equation (30) into account, the following can be obtained:

$$\frac{n^*(s)}{y(s)} = \frac{\alpha\,(1 - T_w s)}{0{,}5 T_a T_w y_A s^2 + [(T_a + T_w y_A)\alpha + T_w y_A(\alpha - 1) + 0{,}5 e_c T_w y_A]s + e_c + 1 - \alpha} \tag{32}$$

If $y_A = 1$ the equation (32) can be obtained in the following form:

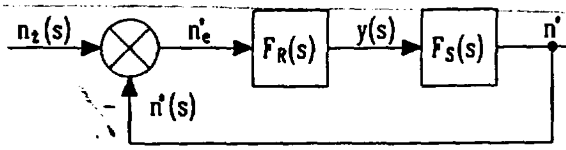
$$\frac{n^*(s)}{y(s)} = \frac{\alpha\,(1 - T_w s)}{0{,}5 T_a T_w s^2 + [(T_a + T_w)\alpha + T_w(\alpha - 1) + 0{,}5 e_c T_w]s + \alpha(e_c - 1) + 1} \tag{32a}$$

If in the equations (31), (31a), (32), (32a) we replace α with value 1, we can obtain equations valid for an equal-pressure turbine and we can make sure that the equation (31) corresponds to the equation (19) and the equation (32) corresponds to the equation (20).

1.5. Transfer Functions (19),(20),(31),(31a),(32),(32a)

define, in a truthful way, basic characteristics of a controlled system of a hydroelectric generating set which must be taken into account in a speed control considering any equal-pressure or over-pressure turbine. This controlled system also contains many non-linearities which were not considered to a full extent and which cannot be simplified any way, some of them can be linearized only in a certain neighbourhood of a working point, some turbines have even two control mechanisms (e.g. Kaplan turbines), some turbines operate in regions of large head fluctuations, etc. These facts should be considered correspondingly when designing a control circuit.

If a system transmission is designated as $F_s(s) = n^*(s)/y(s)$ and that of a controller as $F_R(s)$, a control circuit of a speed control can be expressed with a block diagram, as shown in fig.1.



$$\frac{n^*(s)}{n_z(s)} = \frac{F_R(s).F_S(s)}{1 + F_R(s).F_S(s)}$$

Characteristic equation for closed circuit : $1 + F_R(s).F_S(s) = 0$

Fig. 1

2. Mathematical Description of a Synchroneous Generator of a Hydroelectric Generating Set from the Point of View of its Control in a Large Capacity ES

A synchronous generator represents a complicated non-linear, multiple-parameter system, a reliable mathematical description of which results in a system of non-linear differential equations of a seventh order. Such kind of a system is difficult to realize for general purpose of control of its excitation and thus both the effect of transient processes in stator windings and in an absorber and the non-linear characteristic of a generator magnetic circuit are neglected in excitation control circuits.

We will consider the fact that multi-pole synchronous generators with salient poles are used in VE and PVE and when taking into account the fact that hydroalternators connected to ES are substantially of a lower capacity than that of ES, into which they operate, a design of models can then be based on a vector diagram of a synchronous machine with salient poles with simple replacements of ES taking into account only corresponding reactances of the generator circuits and ES. Fig.2 shows a vector diagram of a synchronous machine with salient poles.

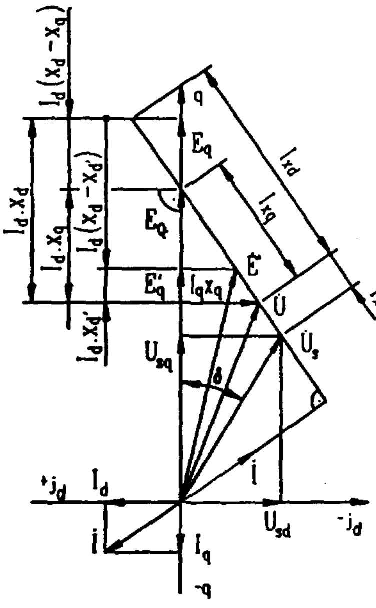


Fig.2

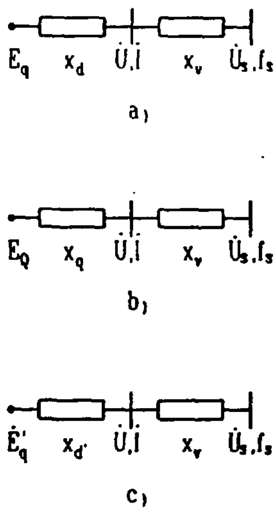


Fig.3

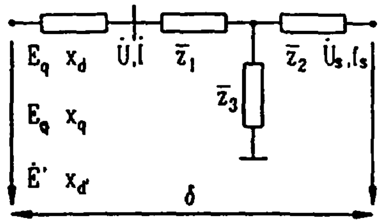


Fig.4

Fig.3 shows simplified models of a synchronous generator connected to ES through lines connected in parallel or one line with a total reactance of the line x_v. Fig.4 shows the same models of a synchronous generator as those in fig.3 but they are connected to ES through impedances $\bar{Z}_1, \bar{Z}_2, \bar{Z}_3$.

2.1. A Simplified Model of a Synchronous Generator (SG) Shown in Fig.3a)

In this case, SG is modelled with an electromotive force proportional to an excitation current of SG (E_q), which has the same reactances in both the direct and quadrature axes ($x_d = x_q$).

This model especially meets the conditions of a synchronous machine with a solid hollow rotor. This model corresponds to a display of physical variables of SG and ES, which is shown in fig.2, in the case if $x_d = x_q$, whereas $E_Q = E_q$, because Id $(x_d - x_q) = 0$.

U ... terminal voltage of SG; U_s, f_s... voltage and frequency of a large capacity ES, respectively

$x_{ds} = x_d + x_v$; $x_{ds}' = x_d' + x_v$

x_d'... transient reactance of SG in a direct axis; δ ... load angle

The following applies for ES voltage:

$$\dot{U}_s = U_s e^{-jd} = U_s(\cos\delta - j\sin\delta) \tag{33}$$

The following applies for SG current:

$$j\dot{I}x_{ds} = E_q - U_s(\cos\delta - j\sin\delta)$$

$$\dot{I} = \frac{U_s\sin\delta}{x_{ds}} + j\left(\frac{U_s\cos\delta - E_q}{x_{ds}}\right) \tag{34}$$

$$I_q = \frac{U_s\sin\delta}{x_{ds}}\ ;\ I_d = \frac{U_s\cos\delta - E_q}{x_{ds}} \tag{35}$$

The following applies for an apparent power of SG:

$$\dot{S} = E_q \cdot \dot{I}^* = E_q(I_q - jI_d) = \frac{E_q \cdot U_s}{x_{ds}}\sin\delta - j\left(\frac{U_s\cos\delta - E_q}{x_{ds}}\right)E_q \tag{36}$$

Then, the following applies for an active power:

$$P = \frac{E_q U_s}{x_{ds}}\sin\delta = P_M\sin\delta;\quad P_M = \frac{E_q \cdot U_s}{x_{ds}} \tag{37}$$

The following applies for a reactive power:

$$Q = \frac{E_q^2 - E_q U_s\cos\delta}{x_{ds}} \tag{38}$$

The following applies for a terminal voltage of the generator:

$$U = [(E_q + I_d x_d)^2 + (I_q x_d)^2]^{0,5} \tag{39}$$

2.2. A Simplified Model of SG shown in fig.3b)

In this case, SG is simplified by a replacement for a virtual electromotive force (E_Q) and reactancy acting in a quadrature axis x_q. A vector diagram for SG with salient poles shown in fig.2 applies in this case.

The following relationship is valid between E_q and E_Q:

$$E_Q = E_q + I_d\,(x_d - x_q)$$

The following applies for ES voltage:

$$\dot{U}_s = E_Q - j\,\dot{I}x_{qs};\quad x_{qs} = x_q + x_v \tag{40}$$

The following applies for SG current:

$$j\,\dot{I}\,x_{qs} = E_Q - \dot{U}_s e^{j\delta}$$

$$I = \frac{U_s \sin\delta}{x_{qs}} + j\left(\frac{U_s \cos\delta - E_Q}{x_{qs}}\right) \tag{41}$$

$$I_q = \frac{U_s \sin\delta}{x_{qs}};\; I_d \frac{U_s \cos\delta - E_Q}{x_{qs}} \tag{42}$$

The following applies for an apparent power:

$$\dot{S} = E_Q \dot{I}^* = E_Q\,(I_q - jI_d) = \frac{E_Q U_S}{x_{qs}} \sin\delta - j\left(\frac{U_s \cos\delta - E_Q}{x_{qs}}\right)E_Q \tag{43}$$

The following applies for an active power:

$$P = \frac{E_Q U_S}{x_{qs}} \sin\delta;\quad Q = \frac{E_Q^2 - E_Q U_s \cos\delta}{x_{qs}} \tag{44}$$

The following applies for a terminal voltage of SG:

$$\dot{U} = E_Q - j\dot{I}x_q;\; U = [(E_Q + I_d x_q)^2 + (I_q x_q)^2]^{0,5} \tag{45}$$

2.3. A Simplified Model of a Synchronous Generator according to a Diagram Shown in Fig.4 Taking into Account the Alternative Expressed by a Transient Induced Voltage of a Generator $\dot{E}'$ and a Transient Reactance in a Direct Axis x_d'.

A transient induced voltage of SG can be expressed as follows:

$$\dot{E}' = E_q' + jE_d' \tag{46}$$

Complex impedances of a line and SG in the considered case can be recalculated according to the following expressions:

$$\bar{z}_{11} = jx_d + \bar{z}_1 + \frac{\bar{z}_2 \cdot \bar{z}_3}{\bar{z}_2 + \bar{z}_3} = z_{11} e^{j\varphi 11} \tag{47}$$

$$\bar{z}_{12} = jx_d' + \bar{z}_1 + \frac{\bar{z}_2}{\bar{z}_3}(jx_d' + \bar{z}_1 + \bar{z}_3) = z_{12}\, e^{j\varphi 12} \tag{48}$$

The following applies for voltage and current vectors of SG:

$$\dot{U} = U_q + jU_d \tag{49}$$

$$\dot{I} = I_q + jI_d \tag{50}$$

$$\dot{I} = \frac{\dot{E}'}{\bar{z}_{11}} - \frac{U_s e^{j\delta}}{\bar{z}_{12}} \tag{51}$$

An apparent power of SG can be expressed as follows:

$$\dot{S} = \dot{U}\dot{I}^* = (U_dI_d + U_qI_q) + j(U_dI_q - U_qI_d) \tag{52}$$

whereas the following applies for active and reactive powers:

$$P = U_dI_d + U_qI_q; \quad Q = U_dI_q - U_qI_d \tag{53}$$

Relationships between voltage and current in a stator winding of SG are determined from the following equation:

$$\begin{aligned} U_d &= - RI_d - x_qI_q \\ U_q &= - RI_q + E_q' + x_d'I_d \end{aligned} \tag{54}$$

R ... stator winding resistance (in our case $R<<x_d$ is considered and thus it is neglected, whereas the components with R are eliminated from the equations).

A transient induced voltage in q axis depends on excitation currents of SG:

$$E_q' = x_{ab} \cdot I_b + (x_d - x_d') \cdot I_d \tag{55}$$

whereas $x_{ab} \cdot I_b = E_q$

$$E_q' = E_q + (x_d - x_d')I_d \tag{55a}$$

I_b... SG excitation winding current;
x_{ab}.. mutual reactance of excitation and stator windings

E_q' can also be expressed with an excitation winding flux φb:

$$E_q' = \frac{L_{ab}}{L_b} \varphi_b \omega \tag{56}$$

φ_b... magnetic flux coupled with an excitation winding
L_{ab}.. mutual inductance of excitation and stator windings
L_b... excitation winding inductance
ω... angle velocity

Referring to a differential equation of SG excitation circuit:

$$U_b = R_bI_b + \frac{d\varphi_b}{dt} \tag{57}$$

and using the equations (55), (56) the following can be derived:

$$\frac{d\psi_b}{dt} = U_b - \frac{1}{T}\psi_b + \frac{1}{K_b\omega}(x_d - x_d')\, I_d \tag{58}$$

if $T_b = \frac{L_b}{R_b}$; $K_b = \frac{L_{ab}}{R_b}$

U_b... SG excitation voltage; R_b ... excitation winding active resistance

If the equation (58) is further processed, the following can be obtained:

$$T_b \frac{dE_q'}{dt} = U_b \,.K_b.\omega - E_q' + (x_d - x_d')I_d \tag{59}$$

Transient induced voltage in d axis can be defined as follows:

$$E_d' = \frac{x_d - x_d'}{z_{11} - (x_d - x'_d)\sin\varphi_{11}} \left[E_q'\cos\varphi_{11} + \frac{z_{11}}{z_{12}} U_s \cos(\delta + \varphi_{12})\right] \tag{60}$$

Defining the equation (51) for a stator current in a component form, equations for generator current components can be obtained after some modifications:

$$I_q = \frac{E_q'\cos\varphi_{11} + E_d'\sin\varphi_{11}}{z_{11}} - \frac{U_s\cos(\delta + \varphi_{12})}{z_{11}}$$

$$I_d = \frac{E_d'\cos\varphi_{11} - E_q'\sin\varphi_{11}}{z_{11}} - \frac{U_s\sin(\delta + \varphi_{12})}{z_{12}} \tag{61}$$

For a module of a stator current and a terminal voltage of SG the following can be stated:

$$U = (U_d^2 + U_q^2)^{0,5}; \quad I = (I_d^2 + I_q^2)^{0,5} \tag{62}$$

The types of models mentioned above in sections 2.1, 2.2, 2.3 of a synchronous generator and its connection to a large capacity ES for the purposes of a control system of a hydroelectric generating set can be completed, as required, with other parts which were not taken into account (damping rotor winding of SG, etc.). See also e.g. [1].

2.4. Synchronous Machine (Momentum) Equation of Motion

An equation of motion is defined by the following expression:

$$J \frac{d\Omega}{dt} = M_T - M \tag{63}$$

J...moment of inertia
Ω...mechanical angle velocity
M_T..driving turbine moment

M...electrical moment (including a loss moment)

$$\omega = n_p \Omega \qquad (64)$$

ω... electrical angle velocity of SG; n_p.. number of pole pairs of SG

If $n_p.J.\Omega_0^2 = T_m$, then the equation (63) is changed into the following form:

$$\frac{T_m}{\omega_s} \frac{d\omega}{dt} = M_T\omega_0 - M\omega_0 \doteq P_T - P \qquad (65)$$

if SG operates in a parallel operation in ES, then

$$\omega = \omega_s + \frac{d\delta}{dt} \qquad (66)$$

ω_s...synchronous angle velocity of SG, δ...load angle of SG

then $\frac{d\omega}{dt} = \frac{d^2\delta}{dt^2}$

if $T_m/\omega_s = T_j$, the equation (63) will be expressed as follows:

$$T_j \frac{d^2\delta}{dt^2} + P = P_T \qquad (67)$$

An equation of motion expressed using the equation (67) is used very often. Its solution very strongly depends on that what kind of a model is used to express an electric capacity P, but at the same time also on that what kind of expression is used to express turbine power output (P_T). This relation expresses connection of a turbine and a generator as a single unit the control of which must be designed as a uniformly controlled system.

2.5. A Stability of a Synchronous Generator in Cooperation with a Large Capacity ES

Let's consider a simplified model of SG connection to a large capacity ES according to a scheme shown in fig.3a.

More over, we will start from the equation of motion (67) in which the synchronous capacity will be determined from the equation (37) and it will be completed with an asynchronous component expressed by the following equation:

$$P_{as} = D \frac{d\delta}{dt} \qquad (68)$$

For an excitation circuit, we will use knowledge mentioned in the equations (55) to (62) whereas instead of the designation ωK_b we will introduce SG no-load amplification K_{Go}, which is defined as follows:

$$K_{Go} = \frac{\text{stator no-load voltage steady value}}{\text{rotor excitation voltage steady value}} = \frac{E_{qo}}{U_{bo}} = \frac{I_b L_{ab}\omega_s}{I_b R_b} = \frac{L_{ab}\omega_s}{R_b} \tag{69}$$

The equation (59) will be expressed in the following form:

$$U_b K_{Go} = E_q + T'_{do}\frac{dE_q}{dt} + T'_{do}\frac{dI_d}{dt}(x_{ds} - x'_{ds});\ T'_{do} = L_b/R_b = T_b \tag{70}$$

The following can be written for linearized equations (67) and (70):

$$T_j \frac{d^2\delta}{dt^2} + D\frac{d\delta}{dt} + \frac{E_q U_s}{x_{ds}} \sin\delta = P_T \tag{71}$$

$$\text{when } P = \frac{E_q \cdot U_s}{x_{ds}} \sin\delta \rightarrow \Delta P = (\frac{\partial P}{\partial \delta})\ \Delta\delta + (\frac{\partial P}{\partial E_q})\Delta E_q = \frac{E_q U_s}{x_{ds}} \cos\delta_o \Delta\delta + \frac{U_s}{x_{ds}} \cdot \sin\delta_o \Delta E_q$$

$$T_j \frac{d^2\Delta\delta}{dt^2} + D\frac{d\Delta\delta}{dt} + \frac{E_q U_s}{x_{ds}} \cos\delta_o \Delta\delta + \frac{U_s}{x_{ds}} \sin\delta_o \Delta E_q = \Delta P_T \tag{72}$$

$$\Delta U_b \cdot K_{Go} = \Delta E_q + T'_{do}\frac{d\Delta E_q}{dt} + T'_{do}(x_{ds} - x'_{ds})\frac{d\Delta I_d}{dt} \tag{73}$$

$$I_d = \frac{U_s\cos\delta - E_q}{x_{ds}} \rightarrow \Delta I_d = \frac{\partial I_d}{\partial \delta}\Delta\delta + \frac{\partial I_d}{\partial E_q}\Delta E_q = -\frac{U_s\sin\delta_o}{x_{ds}}\Delta\delta - \frac{1}{x_{ds}}\Delta E_q$$

$$\Delta U_b \cdot K_{Go} = \Delta E_q + T'_{do}\frac{d\Delta E_q}{dt} + T'_{do}(x_{ds} - x'_{ds})\frac{d}{d_t}[-\frac{U_s\sin\delta_o}{x_{ds}}\Delta\delta - \frac{1}{x_{ds}}\Delta E_q] \tag{74}$$

If we express:

$$T_{dz} = T'_{do}\, x'_{ds}/x_{ds};\ T_\delta = \frac{T'_{do}U_s(x_{ds} - x'_{ds})}{x_{ds}} \cdot \sin\delta_o \tag{75}$$

$$B_p = \frac{\partial P}{\partial E_q} = \frac{U_s}{x_{ds}} \sin\delta_o;\ C_p = \frac{\partial P}{\partial \delta} = \frac{E_q U_s}{x_{ds}} \cos\delta_o \tag{76}$$

the equations (72) and (74) can be expressed in the following form:

$$(\Delta U_b + T_\delta \cdot s \cdot \Delta\delta/K_{Go})\ K_{Go}/(1+T_{dz}\cdot s) = \Delta E_q \tag{77}$$

$$(T_j s^2 + D_s + C_p)\Delta\delta = \Delta P_T - B_p \Delta E_q \tag{78}$$

and a structural scheme of a synchronous machine operating into a large capacity ES shown in fig.5 can be designed.

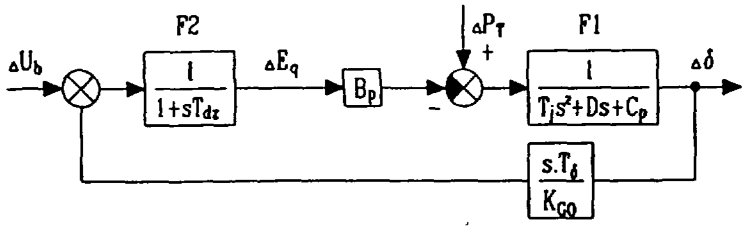


Fig.5

The following applies for the considered system:

$$\Delta\delta = \frac{1 + sT_{dz}}{H(s)}\Delta P_T - \frac{K_{Go}B_p}{H(s)}\Delta U_b \qquad (79)$$

$$\text{where } H(s) = T_jT_{dz}s^3 + (T_j + DT_{dz})s^2 + (D + T_\delta B_p + C_pT_{dz})\,s + C_p \qquad (80)$$

H(s) is a characteristic equation of the considered linearized model of a synchronous generator connected to a large capacity ES in a reactance x_v (fig.3a).

A well-known fact results from the equation (79), i.e. if ΔP_T increases, $\Delta\delta$ increases and if ΔU_b increases $\Delta\delta$ decreases.

More detailed discussion of a solution to the considered linearized model stability, studying the equation (80), discussion of further complicated models of work of SG in large ESs cannot be covered in this entry. However, the author's effort was to partially clarify this problem in a limited extent at least.

2.6. A Stability of SG with a Voltage Controller Including Consideration of Feedback Stabilization Loops (SSV-PSS) in Cooperation with a Large capacity ES

A considerable attention is paid to these issues by experts both in our country and abroad. We would like to point out to the materials [2], [3] by our scientists.

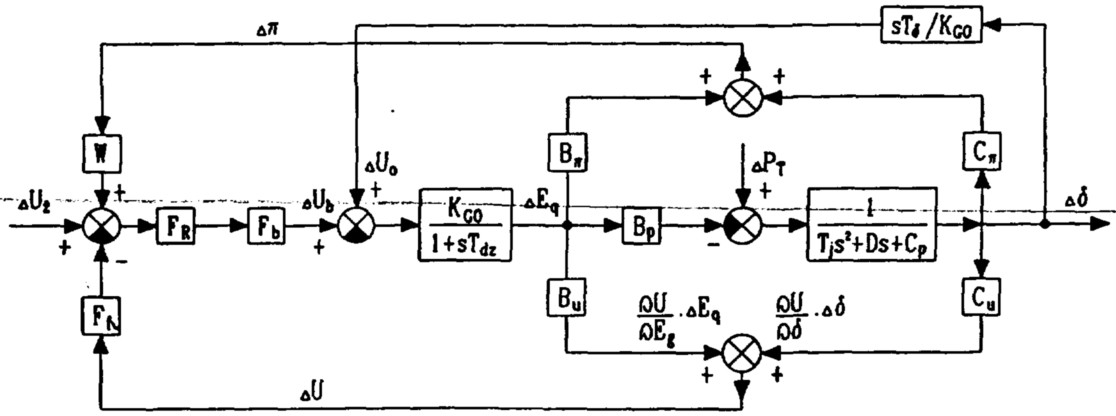


Fig.6

A structural scheme of a linearized model of SG operating into ES considering stabilizing feedback loops with a voltage controller with a general transmission $F_R(s)$ is shown in fig.6. This scheme includes a structure of a linearized model shown in fig.5.

The following applies for a small change of a terminal voltage of SG in the working point (E_{qo}, δ_o) neighborhood:

$$\Delta U = \frac{\partial U}{\partial \delta} \cdot \Delta \delta + \frac{\partial U}{\partial E_q} \Delta E_q = C_u \Delta \delta + B_U \Delta E_q \tag{81}$$

where B_U and C_U can be calculated from the equation (39), into which the expressions (35) are inserted instead of I_d, I_q.

The following can be written for a small change in a stabilizing signal π in the working point neighborhood:

$$\Delta \pi = \frac{\partial \pi}{\partial \delta} \Delta \delta + \frac{\partial \pi}{\partial E_q} \Delta E_q = C\pi \Delta \delta + B\pi \Delta E_q \tag{82}$$

π... stabilizing signal (e.g. generator capacity, slip, ...)
w... transmission function of a filter and a stabilization algorithm of control

$$U_{stab} = w \Delta \pi = w \Delta \delta C_{\pi} + w \Delta E_q B_{\pi} \tag{83}$$

A characteristic equation of the control circuit shown in fig.6 has the following form:

$$H(s) = T_j T_{dz} s^3 + (T_j D T_{dz}) s^2 + (D + C_p T_{dz} + T_{\delta} B_p) s + C_p + (wc_{\pi} - F_f U_u) F_R F_b B_p K_{Go} \tag{84}$$

C. Conclusion

The main goal of this entry was to provide a complex mathematical description of a system in which a conversion of a potential energy of water into a kinetic energy, a kinetic energy into a mechanical one and a mechanical one into an electrical one takes place in two closely related phases.

The first phase takes place in a hydraulic circuit with a water turbine the shaft of which is connected with a rotor of SG. This phase is described in general for a basic principle of an energy conversion in any turbine the selection of which is done of two basic types of turbines (equal-pressure and over-pressure ones) and results through a description of static and dynamic characteristics into an expression of transmissions of a controlled system in which a dynamic behavior described using differential equations is expressed in an operator form and a general characteristic equation of a control circuit of a hydroelectric generating set is written. With new realization objectives of control systems of a hydroelectric generating set, a special attention should be paid to a non-linear function $Q=f(Y)$ for an entire range of water head fluctuations. Meeting this requirement will result in a use of a corresponding configuration of adaptive speed controllers the parameters of which should be changed depending on a turbine opening and a head.

The other phase takes place in SG connected to ES or an electrical load, respectively. This phase is described using differential equations of a stator circuit of SG connected to ES, a differential equation of an excitation circuit including mutual relationships of both the circuits and an equation of motion of SG and results into an expression of a characteristic equation of a control circuit which also contains stabilizing feedback.

A structural scheme of a linearized model of SG operating into ES taking into account stabilizing feedback is designed for a small change in a terminal voltage ΔU of SG and a small change in a stabilizing signal $\Delta \pi$.

It would be preferable, especially for larger hydroelectric generating sets, to make use of introduction of a stabilizing feedback from a large change in a stabilizing signal (a parallel line failure switching off, thus substantially changing ES conductivity and SG capacity, too), whereas the stabilizing signal would be derived from SG capacity and its first derivation. Certainly provided that a corresponding stabilization filter and a special control algorithm (W_x) are used.

From the a.m. models of first and second phases of energy conversion, it is clearly visible that a turbine control and SG control cannot be separated from each other into independent units because these two components are closely connected into one unit with an equation of motion of a hydroelectric generating set which is the most expressly shown up in a control of transient processes where the most complicated operational states must be controlled.

Enhanced demands for control quality and stability of hydroelectric generating sets in ES will also require, except the use of the newest exact methods, introduction of simulation models of hydroelectric generating sets into a real life for a design of which the knowledge mentioned in this entry can be used.

D. References

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