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# TRANSIENT PROCESSES AND DYNAMIC OF VARIABLE SPEED PUMP STORAGE UNIT

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***Abstract.*** *In this paper, a mathematical model and the structure of variable speed pump storage unit (VSPSU) are proposed. Transient processes of VSPSU main parameters are analyzed. The influence of transients on the operating conditions of electrical power system is discussed. The system of non-linear differential equations given in matrix form and representing the VSPSU mathematical model is solved by digital integration. Electrodynamic transients of VSPSU generator and pump operation are simulated by imitation of the active and reactive power variation in the electrical power system. Marginal hydroelectric parameters of the pump storage unit are evaluated. Excitation control algorithms are based on the functional structures of voltage and current controllers represented by compensation units consisting of proportional integrating and integrating-differentiating filters.*

***Keywords:*** *variable speed pump storage unit, dynamic model, operating characteristics, frequency control, voltage quality.*

## 1. Introduction

Several decades ago variable speed pump storage units were started to use for determining primary and secondary power reserves of an electrical power system and for balancing the changeable load power. VSPSUs effectively use hydropower resources and rapidly respond to load power changes [1]. The application of VSPSUs to the fast control of active and reactive powers may cause hydraulic shocks, instability of an electrical power system and axial vibration of the VSPSU rotor. Negative consequences may be avoided by the proper matching of electrical, mechanical and hydraulic parameters of VSPSU, as well as parameters of the excitation control system. The required quality of frequency and voltage in the electrical power system may be obtained by a reliable control of the system's active and reactive power

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under VSPSU generator and pump operation conditions. It is very important for electrical power systems including wind power stations [2]. Therefore it is essential to evaluate the response of VSPSU to the disbalance of active and reactive power in the electrical power system and fast control during generator and pump operation. For this purpose it is necessary to determine functional dependences of hydroelectric parameters and change parameters of the excitation control system accordingly. This paper deals with a mathematical model of power circuits and corresponding computations needed for analysis of VSPSU transients.

## 2. Mathematical model of variable speed pump storage unit

Known mathematical models of VSPSU have not been constructed sufficiently strictly and should be modified [2–5]. It has been established that a universal mathematical model of power circuit dynamics is described by systems of non-linear differential equations having rather complicated solutions. Solutions suitable to compute the time dependence of variable parameters may be determined by the method of spatial state digital integration.

The electric circuits of VSPSU consist of three-phase symmetrical stator and rotor windings. This construction is similar to that of the asynchronous machine with a phase-wound rotor. With reference to the fundamentals of the electric circuit theory equivalent diagrams of given rated power VSPSU electric circuits corresponding to direct-axis and quadrature-axis parameters are constructed (Fig. 1).

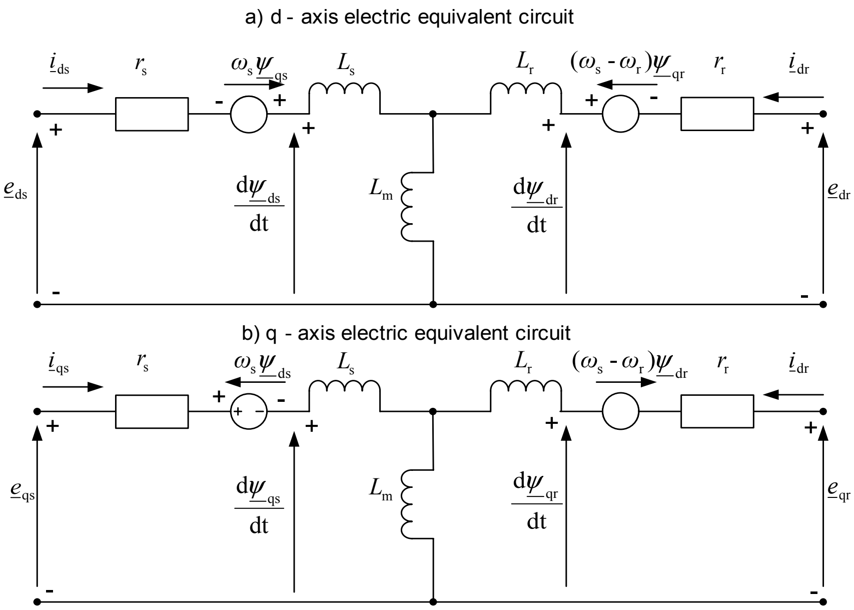


Fig. 1. Equivalent diagrams of VSPSU corresponding to d and q parameters.

Equivalent diagrams (Fig. 1) and their main parameters represented by stator and rotor active resistances $r_s$ ir $r_r$, inductances $L_s$ ir $L_r$, mutual inductance $L_m$, also main quantities, i.e. stator and rotor magnetic fluxes in d and q directions $\underline{\psi}_{(dq)s}$ and $\underline{\psi}_{(dq)r}$, and stator and rotor angular frequencies $\omega_s$ $\omega_r$ may be transformed to Park's d- and q-coordinate system corresponding to one phase data. Non-linear systems of differential equations consist of Ohm's and Kirchoff's laws for voltages of stator and rotor circuits shown in the diagrams of Figure 1 and correspond to the chosen directions of currents, voltages and magnetic fluxes.

Equations for the stator voltage space phasor balance are the following:

$$\begin{cases} \underline{e}_{ds} = \underline{i}_{ds} r_s + \dfrac{d\underline{\psi}_{ds}}{dt} + j\omega_s \underline{\psi}_{qs}, \\ \underline{e}_{qs} = \underline{i}_{qs} r_s + \dfrac{d\underline{\psi}_{qs}}{dt} + j\omega_s \underline{\psi}_{ds}, \end{cases} \tag{1}$$

and equations for the rotor voltage space phasors may be written similarly:

$$\begin{cases} \underline{e}_{dr} = \underline{i}_{dr} r_r + \dfrac{d\underline{\psi}_{dr}}{dt} - j(\omega_s - \omega_r)\underline{\psi}_{qr}, \\ \underline{e}_{qr} = \underline{i}_{qr} r_r + \dfrac{d\underline{\psi}_{qr}}{dt} - j(\omega_s - \omega_r)\underline{\psi}_{dr}. \end{cases} \tag{2}$$

The system is also supplemented with the moment of momentum equation according to Newton's second law:

$$J\frac{d\omega_r}{dt} = T_e \pm T_m + D\omega_r, \tag{3}$$

where $T_e$ and $T_m$ are electromagnetic and mechanical driving torques and $D$ is the damping coefficient.

The matrix form of the equation system (1–3) is the following:

$$\begin{bmatrix} \underline{e}_{ds} \\ \underline{e}_{qs} \\ \underline{e}_{dr} \\ \underline{e}_{qr} \end{bmatrix} = \begin{bmatrix} r_s + \dfrac{d\underline{\psi}_{ds}}{dt} & \omega_s \underline{\psi}_{qs} & \dfrac{d\underline{\psi}_{dr}}{dt} & \omega_s \underline{\psi}_{qr} \\ -\omega_s \underline{\psi}_{ds} & r_s + \dfrac{d\underline{\psi}_{qs}}{dt} & -\omega_s \underline{\psi}_{dr} & \dfrac{d\underline{\psi}_{qr}}{dt} \\ \dfrac{d\underline{\psi}_{ds}}{dt} & (\omega_s - \omega_r)\underline{\psi}_{qs} & r_r + \dfrac{d\underline{\psi}_{dr}}{dt} & (\omega_s - \omega_r)\underline{\psi}_{qr} \\ -(\omega_s - \omega_r)\underline{\psi}_{ds} & \dfrac{d\underline{\psi}_{qs}}{dt} & -(\omega_s - \omega_r)\underline{\psi}_{dr} & r_r + \dfrac{d\underline{\psi}_{qr}}{dt} \end{bmatrix}. \tag{4}$$

For simplifying calculations magnetic flux phasor components in matrix equation (4) may be replaced by products of currents and inductances:

$$\begin{bmatrix} \underline{e}_{ds} \\ \underline{e}_{qs} \\ \underline{e}_{dr} \\ \underline{e}_{qr} \end{bmatrix} = \begin{bmatrix} r_s + \frac{d\underline{i}_{ds}}{dt} L_s & \omega_s \underline{i}_{qs} L_s & \frac{d\underline{i}_{dr}}{dt} L_m & \omega_s \underline{i}_{qr} L_m \\ -\omega_s \underline{i}_{ds} L_s & r_s + \frac{d\underline{i}_{qs}}{dt} L_s & -\omega_s \underline{i}_{dr} L_m & \frac{d\underline{i}_{qr}}{dt} L_m \\ \frac{d\underline{i}_{ds}}{dt} L_s & (\omega_s - \omega_r)\underline{i}_{qs} L_m & r_r + \frac{d\underline{i}_{dr}}{dt} L_r & (\omega_s - \omega_r)\underline{i}_{qr} L_r \\ -(\omega_s - \omega_r)\underline{i}_{ds} L_m & \frac{d\underline{i}_{qs}}{dt} L_s & -(\omega_s - \omega_r)\underline{i}_{dr} L_r & r_r + \frac{d\underline{i}_{qr}}{dt} L_r \end{bmatrix}. \quad (5)$$

Inductance matrix is determined for initial instant when angular frequencies of the stator and rotor are equal to zero ($\omega_s = 0$, $\omega_r = 0$):

$$\mathbf{L} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix}. \quad (6)$$

After some manipulations with moment of momentum equation (3) and matrix equation (5), we get a system of equations for space state variables in Cauchy form:

$$\begin{cases} \frac{d}{dt}\begin{bmatrix} \underline{i}_{ds} \\ \underline{i}_{qs} \\ \underline{i}_{dr} \\ \underline{i}_{qr} \end{bmatrix} = \mathbf{A}_1 \begin{bmatrix} \underline{i}_{ds} \\ \underline{i}_{qs} \\ \underline{i}_{dr} \\ \underline{i}_{qr} \end{bmatrix} + \mathbf{B}_1 \begin{bmatrix} \underline{e}_{ds} \\ \underline{e}_{qs} \\ \underline{e}_{dr} \\ \underline{e}_{qr} \end{bmatrix}, \\ \frac{d}{dt}\begin{bmatrix} \theta_r \\ \omega_r \end{bmatrix} = \mathbf{A}_2 \begin{bmatrix} \theta_r \\ \omega_r \end{bmatrix} + \mathbf{B}_2 \end{cases} \quad (7)$$

where $\boldsymbol{A}_1$, and $\boldsymbol{B}_1$ are the stator and rotor coefficient matrixes; $\boldsymbol{A}_2$, and $\boldsymbol{B}_2$ are moment of momentum coefficient matrixes.

By substituting matrix equation (5) for moment of momentum equation (3) in system (7), the coefficient matrix representing VSPSU space state equations with respect to the stator and rotor current phasors and rotor current frequency may be obtained:

$$\begin{cases} \dfrac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} \underline{i}_{\mathrm{ds}} \\ \underline{i}_{\mathrm{qs}} \\ \underline{i}_{\mathrm{dr}} \\ \underline{i}_{\mathrm{qr}} \end{bmatrix} = -\underbrace{\left\{ \mathbf{L}^{-1} \begin{bmatrix} r_{\mathrm{s}} & \omega_{\mathrm{s}} L_{\mathrm{s}} & 0 & \omega_{\mathrm{s}} L_{\mathrm{m}} \\ -\omega_{\mathrm{s}} L_{\mathrm{s}} & r_{\mathrm{s}} & -\omega_{\mathrm{s}} L_{\mathrm{m}} & 0 \\ 0 & (\omega_{\mathrm{s}} - \omega_{\mathrm{r}}) L_{\mathrm{m}} & r_{\mathrm{r}} & (\omega_{s} - \omega_{\mathrm{r}}) L_{\mathrm{r}} \\ -(\omega_{\mathrm{s}} - \omega_{\mathrm{r}}) L_{\mathrm{m}} & 0 & -(\omega_{\mathrm{s}} - \omega_{\mathrm{r}}) L_{\mathrm{r}} & r_{\mathrm{r}} \end{bmatrix} \right\}}_{\mathbf{A}_1} \\ \qquad \times \begin{bmatrix} \underline{i}_{\mathrm{ds}} \\ \underline{i}_{\mathrm{qs}} \\ \underline{i}_{\mathrm{dr}} \\ \underline{i}_{\mathrm{qr}} \end{bmatrix} + \underbrace{\mathbf{L}^{-1}\mathbf{E}}_{\mathbf{B}_1} \begin{bmatrix} \underline{e}_{\mathrm{ds}} \\ \underline{e}_{\mathrm{qs}} \\ \underline{e}_{\mathrm{dr}} \\ \underline{e}_{\mathrm{qr}} \end{bmatrix}, \\ \dfrac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} \theta_{\mathrm{r}} \\ \omega_{\mathrm{r}} \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 \\ 0 & \dfrac{D}{J} \end{bmatrix}}_{\mathbf{A}_2} \begin{bmatrix} \theta_{\mathrm{r}} \\ \omega_{\mathrm{r}} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ \dfrac{1}{J}(T_{\mathrm{e}} \pm T_{\mathrm{m}}) \end{bmatrix}}_{\mathbf{B}_2}, \end{cases} \tag{8}$$

where $\boldsymbol{E}$ is the unit matrix, $\theta_{\mathrm{r}}$ is the angle of rotor, $-T_{\mathrm{m}} = T_{\mathrm{m(g)}}$ is the negative moment of momentum for generator operation, and $T_{\mathrm{m}} = T_{\mathrm{m(p)}}$ is the positive moment of momentum for pump operation.

Values of stator and rotor currents at given instant $t$ and also values of rotor angle and rotor angular frequency are determined from equations (7) and (8) by digital integration:

$$\begin{cases} \begin{bmatrix} \underline{i}_{\mathrm{ds}} \\ \underline{i}_{\mathrm{qs}} \\ \underline{i}_{\mathrm{dr}} \\ \underline{i}_{\mathrm{qr}} \end{bmatrix}(t) = e^{\mathbf{A}_1(t)} \begin{bmatrix} \underline{i}_{\mathrm{ds}} \\ \underline{i}_{\mathrm{qs}} \\ \underline{i}_{\mathrm{dr}} \\ \underline{i}_{\mathrm{qr}} \end{bmatrix}(t) + \int\limits_0^t \left( \left(e^{\mathbf{A}_1(h)}\right) \mathbf{B}_1 \begin{bmatrix} \underline{e}_{\mathrm{ds}} \\ \underline{e}_{\mathrm{qs}} \\ \underline{e}_{\mathrm{dr}} \\ \underline{e}_{\mathrm{qr}} \end{bmatrix}(\tau) \right) \mathrm{d}\tau \\ \begin{bmatrix} \theta_{\mathrm{r}} \\ \omega_{\mathrm{r}} \end{bmatrix}(t) = e^{\mathbf{A}_2(t)} \begin{bmatrix} \theta_{\mathrm{r}} \\ \omega_{\mathrm{r}} \end{bmatrix}(t) + \int\limits_0^t \left( \left(e^{\mathbf{A}_2(h)}\right) \mathbf{B}_2 \right) \mathrm{d}\tau \end{cases}, \tag{9}$$

where $h = t - \tau$ is the integration step and $\tau$ is the time delay.

Summary active power $P_{\mathrm{e}}$, reactive power $Q_{\mathrm{e}}$, electromagnetic moment of momentum $T_{\mathrm{e}}$, rotor slip angular frequency $\omega_{\mathrm{m}}$ and rotor angle $\theta_{\mathrm{m}}$ may be computed by use of the proposed mathematical model of VSPSU power circuits and method of solution:

$$P_{\mathrm{e}} = 3\left(\underline{e}_{\mathrm{ds}}\underline{i}_{\mathrm{ds}} + \underline{e}_{\mathrm{qs}}\underline{i}_{\mathrm{qs}} + \underline{e}_{\mathrm{dr}}\underline{i}_{\mathrm{dr}} + \underline{e}_{\mathrm{qr}}\underline{i}_{\mathrm{qr}}\right), \tag{10}$$

$$Q_{\mathrm{e}} = 3\left(\underline{e}_{\mathrm{qs}}\underline{i}_{\mathrm{ds}} - \underline{e}_{\mathrm{ds}}\underline{i}_{\mathrm{qs}} + \underline{e}_{\mathrm{qr}}\underline{i}_{\mathrm{dr}} - \underline{e}_{\mathrm{dr}}\underline{i}_{\mathrm{qr}}\right), \tag{11}$$

$$T_e = 1.5 p L_m \left( \underline{i}_{qs} \underline{i}_{dr} - \underline{i}_{ds} \underline{i}_{qr} \right), \quad (12)$$

where $p$ is the pole pair number.

$$\omega_m = \frac{\omega_r}{\omega_s}, \quad (13)$$

$$\theta_m = \int \omega_m \mathrm{d}t. \quad (14)$$

The gross output or consumed power of the VSPSU depends on potential water power [3, 4]:

$$P = kG\sqrt{H^3}, \quad (15)$$

where $k$ is the proportionality factor, $H$ is the pressure height and $G$ is the position of the deflection wheel.

Considering the potential water power the power of the hydroelectric generator may be determined in terms of mechanical water power for generator operation:

$$\begin{cases} P_g = P \\ P_g(\omega_p) = \alpha_g P_g^2 + \beta_g P_g + \gamma_g \end{cases}, \quad (16)$$

where $\alpha_g$, $\beta_g$ and $\gamma_g$ are the coefficients of the function computed by the method of least squares. The power of the pump is the function of mechanical water power for generator power $P_g < 10\%$:

$$\begin{cases} P_p = P + 0{,}1P \\ P_p(\omega_p) = \alpha_p P_p^2 + \beta_p P_p + \gamma_p \end{cases}, \quad (17)$$

where $\alpha_p$, $\beta_p$ and $\gamma_p$ are the coefficients of the function computed by the method of least squares.

By using functions (16) and (17) dependences of the mechanical hydraulic turbine power on the angular frequency are established for generator and pump operation (Fig. 2).

The dependence of the main parameters of the hydraulic turbine power on the angular frequency (Fig. 2) is as follows: maximum water power $P_{g\,max}$ and $P_{p\,max}$, minimum water power $P_{g\,min}$ and $P_{p\,min}$, average water power $P_{g\,avg}$ and $P_{p\,avg}$, maximum angular speed of the turbine $\omega_{g\,max}$ and $\omega_{p\,max}$, minimum angular speed of the turbine $\omega_{g\,min}$ and $\omega_{p\,min}$ (each of them separately determined under generator and pump operation conditions).

The mechanical moment of momentum $T_m$ may be found as follows for generator operation:

$$T_{m(g)} = \frac{P_g(\omega_g)}{\omega_g}, \quad (18)$$

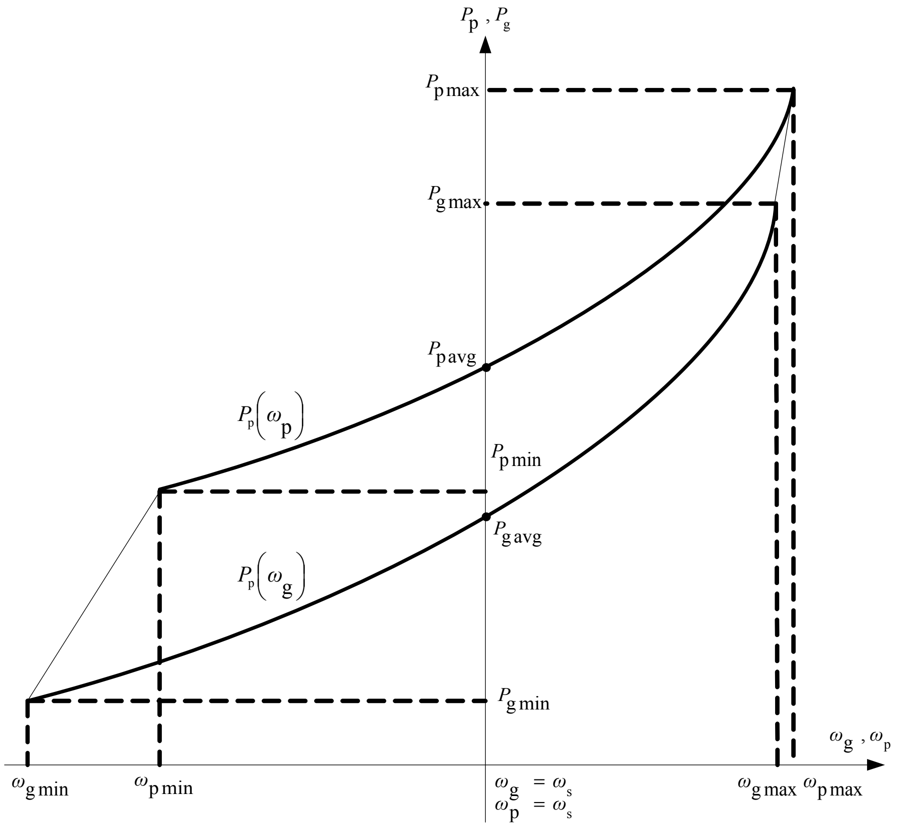


Fig. 2. Dependence of the hydraulic turbine power on the angular frequency.

and similarly for the pump one:

$$T_{m(p)} = \frac{P_p(\omega_p)}{\omega_r}. \tag{19}$$

Maximum powers $P_{g\,max}$ and $P_{p\,max}$ under generator and pump operation conditions are limited by pressure height $H$. Minimum powers $P_{g\,min}$ and $P_{p\,min}$ for the corresponding operation are limited by the technical parameters of the hydraulic turbine. Average powers of the hydraulic turbine $P_{g\,avg}$ and $P_{p\,avg}$ may be calculated by means of dependence shown in Fig. 2 for angular frequency $\omega_r = \omega_s = 1\text{pu}$.

The structure of the exciter control system must be composed for the proposed mathematical model of the VSPSU power circuit and functions of the system elements must be matched with the parameters of the power circuit.

## 3. Structure of exciter control system

The structure of the VSPSU exciter control system includes the same control elements with the same mathematical definitions as that of the exciter control systems of synchronous hydroelectric units. With reference to the exciter control system structure of a synchronous generator and wind power station with asynchronous machines, a modified structure of mathematical model elements of the VSPSU exciter control system may be constructed [5].

Mathematical control elements maintain stable converter and inverter current and voltage level to ensure the system stability (Fig. 3). The exciter control system structure diagram consists of current, voltage, active and re-active power and frequency synchronizing controllers, as well as of measured-quantity transformation components with compensation filters executing proportional-integrating (PI) and proportional-integrating-differentiating (PID) functions (Fig. 4). Function structures comprising feedbacks between rotor and stator power circuits and mechanical components of the hydraulic turbine and deflection wheel interact and ensure the reliable operation of the VSPSU exciter control system, the operation being matched with the electrical power system.

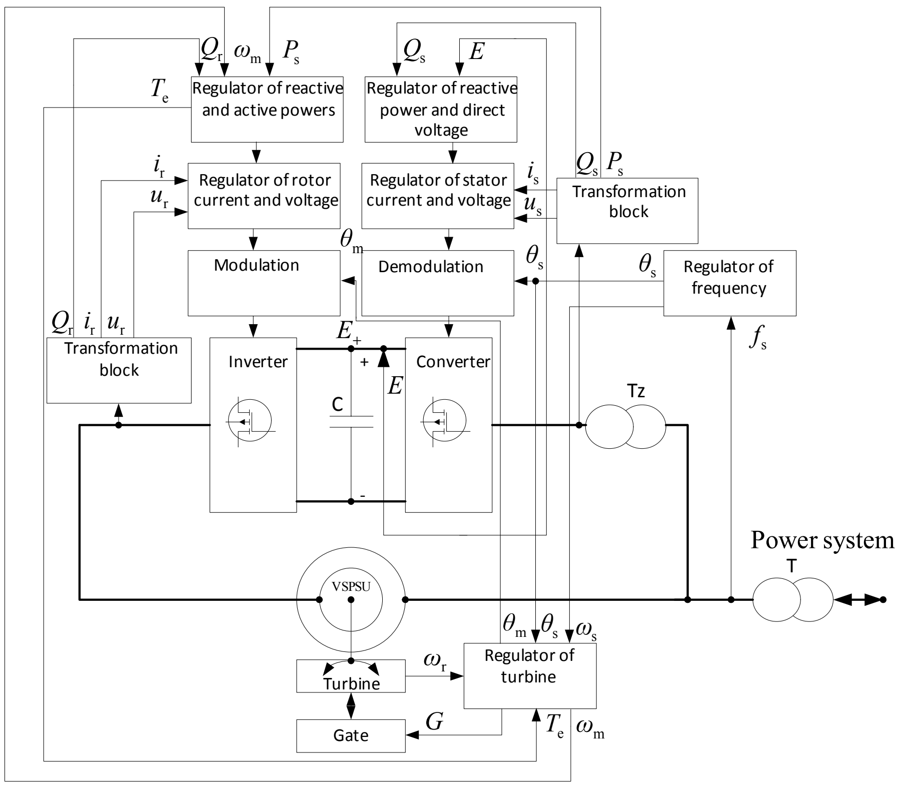


Fig. 3. Structure diagram of an exciter control system.

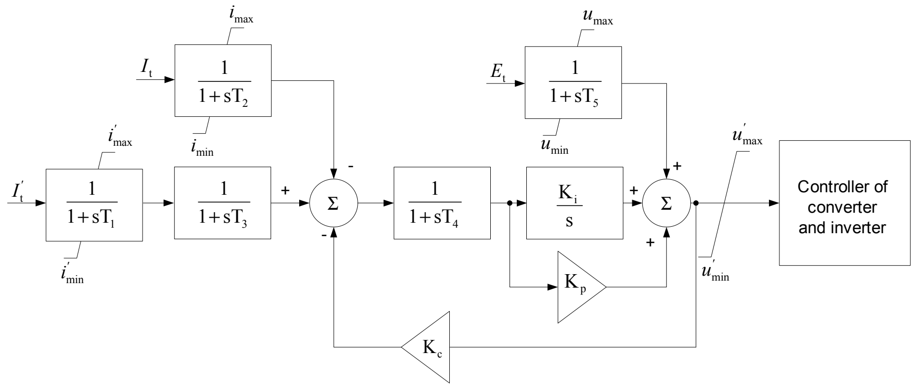


Fig. 4. Mathematical model of a simplified exciter control system.

The proposed mathematical model of the VSPSU exciter control system structure enables one to evaluate properties of the VSPSU generator and pump operation and to perform a mathematical simulation of transient processes. The main parameters of the mathematical model (Fig. 4) describing the structure of the exciter control system are the following: time constants $T_{(1)}$–$T_{(5)}$, integration factor $K_i$, proportionality factor $K_p$, compensation factor $K_c$, transformed rotor or stator current $I_t$, transformed summary current $I'_t$, transformed rotor or stator voltage $E_t$, maximum current limits $i'_{max}$ and $i_{max}$, minimum current limits $i'_{min}$ and $i_{min}$, maximum voltage limits $u'_{max}$ and $u_{max}$, minimum voltage limits $u'_{min}$ and $u_{min}$.

Theoretical research is performed in accordance with proposed mathematical models of VSPSU power circuits and exciter control system.

## 4. Research results

Simulations have been carried out on the VSPSU of 250 MW rated power, with a 100 m pressure height. After matching mathematical models of VSPSU power circuits and exciter control system with hydroelectric parameters of the turbine, the initial conditions for steady-state generator and pump operation are determined. The balance of active and reactive powers in the electrical power system is maintained if the average active power of VSPSU is $P_{g\ avg}$ = 178 MW for cos$\gamma$ = 0.8 under generator operation conditions and $P_{p\ avg}$ =200 MW for cos$\gamma$ = 0.9 under pump operating conditions. Initial conditions and the limits of the mathematical model solution convergence are determined in accordance with these operation conditions of VSPSU. Power flow variation is evaluated by applying the Newton-Raphson method and the influence of this variation to the VSPSU operation conditions considered is established. For this purpose the active power variation in the electrical power system load equal to ±50% of

VSPSU rated power is imitated. The time dependence of angular frequency $\omega_m$ of the rotor slip, current $I_t$, active power $P_e$ and reactive power $Q_e$ corresponding to the generator and pump operation (Figs. 5–8, a and b, respectively) are determined for the time interval $t$ = 1 s, using the digital integration method.

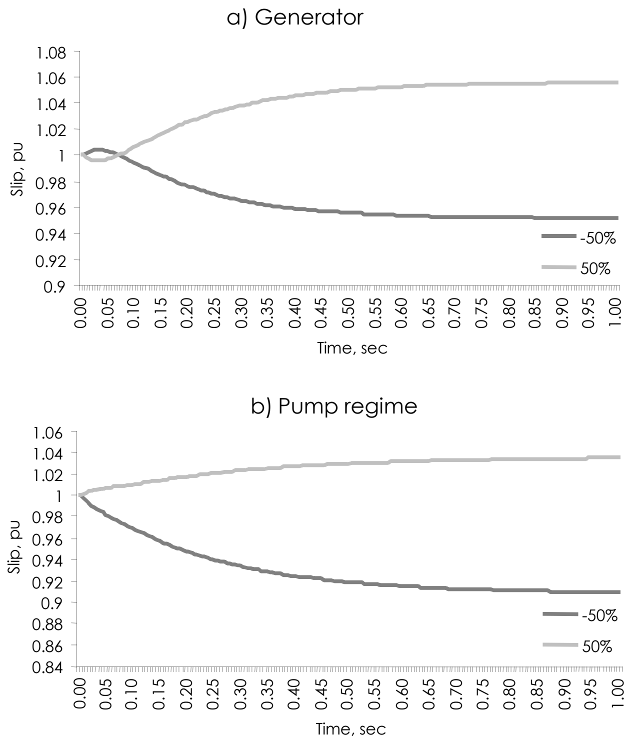


Fig. 5. Graphics of the time dependence of rotor slip.

If the angular frequency of the rotor slip is being varied at a rate of 1.2 %/ms in the interval between +10% and –6% under generator operation conditions, active power may be changed in the interval between 0 and 150 MW (Fig 5, a). Under generator operation conditions some acceleration of the current and active power variation may be originated by the mechanical power of water which may cause the hydraulic shock (Figs. 6, a and 7, a). This acceleration is controlled by regulators of current and voltage in the rotor circuit using the correction of rotor angular frequency $\omega_r$ by changing time constants. The rate of dependence variation (Figs. 5–8) is determined in a 0.1 s time interval. This rate determines the possibility of VSPSU power control under generator and pump operation conditions. The maximum rate of active power variation corresponding to the VSPSU generator operation is 28 MW/ms (Fig. 7, a), the maximum rate of reactive power variation is 17 Mvar/ms (Fig. 8, a), accordingly, the value of maximum current variation rate is 0.7 kA/ms (Fig. 6, a).

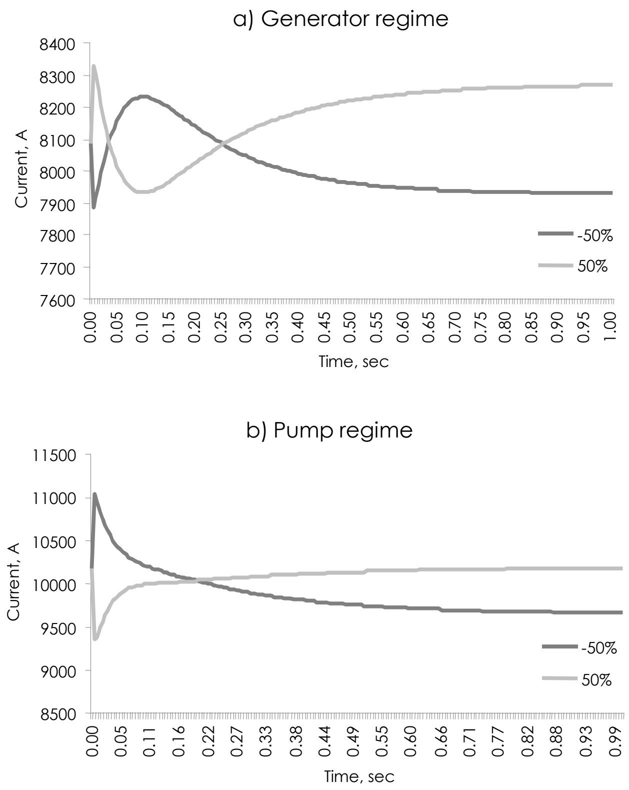


Fig. 6. Graphics of the time dependence of current.

If the angular frequency of the rotor slip is being varied at a rate of 2.0 %/ms in the interval ±6% under pump operation conditions, the active power may be changed in the interval between 0 and 100 MW (Fig 5, b). The maximum rate of active power variation corresponding to the VSPSU pump operation is 33 MW/ms (Fig. 7, b), the maximum rate of reactive power variation is 13 Mvar/ms (Fig. 8, b), accordingly, the value of maximum current variation rate is 1.4 kA/ms (Fig. 6, b).

Comparison of generator and pump operations shows that the pump operation of VSPSU is more preferable for the more continuous performance due to the fact that the sensitivity of loaded hydraulic turbine regulators to the mechanical actions and hydraulic shocks under pump operation conditions is lower than that under generator operation conditions.

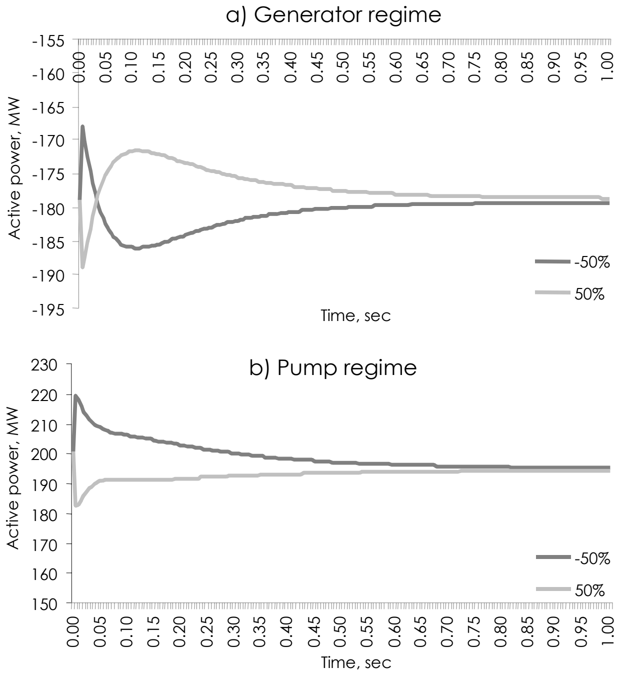


Fig. 7. Graphics of the time dependence of active power.

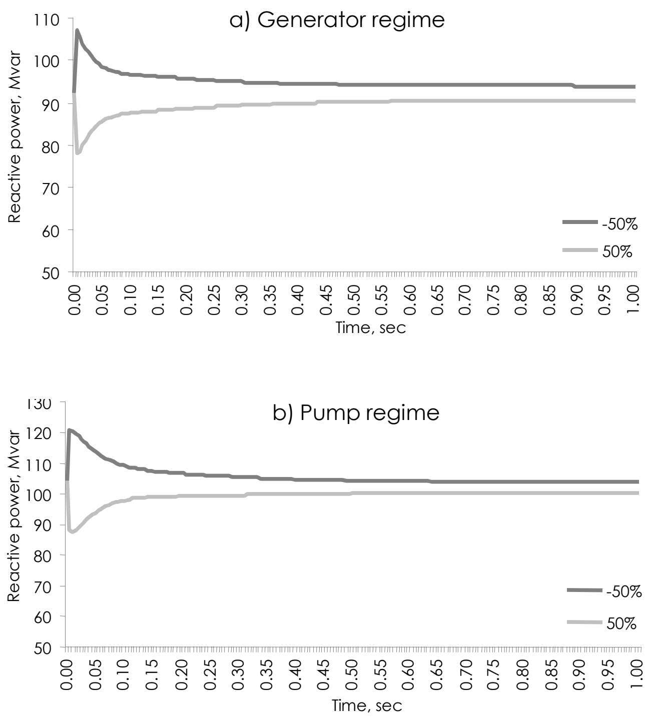


Fig. 8. Graphics of the time dependence of reactive power.

## 5. Conclusions

1. A mathematical model of the variable speed pump storage unit is constructed and computations are performed.
2. The active power of a 250 MW variable speed pump storage unit may be changed at a rate of 28 MW/ms under generator operation conditions, and at a rate of 33 MW/ms under pump operation conditions. An effective control of the active power in the electrical power system and small frequency deviations may be ensured under energy generation and consumption conditions.
3. The reactive power of the variable speed pump storage unit may be changed at a rate of 17 Mvar/ms under generator operation conditions and at a rate of 13 Mvar/ms under pump operation conditions. Reactive power demand in the electrical power system may be satisfied and high voltage quality may be ensured.
4. The maximum possible active power change of 150 MW may be reached during 6.5 ms under generator operation conditions, and the corresponding change of 100 MW may be achieved during 3.0 ms when the unit operates as a pump.
5. The variable speed pump storage unit may be used for effective power control with a stable operation when the variation of the rotor angular frequency is in the interval of from +10% to –6% in respect of synchronous frequency under generator operation conditions and in the interval ±6% under pump operation conditions.

## REFERENCES


1. Medvedeva-Tšernobrivaja, V., Attikas, R., Tammoja, H. Characteristic numbers of primary control in the isolated Estonian power system. *Oil Shale*, 2011, **28**(2S), 214–222.
2. Suul, J. A., Uhlen, K., Undeland, T. Variable speed pumped storage hydropower for integration of wind energy in isolated grids – case description and control strategies. *Proc. Nordic Workshop on Power and Industrial Electronics*, *NORPIE/2008,* June 9–11, 2008, Espoo, Finland, 8 pp.
3. Lung, J.-K., Lu, Y., Hung, W.-L., Kao, W.-S. Modeling and dynamic simulations of doubly fed adjustable-speed pumped storage units. *IEEE T. Energy Conver.,* 2007, **22**(2), 250–258.
4. Nagura, O., Higuchi, M., Tani, K., Oyake, T. Hitachi's adjustable-speed pumped-storage system contributing to prevention of global warming. *Hitachi Review*, 2010, **59**(3), 99–105.
5. Takahashi, R., Tamura, J., Tada, Y., Kurita, A. Model derivation of an adjustable speed generator and its excitation control system. *14$^{th}$ Power Systems Computation Conference (PSCC)*, 24–28 June 2002, Seville, Spain, **1**, 200–205.


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