

## FEASIBILITY STUDY OF ASYNCHRONOUS GENERATOR AT KRUONIS PUMPED STORAGE PLANT

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**Abstract.** Variable speed turbine with asynchronous generator is planned to build in Kruonis Pumped Storage Plant for plant schedule chart improvement. The fifth unit with variable speed turbine and asynchronous generator is planned to install under revised National Energy Strategy project. Variable speed turbine with asynchronous generator of 250 MW maximum power has been analyzed in this article. The purpose of this experimental study is to determine relation between asynchronous generator's electrical, mechanical and hydraulic parameters. Mathematical model of asynchronous generator and excitation control system had been created. Variation of generator's rotor speed due to height differences in reservoirs and also active, reactive power characteristic dependence of pump and turbine operating regimes has been taken in consideration. Experimental study has been executed on the basis of classical theory of asynchronous machines with phase-wound rotor.

**Keywords:** pumped storage, asynchronous generator, variable speed, synchronization.

### 1. Introduction

Great attention is paid to renewable energy development in modern power systems. Wind energy is considered one of the most promising technologies. However, development of wind energy results in unstable power and frequency balance. Problems can be solved by using various technologies such as pumped storage plants (PSP). These plants can balance the Wind power plant parks generated power but most of PSPs are equipped with synchronous generators, which can complicate power balancing at hot reserve. Wind power plant parks generated energy in Lithuania is increasing which results the need of additional hot reserve. It is necessary to investigate Kruonis PSP schedule chart and new unit expansion perspective (Krishnan 2001, Stelzer and Walters, 1977). Asynchronous generator with excitation system and its operation in Kruonis PSP depends on the technical parameters. The classical mathematical modeling methodology is used in this feasibility study.

### 2. Overview of the Kruonis Pumped Storage Plant

Kruonis PSP has four synchronous generators of 225 MW power. There is planned to build fifth unit with asynchronous generator (AG) of 250 MW power. Hydro technical parameters would not change significantly in PSP. AG performance characteristics will be determined by Francis turbine which characteristics differs from the currently installed ROHT turbines. PSP efficiency de-

pends on water pressure and water flow rate (Fig 1) (Stelzer and Walters 1977).

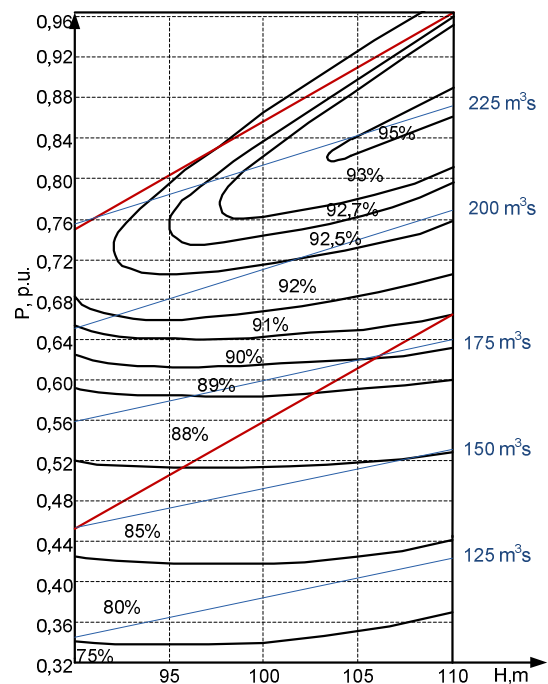


Fig 1. PSP hydro technical characteristics

Water pressure, water flow and efficiency are variable values, which expresses the power of water (Sul and Uhlen 2009, Jablonskis *et al.*, 2008):

$$P_{water} (p.u.) = \frac{\rho g H Q \eta}{P_E} ; \quad (1)$$

where  $H$  - height of water pressure between the reservoirs (from 96 to 111.5 m)  $Q$  - water flow rate in generator mode (185-240 m<sup>3</sup>/s),  $\rho$  - density of water at normal conditions m<sup>3</sup>/s,  $g$  - free fall acceleration,  $P_B$  – base power,  $\eta$  – efficiency AG.

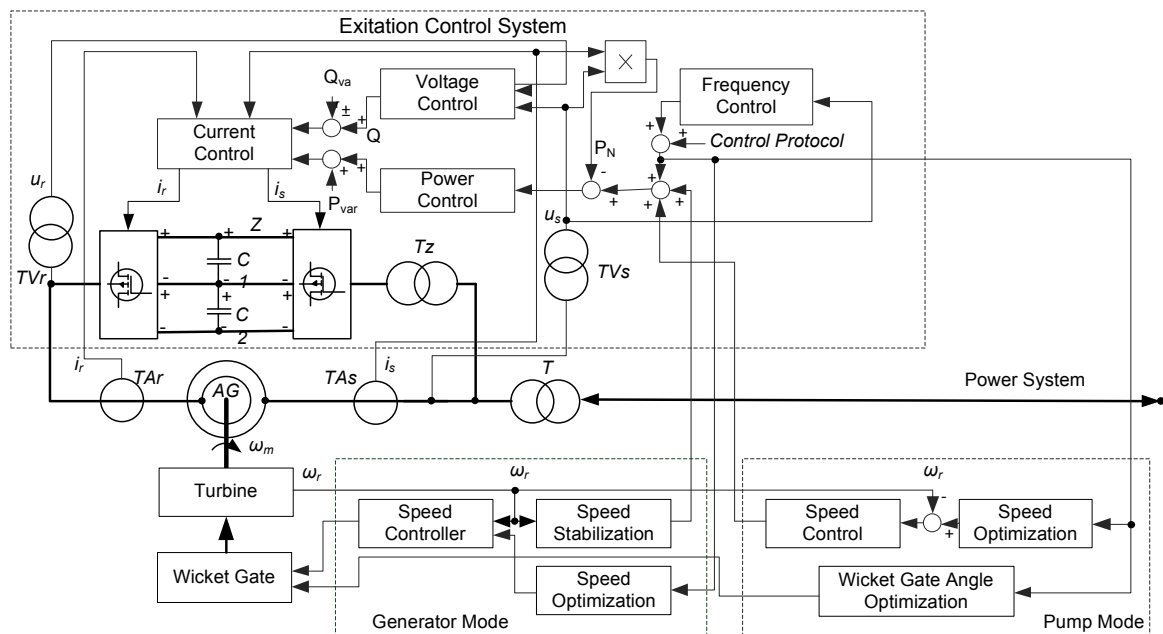
AG performance characteristics are determined by expression 1 and the characteristics of the turbine (Fig 1). AG technical parameters are determined by the maximum total output of 280 MVA, and the active power output of 250 MW (Stelzer and Walters 1977).

Basic parameters of AG are calculated (table 1). Operating characteristics depends on basic AG parameters which might be exchanged.

**Table 1.** Basic AG parameters

Parameters	Values	p.u.
Active Power, MW (P)	250	1.0
Voltage, kV ( $U_s$ ),	15.75	1.0
Frequency, Hz ( $f_s$ )	50	1.0
Synchronous frequency, rad/s, ( $\omega_s = \omega_r$ )	17.45	1.0
No. of poles, u. (p)	18	
Stator active resistance, ( $r_s$ )		0.022
Stator reactance, ( $x_s$ )		0.804
Active rotor resistance, ( $r_r$ )		0.051
Rotor reactance, ( $x_r$ )		0.875
Relationship between reactance, ( $x_m$ )		1.3

AG excitation control system, excitation and power transformers form PSP unit. Simplified principal scheme is given in Fig 2, where the excitation control system (Z)



**Fig 2.** Asynchronous Generator Control System

is connected with stator circuit terminals through power transformer (Tz). Its function is to change the rotor circuit power supply voltage, active, reactive power by amplitude, phase and frequency. AG stator windings connected to the power through the power transformer (T). Excitation control system connected to the rotor windings controls the rotor angular frequency in  $\pm 6\%$  range (Krishnan 2001, Boldea 2006).

slip changes from -1 to 1 ( $s = \pm 1$  p.u.). However optimal operating regime is reached when the slip changes in the  $\pm 6\%$  range with regard to synchronous frequency. Rotor angular frequency is determined according to the expression:

$$\omega_r = (1s)\omega_s \quad (2)$$

where  $\omega_r$  - rotor angular frequency,  $\omega_s$  - stator angular frequency,  $s$  - slip.

### 3. Excitation control system of asynchronous generator

Sub-systems control structure, parameters and characteristic has to be evaluated while modeling and analyzing AG operating conditions and related processes. Mathematical model developed according to the chosen control structures (Fig 2). Power and voltage characteristics depend on currents flowing in the stator and rotor windings which are controlled by rotor power converter. Converter separates the active and reactive power, which is performed by frequency – impulse or vector modulation (Babypriya and Anita 2009, Takahaslii *et al.* 2002). Rotor angular frequency control system maintain frequency angle within the specified range. This frequency control is direct frequency control.

AG performance characteristics management is connected with turbine rotor and wicket gate circuit parameters by feedback links. AG reaction to power changes and process time in excitations control system is less than synchronous generator (Babypriya and Anita 2009). This provides unit agility.

The power change correction depends on the laws of mechanics and hydraulics (cavitation, vibration, water pressure, etc.) (Suul and Uhlen 2009). Control is performed by the speed controller in the excitation system when AG operates in generator mode. When generator switches to the pump mode control is performed by optimization block which controls turbine blade angle, water flow rate and active power (Fig 1, 2). AG can operate at several synchronization modes, which are determined by the excitation system (Boldea 2006).

#### 4. The Static Mathematical Model of the Asynchronous Generator

The simplified mathematical model of the AG is used when the steady electrical, electromagnetic and mechanical processes are researched. Static performance regimes characteristics of AG are researched using the steady state processes. There are many ways of mathematical model creation that can be used investigating and establishing the dependence of AG parameters and static characteristics. Ohm's and Kirchhoff's laws transformed in Park coordinates are used for mathematical description of the model. This reduces the number of variables in calculations (Babypriya and Anita 2009, Krishnan 2001, Boldea 2006, Takahaslii *et al.* 2002). AG equivalent scheme of T form with d, q coordinate axes and additional stator and rotor voltage sources have been created based on classic theory of asynchronous machine (Fig 3).

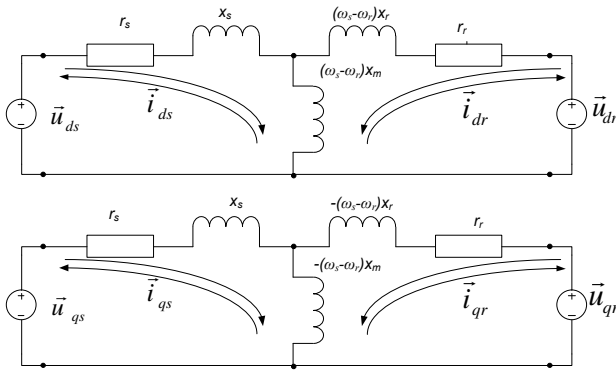


Fig 3. Asynchronous generator equivalent scheme

Power flow distribution in circuits is not put in consideration. Stator and rotor angular frequency ( $\omega_s$ ,  $\omega_r$ ) influence rotor circuit reactive resistance ( $x_m$ ), while stator circuit reactive resistance is influenced by stator synchronous angular frequency ( $\omega_s$ ).

Phase parameters of equivalent scheme are transformed into parameters of Clark ( $\alpha\beta$ ) and Park (dq) coordination systems (formula 3). Component of real parameters are designed on axis d and component of virtual pa-

rameters are designed on axis q. Applying Park's transformation allows to determine variation of parameters and characteristics dependence on the rotor circuit voltage phase angle (Babypriya and Anita 2009, Suul and Uhlen 2009, Boldea 2006).

$$\vec{u}_{dq} = \begin{bmatrix} ua & ub & uc \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & \frac{1}{2} \\ \frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{2} \\ \frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} \cos \gamma & \sin \gamma & 0 \\ \sin \gamma & \cos \gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad (3)$$

where [ua ub uc]– parameters of phases voltages.

Ohm's Law matrix expression has been used for currents calculation of AG equivalent scheme (Fig 3.):

$$\begin{bmatrix} \vec{u}_{ds} \\ \vec{u}_{qs} \\ \vec{u}_{dr} \\ \vec{u}_{qr} \end{bmatrix} = Z \cdot \begin{bmatrix} \vec{i}_{ds} \\ \vec{i}_{qs} \\ \vec{i}_{dr} \\ \vec{i}_{qr} \end{bmatrix}, \quad (4)$$

where  $Z = \begin{bmatrix} r_s & \omega_r x_s & 0 & \omega_r x_m \\ \omega_r x_s & r_s & \omega_r x_m & 0 \\ 0 & (\omega_s \omega_r) x_m & r_r & (\omega_s \omega_r) x_m \\ (\omega_s \omega_r) x_m & 0 & (\omega_s \omega_r) x_m & r_r \end{bmatrix}$ .

Reactive relationship between the resistances is assessed by impedance matrix.

Circuit currents are calculated from formula 3 expression:

$$\begin{bmatrix} \vec{i}_{ds} \\ \vec{i}_{qs} \\ \vec{i}_{dr} \\ \vec{i}_{qr} \end{bmatrix} = Z^{-1} \cdot \begin{bmatrix} \vec{u}_{ds} \\ \vec{u}_{qs} \\ \vec{u}_{dr} \\ \vec{u}_{qr} \end{bmatrix} \quad (5)$$

Total active power in AG circuits is calculated with calculated currents:

$$P = P_s + P_r = \frac{3}{2} \left( (\vec{u}_{ds} \cdot \vec{i}_{ds} + \vec{u}_{qs} \cdot \vec{i}_{qs}) + (\vec{u}_{dr} \cdot \vec{i}_{dr} + \vec{u}_{qr} \cdot \vec{i}_{qr}) \right) \quad (6)$$

The total reactive power:

$$Q = Q_s + Q_r = \frac{3}{2} \left( (\vec{u}_{qs} \cdot \vec{i}_{ds} + \vec{u}_{ds} \cdot \vec{i}_{qs}) + (\vec{u}_{qr} \cdot \vec{i}_{dr} + \vec{u}_{dr} \cdot \vec{i}_{qr}) \right) \quad (7)$$

Electromagnetic torque:

$$T_e = \frac{3}{2} L_m (\vec{i}_{qs} \vec{i}_{dr} \vec{i}_{ds} \vec{i}_{qr}) \quad (8)$$

## 5. Asynchronous Generator Static Characteristics

Matlab software package is used for investigation of asynchronous generator static characteristics. Rotor angular frequency  $\omega_r$  have been changed in range from 0.6 to 1.4 p.u. Electromagnetic torque ( $T_e$ ), reactive and active power ( $P, Q$ ), stator and rotor current characteristics ( $i_s, i_r$ ) have been stimulated.

**The study of AG performance in generator model.** AG parameters (Fig 3) are determined by changing voltage amplitude of the rotor circuit.

Positive rotor voltage ( $u_r$ ) variation is set in range of 0 - 0.6 p.u. with step of 0.2 p.u. When  $u_r = 0$  contacts of rotor circuit are short circuited. In this case, performance characteristics are similar to classical double fed asynchronous generator (Fig 4, 5).

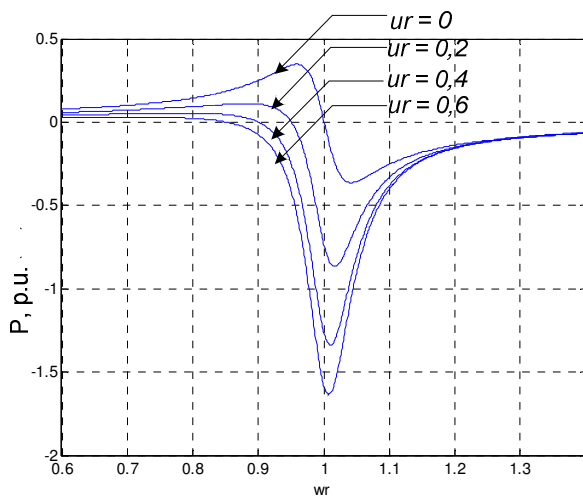


Fig 4. Characteristics of active power in generator mode

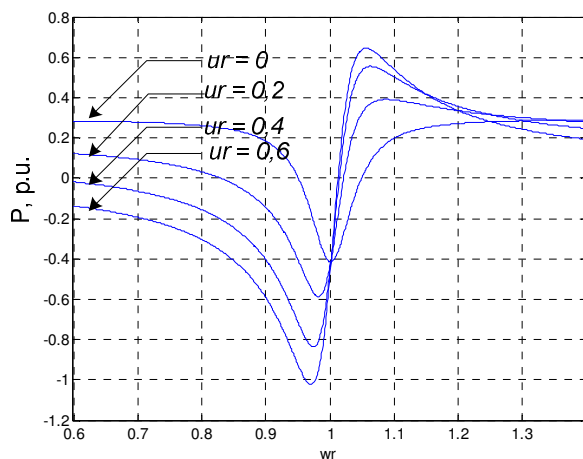


Fig 5. Characteristics of reactive power in generator mode

Under characteristics of working AG mode parameters by changing voltage phase angle in rotor circuit (Fig 6, 7), of 0 - 60° with step of 30° when rotor circuit voltage is  $u_r = 0.3$  p.u.

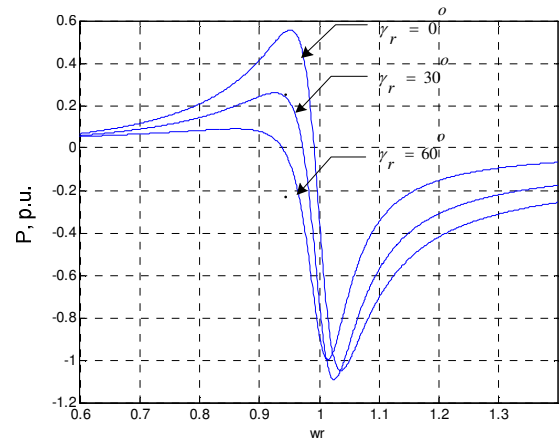


Fig 6. Characteristics of active power in generator mode after phase angle correction

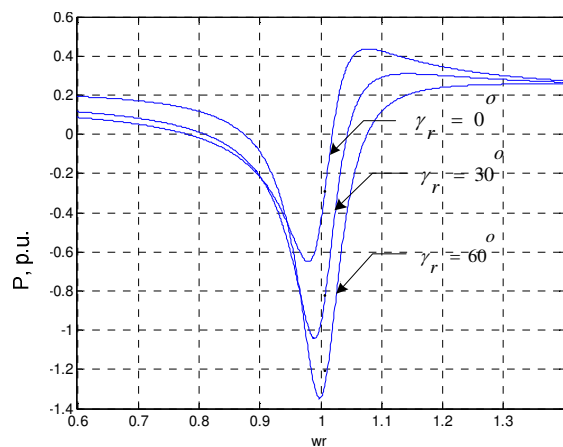


Fig 7 Characteristics of reactive power in generator mode after phase angle correction

### The study of AG performance in pump mode.

Negative voltage range in rotor circuit is 0 - (-0.6) p.u. when step -0.2 p.u. The parameters of pump mode have been determined by changing voltage of rotor circuit when the phase sequence is different (Fig 8, 9).

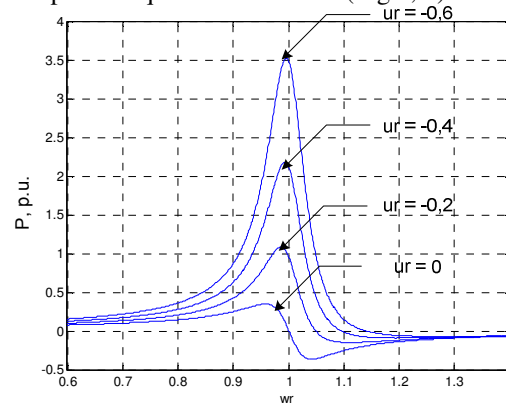


Fig 8. Characteristics of active power in pump mode

Phase angle correction has been performed by changing voltage phase angle in rotor circuit (Fig 10, 11). Rotor voltage phase angle variation is in range of 0 - 60° with step of 30° when voltage in rotor circuit is  $u_r = 0.3$  p.u.

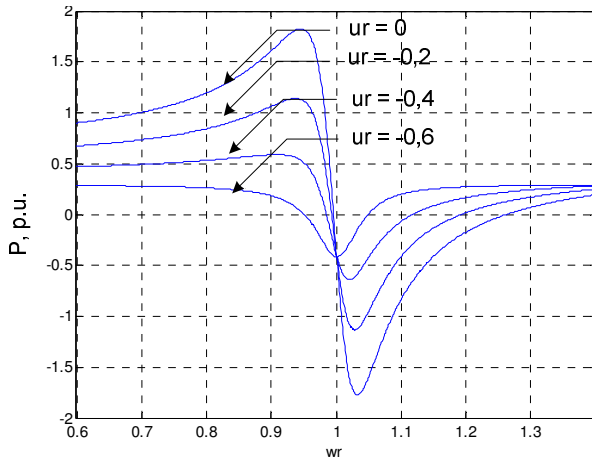


Fig 9. Characteristics of reactive power in pump mode

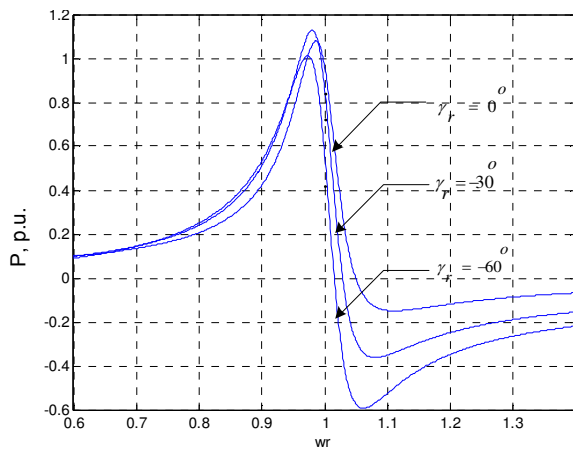


Fig 10. Characteristics of active power in pump mode after phase angle correction

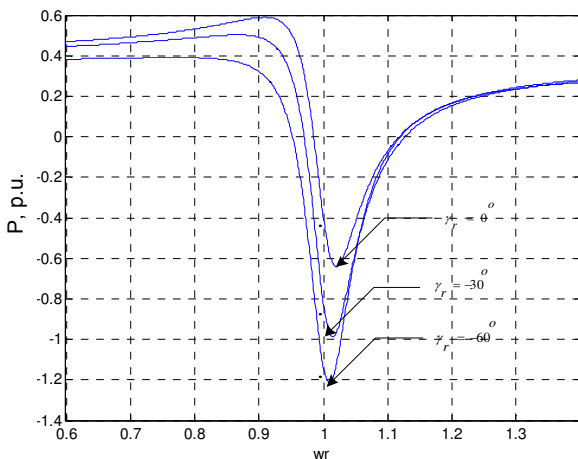


Fig 11. Characteristics of reactive power in pump mode after phase angle correction

Experimental study objective was to determine the graphic dependence of active and reactive power, torque from rotor angular frequency, voltage and phase angle. According to formed graphic characteristics of variable rotor voltage and angle, AG power characteristics nature is negative in generator mode and positive in pump mode

(Fig 4-11). Generated maximum power is reached by changing rotor voltage phase angle ( $\gamma_r$ ) when stator synchronous angular frequency is near  $\omega_s = \omega_r = 1$  p.u. in generator mode (Fig 4-11). Active and reactive power control limits are extended by changing rotor voltage phase angle ( $\gamma_r$ ) in pump mode (Fig 4-11). While changing rotor circuit voltage optimal performance is reached when rotor is  $0.3 u_s$  and voltage phase angle.

Voltage phase angle adjustment allows AG to regulate the rotor rotation and to work in the generator and pump modes in different synchronization modes (sub synchronization, super synchronization).

AG optimal operation mode is determined by excitation control system (variables: rotor voltage and voltage phase angle).

## 6. Kruonis PSP asynchronous generator power characteristics

Kruonis PSP installed generators maintain power balance of Lithuania power system. However, the hydraulics and generators technical characteristics do not allow using full potential of these generators. Many optimal technical solutions are considered according to existing buildings, hydro technical characteristic sand other specific issues (Stelzer 1977).

AG Integration into Kruonis PSP would extend the limits of reserve capacity and increase the total power which would allow adapting generator and pump modes to the specific working conditions of power system.

According to performed experiments and the hydro technical parameters that affect the basis of design features, AG active power and water turbine power characteristics of the different performance regimes have been composed (Fig 12).

AG active power slope is determined by stator ( $x_s$ ) and rotor ( $x_r$ ) reactive resistance and rotor excitation system settings set according to hydro technical turbine parameters restricted by vibration and cavitation

A coefficient is defined by:

$$\frac{dP}{dt} = \frac{\Delta P}{\Delta t} = k \cdot \quad (9)$$

When  $k=0$  the AG power is at maximum ( $P=P_{max}$ ) in generator and pump modes. The slope coefficient determines power change per time unit.

Power minimum value is  $0.44$  p.u. of  $P_{max}$  because AG performance is not allowed in range between  $0$  and  $0.44$  p.u. due to high vibration and cavitation. AG  $P_{max}$  is determined by rated generator capacity.

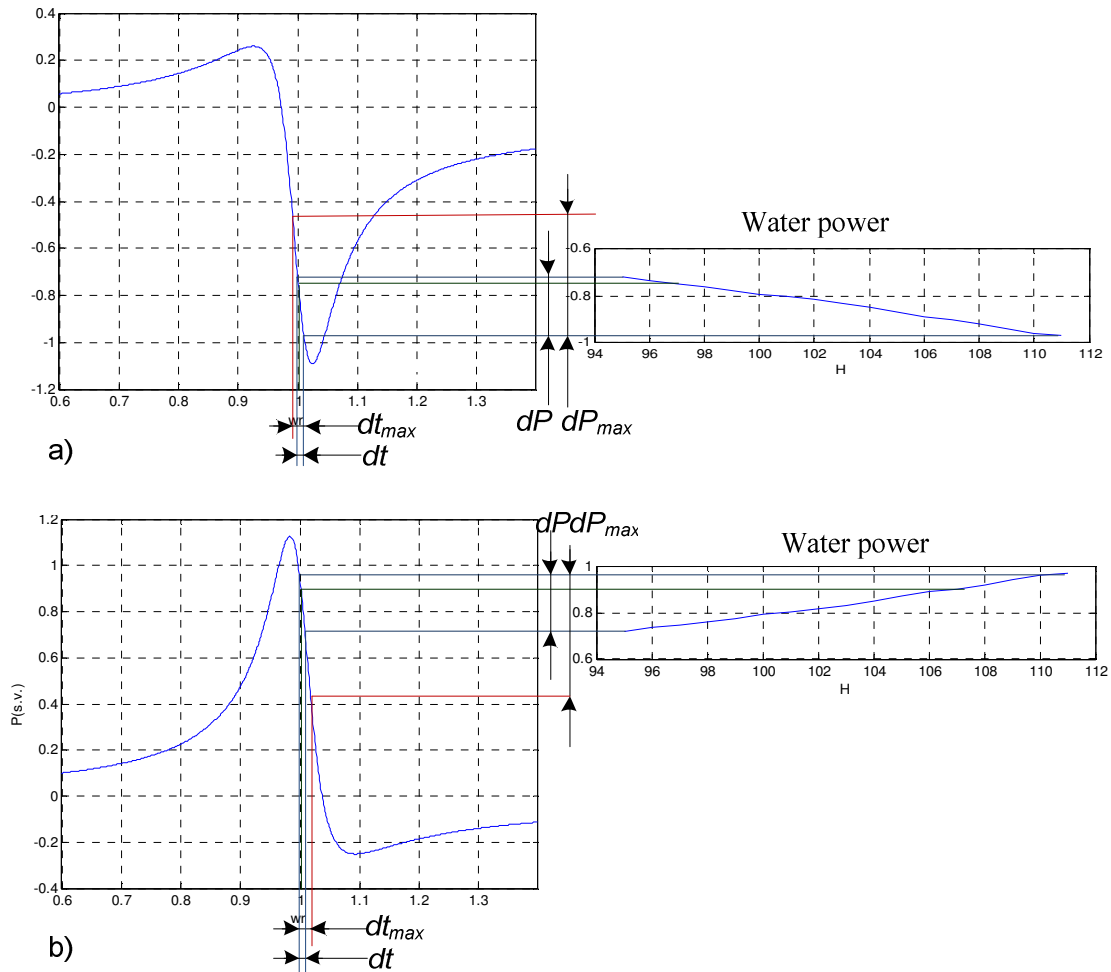


Fig 2. Characteristic of power a) in generator mode, b) in pump mode

## 7. Conclusions

Practically asynchronous generators are restricted in 0.5 p.u.  $<P < 1$  p.u. range of rated power in PSPs, however theoretically hydro technical parameters and turbine restrictions limit Asynchronous generator operation in 0.44 p.u.  $<P < 1$  p.u. range of rated power.

Optimal excitation control system voltage in rotor circuit is  $u_r = u_s = 0.3$  p.u. which moves power characteristics maximum value of 1 to synchronous angular frequency ( $\omega_s = \omega_r = 1$ ).

Turning the rotor voltage phase angle  $\gamma_r = \pm 45^\circ$  power control limits are increased regarding to synchronous frequency by  $\pm 28\%$  in generator and pump modes.

Research showed that new type AG installation would allow expansion of power balancing and control limits in Kruonis PSP.

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