WATER TURBINE POWER CONTROL – FEASIBLE CONCEPTION

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This paper is concerned with Francis water turbine power control issue. There are introduced six conceptions of power controllers and corresponding control loop features are discussed. The control features are illustrated with step responses and the major attention is paid to the undesirable under-control effect. On an example of control system with an elementary description and with relatively short turbine pipeline feeder are the control features compared.

Keywords: *water power plant, water turbine, power control, water turbine control*

1. Introduction

The operation of electricity supply system control is very demanding automatic control task. It is the complexity of physical need to keep permanent and in every moment the balance between the sum of electrical energy output sources on the one hand and the incoming power variety of all electrical appliances on the other hand. Any uncontrolled balance between power supply and offtake conduces to the electric system decline which results in heavy economics claims. These all put very high demands on the quality and speed control.

Owing to reasons mentioned above play water and pumped storage power plant (WPP and PSPP) important roles in the electricity supply system. These are the only electricity sources capable to supply electric energy in relatively quite short time and might afford more high requested dynamic services. Accordingly is heavily important to search and explore methods for reaching the highest turbine power quality control.

The speed of requested power output change, forced by higher (superior) automatic control, with acceptable time behavior is considered as the main task of water turbine process control. The 'under-control' effect of water turbine control, caused by flowing water momentum in feeder pipeline, must be considered as a specific and extremely important issue. In additional to this the water hammer effect could be follow due to fast opening changes of turbine. For instance after fast partial turbine opening may at first power output decline occurred but afterwards the system reached expecting increase power output. In light of automatic control this might be considered as rather difficult non-minimal phase process control with changing dynamic properties depending on the varying wide range of the turbine opening status.

The output power control is the primary and the most used operation mode of the water

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turbine machine set. Regarding output power control conception is mainly important that turbine machine revolutions are exactly rated because its maintenance is superior primary control task.

2. Considerated regulation system, comments to solution

In general the comparison between different concepts of water turbine output power controls is an extensive task, thus in this paper has been chosen only an example of basic process with following properties.

List of symbols:

$G_{ij}(s)$	[–]	Operator transfer between output i and input j,
h	[–]	Proportionate value of effective water declivity (pressure height),
L	[m]	Pipeline length or hydraulic path,
p_{G}	[–]	Proportionate value of generator power output (electric output on generator connectors),
q	[–]	Proportionate water flow volume (throught turbine or pipeline),
s	[s^{-1}]	Laplace transformation operator (for transfer expression),
T_{I}	[s]	Controller integral time constant,
T_{S}	[s]	Force part regulation time constant,
T_{W}	[s]	Water rise time constant (for rated flow rate),
w_{pG}	[–]	Output generator desire value (output power loop control input),
w_{y}	[–]	Turbine opening desire value (force part control loop input),
y	[–]	Turbine opening (proportionate value); alternatively servomotor stroke,
y_{o}	[–]	Working point of turbine opening (also linearization point),
Δ		Deviation mark of working point; e.g. $\Delta y(t) = y(t) - y_{\mathrm{o}}$.

The Francis power plant has been chosen in order to simplification, because it has only one control apparatus – the stator blade opening (connected with y value). The solution for other power-plants (Kaplan, Pelton, Deriaz) is analogical to previous one by reason that the opening of further apparatus is derived from the main one.

The hydraulic part of regulation process is here represented by the simplest dynamic characterization – the water and pipeline elasticity effect is not taken into account. Owing to this might be the process represented by the first order model with one parameter $T_{\mathrm{W}} = 1.5\,\mathrm{s}$. This simplification is acceptable only for short feeder pipeline WPP (for guidance up to 100 m in case of accurate measuring or up to 400 m for less accurate measuring). For long feeder pipelines must be used more accurate system model and regulation properties differ afterwards.

$$\xrightarrow{\Delta w_y(s)} \boxed{G_{pG,wy}(s) = \frac{1 - y_o \cdot T_w \cdot s}{(1 + T_S \cdot s)\cdot(1 + 0{,}5 \cdot y_o \cdot T_w \cdot s)}} \xrightarrow{\Delta p_G(s)}$$

Fig.1: Regulation set; properties expression by operator transfer

Similarly is being used the simplest process characterization along with Fig. 1. Beside hydraulic process model mentioned above includes also linearized water turbine Francis model (flow of water q in direct proportion to power output p_{G} and turbine opening y) and force regulation part model with parameter $T_{\mathrm{S}} = 0.2\,\mathrm{s}$. For more detailed system model description see [1].

Apparently chosen regulation process properties could be observed from the response characteristic in Fig. 2, where great dynamic dependence on the turbine working point is obvious as well, i.e. on the opening y_o.

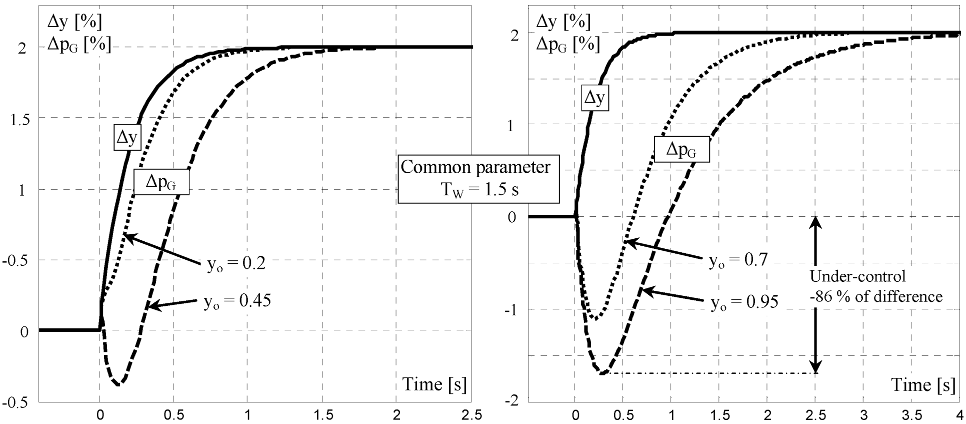

Fig.2: Response characteristics of process control – y_o opening effect

Regulation is considered for linear mode, i.e. for small differences of power output and turbine opening, when adjust speed restriction during turbine opening has not yet been shown.

The power output controller has been designed with integral transfer (I). Thereby the equality of desired and real output power in steady conditions is ensured and the turbine opening is without rapid changes. The proportional-integral transfer (PI) is less applicable because proportional part causes undesirable fast changes and owing to the under-control effect is greater at the beginning of regulation start up.

The more detailed objective quality comparison of regulation might be done by the quality criterion. For this particular purpose has been designed special integral criterion, see [2], including the under-control effect classification, that is the major negative factor. But with respect to limited range of this paper wouldn't be here used.

3. Common regulation, standard solution

The one shown above is the most frequently used regulation loop conception for power output control. The controller has steady value of integral time constant T_I. Its size has been set up for the most unfavorable conditions with respect to overall regulation control loop stability meaning the full turbine opening ($y_o = 1.0$). An acceptable over shot (up to 10 % from change) is enabled in step response characteristic for this state.

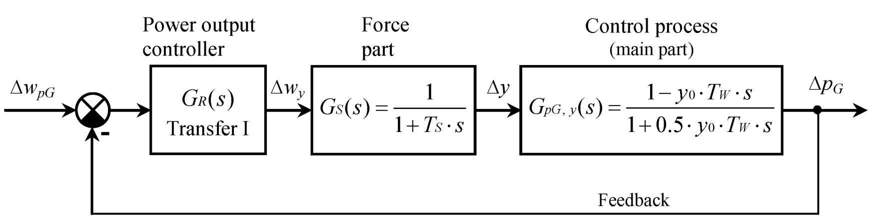

Fig.3: Power output control, commonly used control loop structure

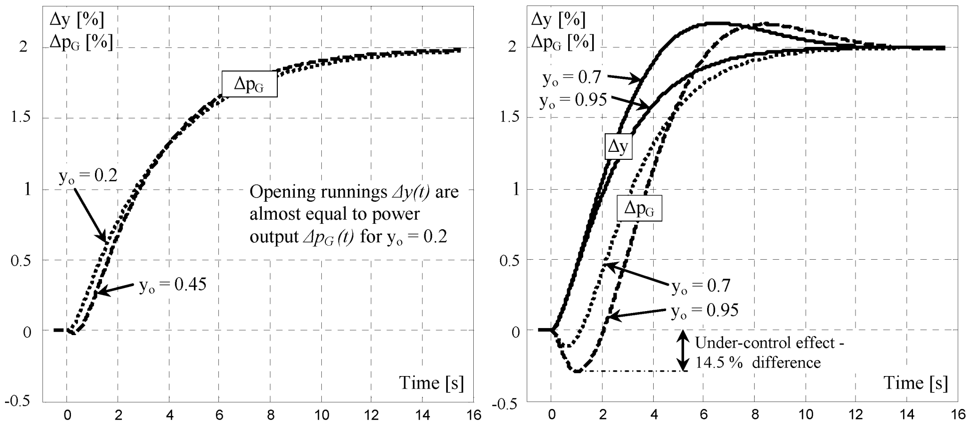

Fig.4: Step responses of standard output power control loop - opening effect y_o

The main advantage is the simplicity. As a major disadvantage might be considered the useless absorption of control process during partial turbine opening, i.e. in lower power output mode process running (see left part of Fig. 4).

4. Output power control with turbine opening adaptation

The aim of the adaptation is to profit from positive dynamic properties of turbo-generator unit in the area of partial turbine opening mode. Fig. 5 shows the principle of this adaptation. In general it is about creating functional relation between integral time constant and related values $T_\mathrm{I} = f(y_\mathrm{o}, T_\mathrm{W}, T_\mathrm{S})$, but particularly the adaptation concerns varying turbine opening, i.e. $T_\mathrm{I} = f(y_\mathrm{o})$. Control process properties according Fig. 6 for instance of adaptation are follows: $T_\mathrm{I} = K_\mathrm{a2}\,(T_\mathrm{W}\,y_\mathrm{o} - T_\mathrm{S})\,(y_\mathrm{o} \geq y_\mathrm{ma}) + K_\mathrm{a2}\,(T_\mathrm{W}\,y_\mathrm{ma} - T_\mathrm{S})\,(y_\mathrm{o} < y_\mathrm{ma})$, where $K_\mathrm{a2} = 3.1$, $y_\mathrm{ma} = 0.4$. Reducing turbine opening y_o linear decreased T_I, but only to value $y_\mathrm{ma} = 0.4$, for less opening remains T_I constant. As fine adaptation set up is considered presence of small overshoot in the power output response even for turbine opening under 50 %.

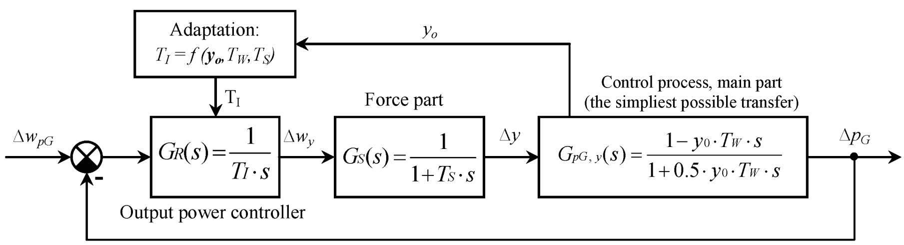

Fig.5: Principle of ouput power control adaption

Distinctive dynamics improvement for minor turbine opening is the main contribution of the adaptation. From comparison of left parts of Fig. 4 and Fig. 6 could be observed up to four-time faster process control speed with regard to classic solution.

Unfortunately the problem with output power under-control effect at the beginning of unit step response remains for major turbine openings.

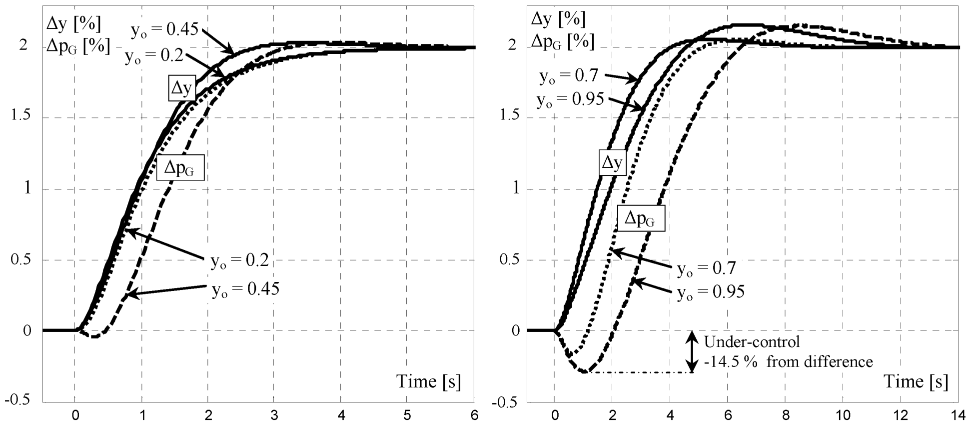

Fig.6: Adaptation process control response characteristics owing to turbine opening y_o

5. Output power process control with correction loop

The principle of control process with correction loop design is to reduce fast variation in desired output power value. This indirectly results in restraining of the under-control effect, because desired value would vary only with limited speed due to output power step response approximates to constant running only in positive area respectively (without distinct positive start part). Fig. 7 shows example for this solution. Actual output power controller should be different kind, here is considered the one used in previous chapter.

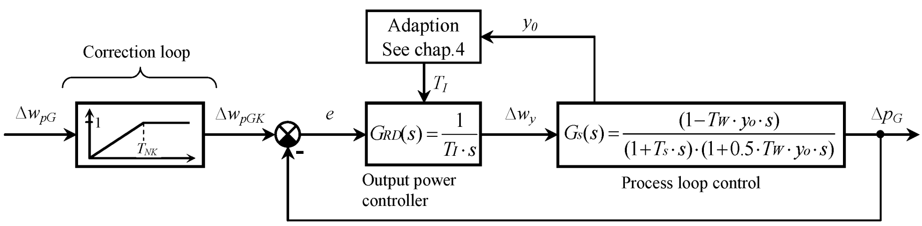

Fig.7: Output power control with correction loop in desired value sub-circuit

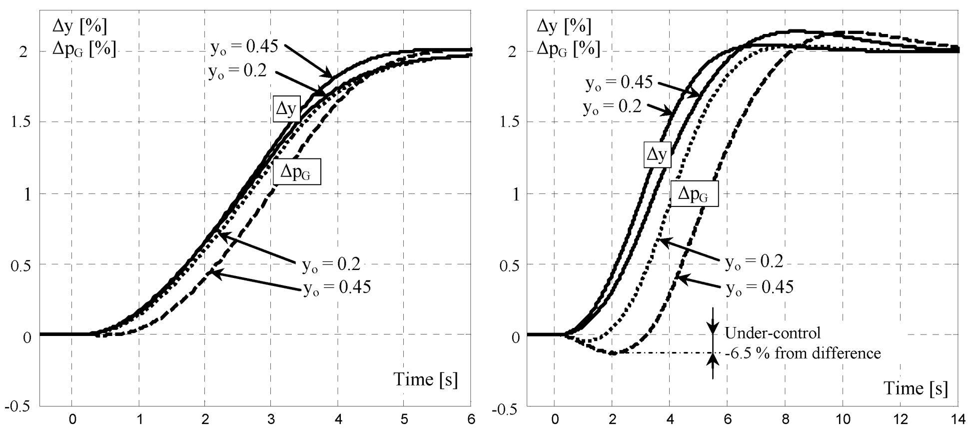

Fig.8: Process control response characteristics with correction loop (with adaptation)

Using the correction loop means inserting non-linear loop with derivation function that has limitation of derivation size. The parameter of the correction is start-up time TNK that is permitted time for full output power change (for 100 %).

From characteristics comparison, Fig. 8 and Fig. 6, apparently might be seen the under-control effect reducing. A farther positive property is that absolute size of the under-control effect not depends on size of output power step response. Owing to this is the value of the under-control effect $(-\Delta p_{\mathrm{G}}/\Delta w_{\mathrm{y}})$ for middle and major changes acceptable.

6. Output power process control with compensation circuits

Output power process control with compensation circuits is characterized by output power controller supplemented with modified process control model that might suppress undesirable system model properties. General disadvantage of compensations methods is small control robustness, i.e. appearance of distinctive differences in process control behavior in case of real process control and model process control that are being used by controller for its internal operations. There have been investigated 3 variations of solution (see [1]) and the best results have been matched by control process with internal model (IMC – Internal Mode Control), scheme shows Fig. 9.

Example of process control behavior is shown in Fig. 10 and was done by controller with following transfer $G_{\mathrm{RC}} = (1 + T_{\mathrm{S}}\, s)\,(1 + 0.5\,T_{\mathrm{W}}\, y_{\mathrm{o}}\, s)/(1 + T_{\mathrm{fC}}\, s)^n$, where filtering constant $T_{\mathrm{fC}} = 0.8\,T_{\mathrm{W}}\, y_{\mathrm{o}}$ and filtering order $n = 3$.

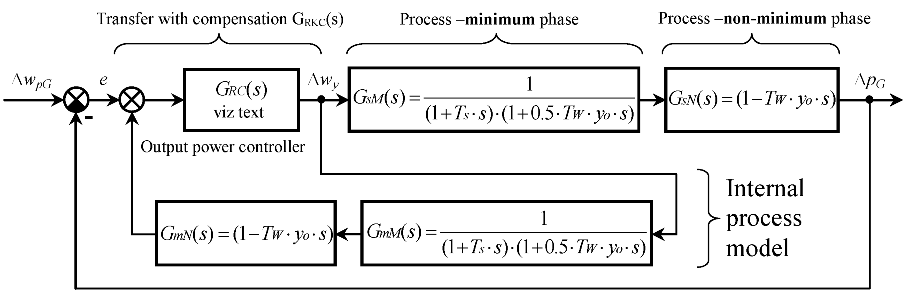

Fig.9: Output power process control with internal process model (IMC)

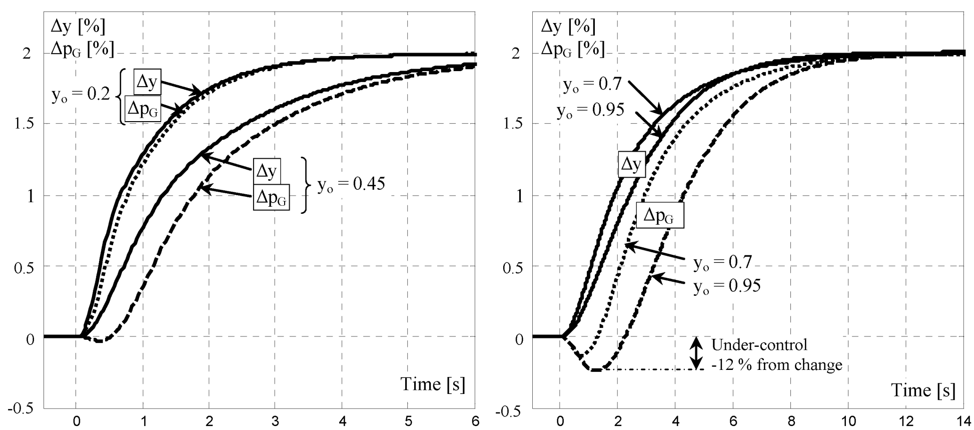

Fig.10: Process control response characteristics with internal model (IMC)

This conception advantage is the opportunity to choose the filtration intensity thereby might be the rate of under-control effect influenced. Over filtering slow down control process running though.

7. State output power control

State process control in general should have achieved the best results due to having whole information about internal status of process control. This advantage is decreased by more complicated control design and actually some state values are non-measured so must be determined by special model, so-called reconstructor. State process control is worth in conjunction with higher order process control than being here discussed thus solution example is not mentioned.

State process control has been tested (see [1]), but for the under-control effect didn't bring up any distinctive improvement. This is because of the non-standard process control properties (non-minimum phase).

8. Prediction output power control

Prediction output power control is very often indicated by short-cut MPC (Model-based Predictive Control), because is based on object controlled mathematics model prediction for future values of controlled values for particular control actions consecution. From the set of possible future control actions are chosen those that are optimal with respect to objective function.

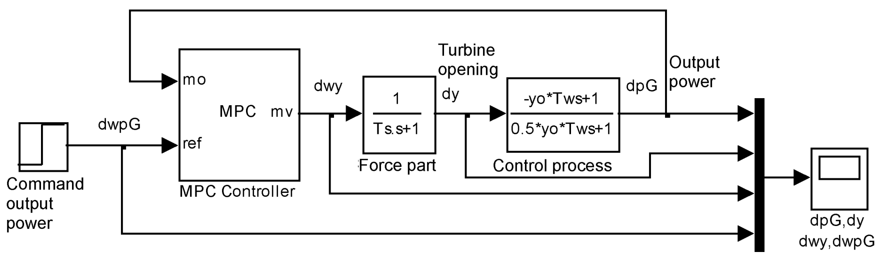

Fig.11: Predictive process scheme of output power control in Matlab-Simulink

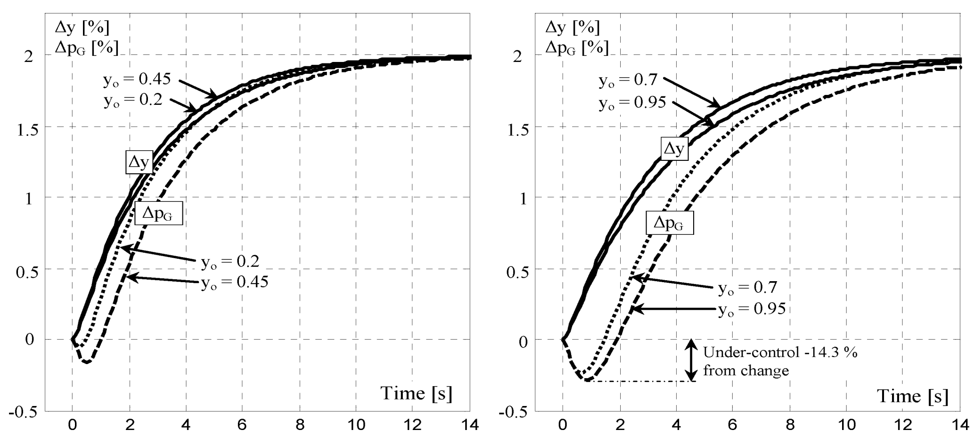

Fig.12: Step response characteristics of predictive control process (MPC)

For considered predictive process control demandingness has been used prepared product by Math Works company marking Model Predictive Control Toolbox (MPC). Fig. 11 shows interface linking for given process control.

Fig. 12 shows approximately the best result for sampling 0.1 s, prediction level 65, control level 5, deviation penalty 1 and speed penalty 36. There might be a question, why so sophisticated control has only middle quality results. Likely causer is again non-standard process control property (non-minimum phase). It is the embedded quality criterion for standard process control that is an issue and not acceptable for here considered water power plant. One of the solutions could be modified by quality criterion implementation, e.g. see [2], that more penalizes negative area (output power under-control) at the step response beginning. But the implementation of such as criterion is very difficult task.

9. Conclusion

In this paper are introduced overall works made during appropriate conception investigation of water power plant turbine generator unit control. With respect to limited range of this paper are the control properties demonstrated only for one control process and with the simplest transfer description.

For the present are considered 6 conceptions of output power control. The investigation is focused on the under-control effect reduction disclosing only during major turbine opening, but it is major disadvantage in electricity supply system stabilization and in general for dynamic energetic services.

For further research was necessary to create mathematical models of control process and controllers. After that it has been experimented with variety of solutions in form of variety control running simulation. The most objective are step response characteristics showing real power output time running of turbine generator unit for desired output power step response.

Technical knowledge could be sum up in following points :

- Up to now largely used classic control is not acceptable (see chap. 3) because of not using good and necessary water power plant dynamic properties.
- Turbine generator dynamic is heavily depending on turbine opening. Thus should be obvious to adapt the main parameter with respect to turbine opening.
- From many points of view is the most advantageous conception according to chap. 4. Main advantage is the simplicity of the realization and robustness compared with under-control by effect even great output power changes.
- Predictive process control would be considered as perspective. But also any modification must be evolved that would respect specific properties of water power plant control process.

During mentioned issue analyzing has been validated a solution using modelling and consequently followed by process simulation. This could fill up a gap in theoretical knowledge and records necessary for a qualified automatic water power plant control design.

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