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Modeling of operating HPP units' state rational control system

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Modeling of operating HPP units' state rational control system

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Abstract. It is very important to provide HPP operation in rational way. Start, stop and other operations of HPP units must be planned within ideas of HPP efficiency and safety. The article describes step by step algorithm for modelling and implementing of operating HPP unis' state rational control system. The rational control system is based on models of hydrounits and HPP joint control system. HPP efficiency is calculated with potential power losses method. HPP safety criterion includes parameters which could affect hydrounit health from automation system. The decision is made on overall criteria with operator preferences. The algorithm is supported by examples. Results can be used for modeling of hydro unit, joint control system and rational control system are easy to implement, and they could help to build up automatic operating HPP units' state rational control system.

Introduction

The main idea of rational control on hydropower plant (HPP) [1, 2] is to provide work optimization over its main and auxiliary equipment using different criteria: HPP water flow, HPP efficiency, water level of reservoirs, equal usage of equipment, energy management of HPP consumption, transformer power loss and so on and so force. The optimization causes changing operational state of hydro units. Each state change expends resources of hydro unit (HU): workout of circuit breaker, wear breaks, etc… So, rational control system must decide which unit should change its state and take into account increasing efficiency, rotation of operated equipment, improvement safety and it's necessary to keep in mind short term effect must not lead to frequent changes of units' state.

HPP power setpoint can be changed every second and it consists of several components: plan and its correction, frequency power addition, emergency power and others. The main HPP system controls and distributes task power among hydro units. The system is named joint control system (JCS). The JCS controls all modes of hydro units, their restrictions and provides power setpoint for every hydro unit on the plant. One of the most popular JCS functions distributes active power among hydro units of the HPP equally. So, if water head for HPP and for each turbine and HPP task power are known then using algorithm JCS it is possible to calculate every hydro unit power generation (setpoint) precisely. This possibility allow us to predict power setpoint for each unit after start any unit in joint control or its stop. Therefore, operating HPP units' state rational control system must be designed as an addition of JCS.

The article suggests step by step optimization of HPP units' state, the modeling of the rational control system (RCS) always uses for calculations and provides recommendations depending on current units' state and power distribution of JCS. There are no compete between RCS and JCS, JCS distributes power setpoints among units, RCS analyses possibilities of optimization units' state and recommends to change one unit's state at once. Operating HPP units' state rational control system uses following criteria: increasing HPP efficiency, improving safety based on calculation units' state estimation with minimizing emergency risks: temperature, vibrations, hydro-parameters and electrical parameters from protection devices. Units' state estimation allows include in the model count of units' starts and stops, work time, and plan them equally for all hydro units on plant for selected period.

Hydro units automated control system realizes control for all its parameters. It handles all parameters, checks its limits, controls for start and stop operations, regulate frequency of rotation, organizes vibrational, hydraulic and thermal protection. Also since 2014 all hydro unit automated control systems in Russia must check restricted zones provided by manufacturer of turbine, count numbers in and out of each zone, calculate operating time in each zone and in every mode of hydro unit and so on. All data could be used in RCS.

Before we start modeling it is necessary to remind that hydro unit is a machine that transforms potential energy of water to electrical energy:

$$P = \rho * g * h * Q * \eta t * \eta g \quad (1)$$

P – active power, ρ – water density, g – Earth gravity constant, h – water head, Q – turbine water flow, ηt – turbine efficiency, ηg – generator efficiency.

For Kaplan turbines [3] calculation of efficiencies of turbine, generator, water flow is based on manufacturers graphs, which could be converted to formulas. Then hydro unit potential power losses caused by inefficient operation could be calculated (2):

$$D^{e}_{GAi} = N_t * \eta g_t - \frac{Q_t}{Q_o} * N_o * \eta g_{\eta->nax} \quad (2)$$

D^{e}_{GAi} – potential power loss (lost power) of i hydro unit, N_t – current turbine power, η_{gt} – current generator efficiency, Q_t – current turbine water flow, Q_o – turbine water flow, when turbine efficiency is maximum with current water head, N_o – turbine power, when turbine efficiency is maximum with current water head; $\eta_{g\eta->max}$ – generator efficiency, when turbine efficiency is maximum with current water head.

The meaning of formula (2) is that the same volume of water allows to provide more power with hydro unit worked with its maximum efficiency. The detailed information about selection criteria HPP efficiency is in the article [5].

Modeling of rational control system

Firstly, it is necessary to describe simulation model of each hydro unit, and it is very important that the model must be identical to a model used in JCS HPP. The model calculates turbine and generator efficiencies, power restrictions and water flow using current values of active power and water head. In real system for description such relations there are often used polynomial or linear approximation for several constant water heads. Polynomial functions are often selected with degree 3-5 and used if sum approximation error is not more than 0.1%.

There are below models of generator efficiency (3), water flow (4), and turbine efficiency (5) with power restrictions (6):

$$\eta g(p) = \sum_{j=0}^{k} c_j * p^j, \quad (3)$$

$$Q_{hi}(p) = \sum_{j=0}^{k} a_{ji} * p^j, i = \overline{0,n} \qquad Q(h,p) = \frac{h - h_{i-1}}{h_i - h_{i-1}} * \left(Q_{h_i}(p) - Q_{h_{i-1}}(p)\right) + Q_{h_{i-1}}(p), \quad (4)$$

under condition of $h_{i-1} \le h \le h_i$

$$\eta t_{hi}(p) = \sum_{j=0}^{k} b_{ji} * p^j, i = \overline{0,n} \qquad \eta t(h,p) = \frac{h - h_{i-1}}{h_i - h_{i-1}} * \left(\eta t_{h_i}(p) - \eta t_{h_{i-1}}(p)\right) + \eta t_{h_{i-1}}(p), \quad (5)$$

under condition of $h_{i-1} \le h \le h_i$

$$p_{min}(h)=\sum_{j=0}^{k} d_j * h^j, p_{max}(h)=\sum_{i=0}^{n} e_i * h^i \text{ under condition of } h_{j-1} \le h \le h_j; h_{i-1} \le h \le h_i \quad (6)$$

In formulas (3)-(6) *p, h* – current values of active power and water head from hydro unit automated control system, h_i, h_{i-1} – water head basis, $Q_{h_i}, Q_{h_i-1}, \eta t_{h_i}, \eta t_{h_i-1}$ – basis of water flow and turbine efficiency provided by water head basis values, a_{ji}, b_{ji}, c_j, d_j – polynomial coefficients.

The second step is a modeling of JCS power distribution, where every hydro unit described with formulas (3)-(6). Undistributed power setpoint is divided by number operated in JCS units, result power setpoint for one unit taking into account its possible power restrictions. Difference between restriction limit and power setpoint of restricted unit is distributed among all others units equally. If all units are on limit and there is undistributed power task, then the setpoint (task) cannot be completed else if power setpoint is done, power distribution algorithm finalizes.

The algorithm of RCS based only on HPP efficiency improvement is described in details in [5, 6]. Here making decision with several criteria for RCS will be provided:

1) The model gathers all necessary data from automated systems: units' states, modes, values of water head, power, power setpoint for JCS(HPP).

2) The model calculates individual power setpoint for every unit on HPP according to algorithm in JCS described above. The values in model must be identical to values in a real joint control system.

3) According manufacturers graphics for current water head the model calculates optimal water flow through turbine, maximum (reachable for the water head) turbine efficiency and corresponding values power and water flow with maximum efficiency. Let's call these optimal efficiency, water flow and power (3)-(6).

4) The model evaluates potential power losses for each hydro unit. It could be calculated as a difference between the current power and a power that could be generated by hydro unit with its maximum efficiency (2). Example:

Table 1. Example calculations of potential power losses for one hydro unit.

P		N, MW		Q, m^3/s	*ηt, %*	*ηg, %*	D, MW
Optimal		Nopt=	40.84	383.1	93.86	96.87	0
p1 =	23.72	N1 =	24.826	242.9	90.077	95.54	0.69
p2 =	39.13	N2 =	40.409	379.26	93.82	96.83	0
p3 =	48.72	N3 =	50.247	470.98	93.773	96.96	0
p4 =	61	N4 =	62.592	593.29	92.83	97.46	0.996

Table 1 contains data calculated with constant water head for one hydro unit. In first row there are optimal parameters: power, water flow, turbine and generator efficiencies. Values of active power p1, p4 show power losses, when hydro unit works close to the end of its ranges, it is not efficient work mode, p2 and p3 illustrate the range of efficient work.

5) The sum of hydro unit power losses describes efficiency of HPP. This value also determines potential maximum of optimization, it is an ideal state that can be reached with units in operation now. So, potential effect of HPP optimization is sum of power losses with negative sign.

6) For all units step by step in turn the model simulates one unit state change in each direction (start, stop, etc), calculates distribution of power after state change, and corresponding values of HPP power losses and efficiency. The result of this algorithm stage is two (or more, if take units with several restricted zones) arrays with HPP potential effects, which will be reached if state of unit number <array index> will be changed (started or stopped).

7) The model sorts the arrays from highest HPP effect to lowest, in the end of array there are units in individual mode (not in joint control) and units under repair.

8) Subtraction current (stage 5 of the algorithm) and possible (first element of array on stage 7) effects gives us maximal effect for one unit state change. The value estimates the minimum of HPP possible optimization effect for one state change.

9) If the result of stage 8 great then zero then it could be considered as RCS recommendation to change unit's state for HPP efficiency improvement. (It is just first step on the way to reach maximum described on stage 5. Negative effect shows any unit's state change makes HPP efficiency worse. There is example recommendations calculation for HPP with 8 Kaplan turbines (see table 2).

10) In Table 2 the row 1 shows that JCS power task for HPP is relatively small for 8 units and because of this they have to work inefficiently. If HU№7 will be stopped, then potential losses of HPP will be decreased E_{min}=1.2-0.4=0.8 MW-s, and still there will be a possibility for next optimizations up to potential effect 1.2 MW-s. The rows 2 and 3 illustrate that any unit's state change leads to increasing of potential power losses. There are no recommendations from RCS. The last row visualizes great HPP power setpoint, then for efficiency improvements it is recommended to start HU№2. Recommended for state change units give maximal HPP effect only with one state change.

Table 2. Calculation RCS recommendations for HPP with 8 units.

No	Number Units in JCS	JCS power task, MW	JCS Power losses, MW	RCS					
				Start unit № unit, power losses, MW		Stop unit № unit, power losses, MW		Min effect, MW	Max effect, MW
1	8	297.8	-1.2	0	0	7	-0.4	0.8	1.2
2	2	88.7	-0.11	7	-2.29	1	-3.77	0	0
3	8	463.7	-23.39	0	0	7	-48.66	0	0
4	3	149.67	-1.62	2	-0.51	8	-11.1	1.1	1.6

11) It is necessary for each type of state change (start, stop, crossing restricted zone) to determine criteria for units health estimation based on hydro unit's parameters from automation control system.

12) Coefficients of participation for every unit in rational control system must be specified. It could be done by experts or calculated modeling of units' health parameters. Units with bad health must be excluded from the model.

13) Decision making criteria should be chosen with user preferences, for example [7]: maximization of expected usefulness, Hodges-Lehmann estimation, minimization of expected regrets (Savage). All data must be normalized.

14) Weight of each criteria with experts υ_j and pessimism coefficient α (if it is necessary) must be set up.

15) Calculations according the selected criteria of decision-making provide unit's start and stop arrays with corresponding HPP optimization effect.

16) Sort the result array in such way, that the unit with maximum effect for its state change will be the first.

Example of RCS decision making with operator preferences

Let imagine hydro power plant with 12 operated units. It is needed to stop one. Going thought stages 1-12 of RCS algorithm we received the source data for decision making. Table 3 row "efficiency, %" means HU efficiency, a row "Stops" means count of unit stops for selected period, "Deviations" means count of units deviations from normal behavior of process (out of some limits) for selected period.

Table 3. Hydro units' parameters.

No. HU	01	02	03	04	05	06	07	08	09	10	11	12
Source data												
Efficiency, %	92.3	91.6	92.2	92.1	93.01	92.6	92	92.1	91.9	92.2	93.0	91.8
Stops	53	21	35	64	28	32	15	1	45	24	11	48
Deviations	200	129	183	180	325	110	152	24	288	157	93	420

To compare criteria lets expert set preferences υ_j for efficiency – 0.5, for stops count – 0.2, deviations count – 0.3 (stage 13 of the algorithm). Then after calculations we get following (see table 4).

Table 4. Sequence of units stops according different methods.

Maximization of expected usefulness (MEU)											
NU	2	12	7	9	8	10	3	4	1	6	5	11
Hodges-Lehmann (HL)											
NU	2	12	9	7	10	8	3	1	4	6	5	11
Minimization of expected regrets (MER)											
NU	2	12	7	9	8	10	3	4	1	6	5	11

According to all decision-making methods the first units to stop are HU№2 and HU№12, HU№7 and HU№9 follow them. The weaknesses of NU№8 were smoothed by operator preferences. The most successful units in current conditions are HU№11, HU№5, HU№6.

Conclusion

The proposed new approach for modeling of operating HPP units' state rational control system is based on sequential plan for improvement of current units (HPP) state. The decision-making algorithm includes several criteria taking into account efficiencies of units and HPP and units health. Main ideas are supported by examples. The described algorithms modeling of hydro unit, joint control system and rational control system are easy to implement, and they could help to build up automatic operating HPP units' state rational control system.

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