TURBINE BY-PASS WITH ENERGY DISSIPATION SYSTEM FOR TRANSIENT CONTROL

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Abstract: The Energy Dissipation System (EDS) is a Hydro Power Plant (HPP) safety device designed to prevent pressure rise in the water conveyance system and to prevent turbine runaway during the transient event by bypassing water flow away from the turbine. The most important part of the EDS is a valve whose operation shall be synchronized with the turbine guide vane apparatus. The EDS is installed where classical water hammer control devices are not feasible or are not economically acceptable due to certain requirements. Recent manufacturing experiences show that environmental restrictions revive application of the EDS.

Energy dissipation: what, why, where, how, ...

Each hydropower plant's operation depends on available water potential and on the other hand (shaft) side, it depends on electricity consumption/demand. During the years of operation every HPP occasionally encounters also some specific operating conditions like for example significant sudden changes of power load change, or for example emergency shutdown. During such rapid changes of the HPP's operation, water hammer and possible turbine runaway inevitably occurs.

Hydraulic transients are disturbances of flow in the pipeline which are initiated by a change from one steady state to another. The main disturbance is a pressure wave whose magnitude depends on the speed of change (slow - fast) and difference between the initial and the final state (full discharge – zero discharge). Numerous pressure waves are propagating along the hydraulic water conveyance system and they represent potential risk of damaging the water conveyance system as well as water turbine in the case of inappropriate design. Rapid speed of change and large difference between the initial and the final state may yield high pressures while slow speed of change may yield partial or even full turbine runaway. Appropriate balance between the speed rise and the pressure is therefore obligatory for safe turbine operation as well as appropriate design of all corresponding turbine structures, other safety devices (surge tank, thicker penstock, air valves, etc.) and manoeuvres.

Over the last 100 years, the EDS's have been designed as turbine bypass with the purpose to divert water flow away from the turbine and thus to protect the water conveyance system against transient loads and the turbine against the runaway. By diverting the flow away from the turbine it is possible to close the turbine safely without extreme unit rotational speed rise and without initiation of pressures in the penstock. When the EDS is in function it enables possibility to control the water flow arbitrarily, i.e. it is possible to safely shutdown the power plant's discharge. Recently, the EDS have got a new role in environmentally sensitive areas with the main goal to reduce the operation influence of the HPP on the environment. For example, the latest EDS system has been ordered due to strong environmental requirement of allowed change of Tail Water Level (TWL) downstream of the turbine. For this particular HPP, the tail race channel was widespread wetland populated by fish and for this reason the restriction was given that the TWL can change only 5 centimetres per hour in order to give the fish enough time to return to the main channel. Turbine operation, including normal start-up and normal shutdown, under such sharp conditions was not possible without the EDS system. Installation of the EDS made the investment into the new HPP feasible.

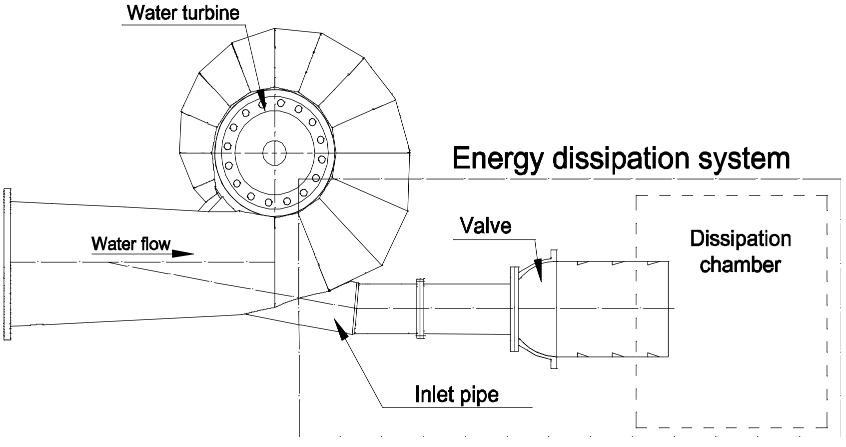


Fig. 1. Example of the EDS system attached to the horizontal Francis turbine with a horizontal Howel-Bunger type valve as PRV and an open space air outlet as the chamber.

The typical EDS system consists of the following elements (Fig.1):

1. **Inlet pipe**: The inlet pipe connects the turbine/penstock with the valve. The EDS is usually connected to the turbine's spiral casing as close as possible to the wicket gates, however, solutions with bifurcation from the penstock are also possible.
2. **Valve**: The water flow through the EDS is controlled by the valve. Due to its role on mitigation of the pressure transients the valve is known as Pressure Regulating Valve (PRV). Operation of the PRV shall be synchronized with operation of the turbine's guide vanes. Various valve types are in use like Howell-Bunger valves, sleeve valves, plunger valves, needle valves, etc. [1], which are oriented either horizontally or vertically.
3. **Dissipation chamber**: The dissipation chamber is a space downstream the valve reserved for dissipation of the high kinetic energy of the water jet exiting the valve (hydraulic jump). Outlet of the valve can be directed into the air, into the water or it is partially submerged into the water. The flow coming out from the chamber shall be smooth without excessive turbulence not endangering the tailrace channel and environment. The size of the chamber depends on the flow (valve diameter), its kinetic energy (water head) and dissipation chamber medium (water and/or air). The most effective dissipation chamber is fully filled by water [2, 3]. Cheap, however significant in environmental influence is release of the jet into the free air [4].

Application of the EDS

The Pressure Regulating Valve (PRV) controls the flow through the EDS. The PRV valve is designed to rapidly divert the water flow away from the turbine into a turbine bypass system when the guide vane apparatus needs to perform a sudden manoeuvre (for example to close suddenly at emergency shutdown, or when the unit is quickly unloaded at sudden load reduction). PRV's primary operation is short term, only to enable safe turbine manoeuvring and to protect the power plant against subsequent transient loads and possible turbine runaway. The PRV can be utilized for long term operation during discharge regulation at ramping. For optimal performance during the transients, operation of the PRV shall be appropriately synchronized with operation of the turbine's guide vane apparatus. Synchronous operation takes the place when the flow through the turbine is quickly reduced and simultaneously the flow through the PRV is increased so that the sum of both flows during the whole transient process is remaining unchanged. It is possible to reduce the water flow through the turbine quickly without any essential alteration of the flow in the penstock and undue pressure rise in the water supply system.

Various types of valves are suitable to perform the PRV function but not all valves are capable to withstand the following challenging requirements for operation: permanent availability, rapid response, durability during transient event and continuous operation (cavitation, erosion, dynamic load, etc.). When EDS is available for operation and the PRV is synchronized with the turbine guide vane apparatus the system is ready to perform the following safety function for the Hydro Power Plant operation [5]:

a. *To bypass the turbine with any water flow from zero up to the maximum turbine flow.* The discharge is adjusted depending on the flow through the turbine in a way that the sum of flows through the EDS and the turbine is being always equal to the requested plant flow and should be less or equal to the maximum turbine flow. The operation in turbine bypass mode depends on site conditions, environmental requirements and operational safety procedures. Long-term turbine bypass operation known as ramping is also feasible.

b. *To reduce the pressure rise in the water conveyance system.* Without EDS the quick reduction of the flow through the turbine would cause the pressure rise in the water conveyance system. In closed conduit water conveyance system this would result in a pressure rise (pipeline damage), while in open channel conveyance system this would result in a rising water level (spill over and flooding). The EDS reduces the pressure rise.

c. *To reduce the transient speed rise of the unit*. During sudden load reductions, the speed of the unit is increased and the governor closes the turbine thus reducing the water flow. Due to operation of the PRV, the flow through the turbine can be adjusted momentarily to prevent the excessive turbine's speed rise. Because of the synchronous PRV's operation, the required inertia of the turbine unit (in particular the generator) can be reduced significantly.

d. *To improve stability conditions of the governing system*. Variations in water flow through the turbine as a consequence of the speed governing cause alterations in water pressure and at the same time alterations of the rotating torque of the turbine. In the case the speed to be reduced by the governor, this effect can be attained by reducing the water flow since it is necessary to decrease the revolving torque. Simultaneously with reduction of the water flow the water pressure is being increased and therefore the rotating torque is increased as well. The turbine water system is always counteracting the tendency of the governor and diminishing the stability of the governing. The stability can be greatly improved by engaging the maximum sensitivity of the PRV (EDS) thus preventing alterations in water pressure due to alterations of water flow through the turbine. This stabilizing effect of the PRV is most frequently necessary during no-load operation of the unit and during its operation on an isolated electrical system.

e. *To increase the rate of frequency and output control*. During the fast closing of the guide vanes the PRV is opening and during the guide vanes opening it is closing. Very quick, almost rapid loading and unloading manoeuvres are possible without any essential alterations in water pressure of the turbine water conveyance system. The required flywheel effect of the rotating parts of the unit is lower and at the same time, the rate of frequency and output regulation is improved.

f. *To increase the rate of acceptance of the load*. When accepting the load, the PRV can be previously opened. If EDS is by-passing a certain flow, then the unit is enabled to accept the load quickly by synchronously closing the PRV. Such an operational case may arise also when the EDS is maintaining the continuity of flow through the system to supply downstream power stations, to provide biological minimum flow or to provide availability to load the unit as quickly as possible (for instance to cover the peak load).

g. *To maintain constant flow through the power plant*. If there is a need to maintain constant flow through the water system, the PRV can be opened or closed in a manner that the sum of the flows through the turbine and the PRV remains constant regardless the turbine operation.

h. *To close the guide vanes in the event of inoperative oil pressure system*. In the event of the governor oil pressure sets being inoperative or due to any reason the necessary oil pressure from the governor pressure device is not available, shutdown of the turbine unit is automatically tripped. The necessary pressure oil for the quick closing of the turbine wicket gates is supplied by the PRV. Opening the PRV presses the oil out of its oil operated servomotor into the closing chamber of the wicket gates servomotor.

Synchronous operation of guide vane apparatus and PRV

Functionality of the EDS strongly depends on the response and availability of the PRV valve. Operation of the PRV valve (opening and closing) is traditionally controlled by two servomotors: water and oil (Fig. 2). Natural tendency of the PRV is to open. The required pressure is provided by the water servomotor which is permanently connected through the pipe to the pressurized water from the penstock. Opening and closing of the PRV is then controlled by the oil servomotor. Oil servomotor is directly connected with distributor’s servomotor.

In **normal operating conditions** the PRV’s oil servomotor is under system oil pressure. The water and the oil servomotors are designed so that the oil servomotor’s force is overcoming the water servomotor’s force and the PRV is closed. Oil pressure to open the guide vanes is at the same time oil pressure to close the PRV. On the contrary, the low pressure to close the guide vanes at the same time lowers the pressure in the PRV’s servomotor and the PRV will open. Such connecting scheme provides sufficient safety to open the PRV as well in the case of oil system failure or electricity loss.

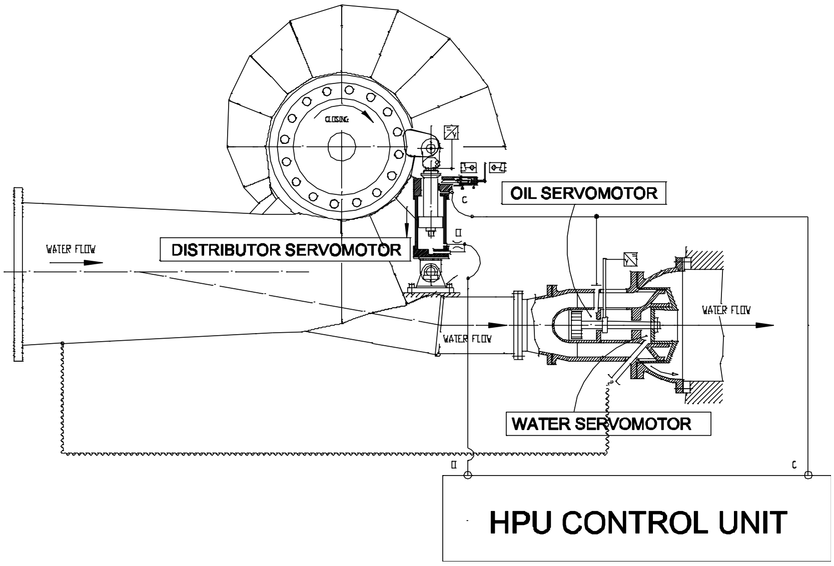
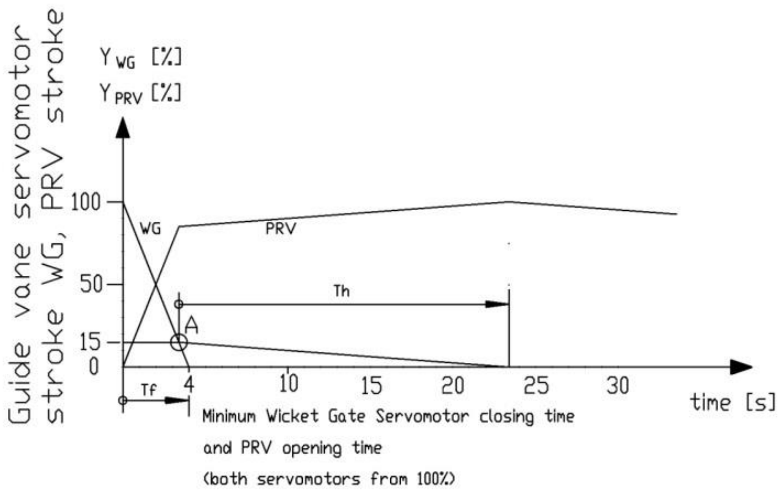


Fig. 2. Schematic drawing showing the power control of the PRV.

At turbine **emergency shutdown**, the oil from the distributor servomotor opening chamber O (Fig. 2) is discharged through the servo valve to the sump tank of the HPU control unit. The oil quantity which is to come in from the HPU control unit through the sequence valve is not enough and the oil pressure in the pipe between the sequence valve, the guide vanes and the PRV servomotors will decrease. At a certain oil pressure, the water and oil force in the PRV servomotors reach their balance of force. Then the water servomotor force supplies the oil from the PRV's oil servomotor into the distributor's servomotor closing chamber C (Fig. 2). Therefore the wicket gates can close simultaneously as the PRV opens. The water discharge in the penstock remains constant during the manoeuvre because the discharge through the PRV increases by as much as the discharge through the wicket gates is reduced. The wicket gates will close rapidly till the servomotor cushioning point A (Fig. 3). From this servomotor cushioning point also the PRV movement is slower. After end of servomotor cushioning stroke, the servomotor of the guide vanes is 100% closed. After that sequence the PRV starts to close slowly by the system oil pressure and with the proposed PRV closing time (unless ramping is required).



Ramping is a special long-term EDS operation with arbitrary discharge up to the maximal turbine discharge. Ramping is possible only when the wicket gates are closed and servomotor locked. The PRV is than isolated from the hydraulic power unit system. Closing and opening of the PRV is controlled by the electromagnetic valves and orifices. Releasing of the oil from the oil servomotor of the PRV will cause opening of the PRV. Supplying pressure oil to the PRV servomotor will cause closing of the PRV. Fig. 3. Typical sequence of the guide vane servomotor closure and synchronous opening and closing of the PRV.

Operating experiences with various EDS systems

System No.1: The simplest EDS in use is with Howell-Bunger valve as PRV which is directed into the open air. The Howell-Bunger valve is equipped with extended hood (Fig. 1) and buffers (obstacles) which prevents backflow and increases dissipation of the jet. The Howell Bunger is designed as a parallel release (bypass) and it is connected to the penstock with bifurcation before the turbine inlet valve. Its main function is to ensure the biological minimum flow downstream the powerhouse; however they are utilized for emergency shutdown as well or when the unit is quickly unloaded at sudden load reduction as safety device to prevent pressure rise in the water conveyance system. The Howell-Bunger valve is not synchronized to the guide vanes as shown in figure 2, but it is controlled by electromagnetic valves. Those types of EDS were installed on Mamquam HPP and Lower Clowhom HPP, Canada.

Operation feedback: Such systems are successfully in operation from 2004. Due to the release of water into the open air, the system has unpredictable and significant influence on the tailrace area. The dissipating jet can be harmful for the river bank. This type of the Howell-Bunger valve and the valve control was designed for lower head systems and for temporary operation only in remote areas.

System No.2: Very similar EDS system was installed at Besy HPP, Canada in 2006. The safety performance of the valve was improved by hydraulic synchronization with turbine governing system as described in Chapter 3. The valve was connected directly to the spiral case.

Operation feedback: The system is operating smoothly and provides sufficient safety during turbine transients initiated by manoeuvring. These solutions are always attractive for investors; however, they are not recommendable due to significant influence on environment.

System No.3: A unique PRV valve has been developed for EDS systems with exit into the water filled dissipation chamber (fully or partly). Two types of PRV have been designed, one with straight water flow and one with 90° elbow inside the valve. More than 30 of these valves have been produced so far starting with Ohau HPP, New Zealand in 1974. The valve was designed so that part of the energy is dissipated already in the valve and the water jet additionally breaks at the outlet from the valve. Synchronous connection with the guide vane apparatus was developed and improved with time. Model size system was investigated for various forms of PRV's exit hood [6] and for partial or fully submerged conditions. The EDS system developed is suitable for net heads up to 400 meters, discharges up to 150 m^3/s and inlet diameter of the PRV up to 3000 mm.

Operation feedback: The system is operating efficiently, smoothly and safely. The solution is compact and is highly recommendable as transient mitigation system. The PRV valve has been designed to dissipate energy already inside the valve and therefore to reduce required space for energy dissipation. For this reason the system is not intended for long term operation (ramping).

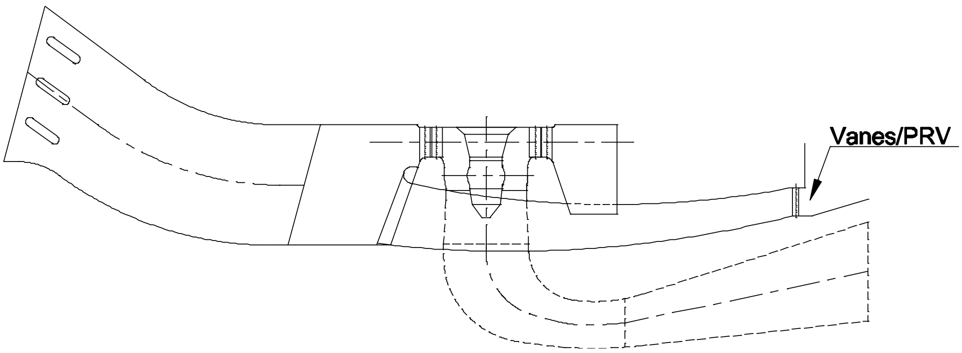


Fig. 4. Example of the EDS system with vaned PRV and submerged outlet to the tail race channel.

System No.4: Special EDS system with the valve assembled from vanes (similar to the guide vanes) has been developed for low head Kaplan turbines with extremely large discharges. Utilization of this system on power plants is very rare; however, it is obligatory system for safe operation of HPP's with long open channel water conveyance system. Because of the large volume of water in the channel, at the emergency shutdown, the pressure wave would raise the channel water level and the water could spill-over the channel embankments. Figure 4 shows the vaned PRV valve which is connected with the semi-spiral case and the outlet is submerged and directed into the tailrace channel. The operation of the vaned PRV is synchronized with turbine governing system and performs the transient safety function. The first system has been installed at 80 MW Kaplan turbine Zlatoličje HPP, Slovenia in 1966 (refurbishment in 2011). The EDS was designed for net head of 32 m and discharge of 270 m^3/s.

Operation feedback: After 45 years of reliable operation the system at Zlatoličje HPP needed only minor repairs. The performance was satisfactorily during the entire period and the system remains in operation also after the turbine refurbishment. More maintenance was required in eroded tailrace channel. After refurbishment the tailrace channel was coated by concrete plates and no further erosion is expected.

System No.5: Typical representative of vertical EDS with submerged PRV valve is the EDS system with the sleeve valve. The sleeve valve is submerged, positioned at the bottom of the vertical dissipation chamber. The valve is designed to break the flow at the valve outlet and to accelerate the dissipation. Cavitation is prevented by significant submergence. The EDS with sleeve valve as the PRV was installed at Alavian HPP, Iran in 1997. The EDS with sleeve valve was designed for net head of 100 m and has nominal diameter of 1200 mm.

System No.6: For the case of the long-term operation (ramping) the EDS system has been developed with needle valve as PRV. The PRV is positioned vertically on top of the chamber and outlet from the PRV is oriented towards the bottom of the chamber. The needle valve enables continuous operation without significant cavitation or erosion damage of the valve. The needle valve is designed to be without losses so all of the potential energy is converted into kinetic energy of the jet. The jet exiting the valve is very compact and has large range of influence. In order to design appropriate dissipation chamber (depth and width) for all operating conditions, the extensive physical model and numerical investigation was performed. The developed system has been installed at Marun Dam HPP, Iran in 1997 where nominal diameter of the needle valve is 1400 mm, net head is 200 m and discharge is 30 m^3/s.

Conclusions

The EDS systems are becoming more and more interesting again mostly in remote areas with strict environmental requirements (due to nature protection, animals migrations, fishery, tourism, local resident requirements, etc). Although some of these systems in the past required significant maintenance and although operation of the EDS system is frequently considered as “wasting water”, our recent experiences show the need to develop new generation of the universal EDS system. The universal EDS have to be compact in size, versatile in operation, reliable and acceptable for investment. The universal EDS will make investments into new HPPs in demanding environments feasible again.

The overview of existing Energy Dissipation Systems has been performed during the development of new generation EDS systems. All available operational feedback information has been collected and analysed in order to establish good database and directives for further work. Experiences showed that there are EDS systems which are simple and cheap, there are EDS systems for special conditions, there are EDS systems for turbine safety operation and there are EDS systems for long-term ramping operation. The new generation EDS system will combine all the above mentioned characteristics within one single design. At the same time, significant step will be made towards reducing the influence of the EDS as well as hydropower plant footprint.

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References

[1] E. Mosonyi, *High-head power plants*, Third Edition, Budapest, 1991.
[2] S.H. Anderson, *Model studies of storm-sewer drop shafts*, Technical paper No.35, Series B, Minneapolis, 1961.
[3] H. D. Briley, G. J. Hornsby, *Hydraulic model studies for the design of the boulder dam power plant energy absorber*, Technical memorandum No. 578, Denver, 1938.
[4] M. C. Johnson, R. Dham, Innovative Energy-Dissipating Hood, *Journal of Hydraulic Engineering* ©ASCE, 2006.
[5] S. Rakčević, *Ohao b&c power station – by-pass val*ve, Litostroj documentation, Ljubljana, 1975.
[6] *Ohau-A Power station, Waves in the admission canals,* Hydraulic Laboratory at Ljubljana - Model test report, Ljubljana, 1973.