Three-Phase Dump Loads in Hydropower Plants: The Story of a Poor Design

Three-phase dump loads in hydropower plants: the story of a poor design

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***Abstract*—Hydroelectric power plants are typically equipped with spillways to drain excess water and regulate power production according to the load. However, these systems are not always available and alternative solutions must be adopted. A possible alternative to spillways is the use of a dump load consisting of a three-phase rheostat. The purpose of this paper is to present the history of a poorly designed refurbishment of a three-phase rheostat and to compare its performance with that of the old solution. Critical insights into the behavior of such devices are provided in order to avoid the same mistakes in the future.**

***Index Terms*—Spillway, hydropower, power regulation, rheostat, dump load.**

I. Introduction

The hydroelectric power plant under study is located along the Po River, in northern Italy. It was built in the late '50s of the last century and it was equipped with four Kaplan vertical axis hydroelectric turbine units. Each of these turbine units could originally deliver about 12.5 MW of electrical power.

In order to match the power production with the load requirements, hydraulic turbines are usually equipped with spillways [4], [5]. The spillway consists in a valve connected to the spiral chamber that opens during abrupt maneuvers to bypass the turbine and keep the water flow nearly constant, preventing water hammer or water overflow.

The turbines of the hydropower plant were, and still are, without synchronous discharge and it is necessary to maintain constant water flow to the discharge channel. For this reason the turbines were equipped with a fictitious electrical load to dissipate excess electrical power [3]. The dump load consists of three fixed electrodes immersed in a water tank that dissipate excess electrical energy. In the event of a malfunction, such as a loss of an electric load, the power that the generators are delivering is switched instantaneously to the dump load that draws the same value of active power drawn from the grid when the event occurs. The constraint to be met, in order to keep the discharged water flow rate constant, is to keep the value of the dump load constantly aligned with that of the load present in the network; thus, it is possible to switch from network service to rheostat service without power transients and therefore without effect on the water level.

As a result of the refurbishment of two turbines at the end of the 1980s, which brought these units to a rated power of about 24 MW, the rheostats were no longer capable of providing full load dissipation service. Interventions were then made to address this problem but with partial and unsatisfactory results.

Fig. 1: Original power dissipation system.

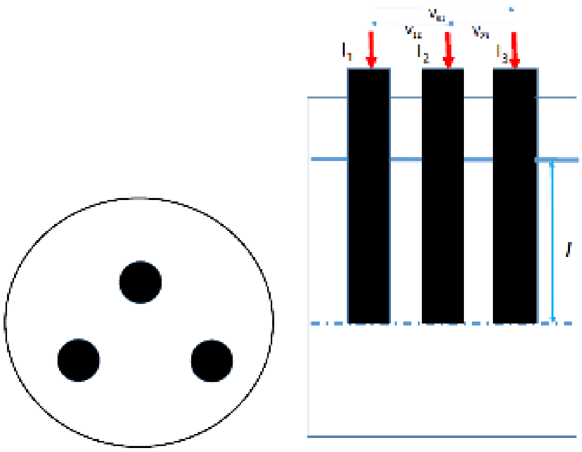
II. Three-phase rheostat configurations

A. Original System: description

The original dissipation systems, consisting of four three-phase rheostats, had dissipation capacities of 7 MW to 15 MW each at the rated voltage of 10 kV.

The rheostat consists essentially of a steel sheet casing, on which are arranged the mechanical control assemblies and feed-through insulators connected to the current-carrying conductors, above a support frame (see Fig. 1). These electrodes, placed 120° apart (see Fig. 2), are made of steel tube with a galvanized outer surface to maintain constant surface conductivity characteristics. Due to operating in a wet environment, the feed-through insulators, arranged on the top frame of the heat sink, were designed for the rated voltage of 10 kV

The original system made the first adjustment by measuring the instantaneous (active) power generated by the unit and positioning the rheostat system accordingly in order to obtain an electrical load equal to that measured. This was done by adjusting the height of the water in the tank through the opening/closing movement of the three floodgates located on



(a) (b)

Fig. 2: Simplified sketch of the original dissipating system: (a) top view, (b) front view.

the perimeter of the container. The water level excursion, is achieved by the simultaneous operation of three floodgates arranged symmetrically with respect to the electrodes along the heatsink casing. The maximum level variation within the equipment is about $1.65\ \mathrm{m}$. With such a level range, it is possible to adjust the power to be dissipated between 10% (for average values of water resistivity) and 100% of the nominal value. The overflows to regulate the dissipator are controlled by a central gear motor unit connected by means of three rigid shafts to the control boxes of the operating screws. Water for the operation of the dissipator is supplied from below through an adductor pipe with a nominal diameter of $400\ \mathrm{mm}$.

A preliminary setup defined the relationship between the water level and water resistivity with the equivalent resistance of the system. The activation of the heat sink occurs as a result of an intervention request from the group protection system, with the rheostat follower active. In this condition, the flow rate in the drain is kept constant, avoiding abrupt changes in level. In the event of an intervention, the electrical network is disconnected and the rheostat is immediately connected to the generator. The condition of no load can occur only when the connection of the rheostat fails (tracker not active, or faulty, or set up in manual operation). Once the generators can be reconnected to the grid, the automatic parallel is activated unless, due to causes caused by frequency or voltage fluctuations, it was not possible to return to the grid; in the latter case, an appropriate alarm is activated.

B. Original System: analysis of power regulation

As explained in the previous section, the regulation of the dissipated power is achieved by changing the water level in the tank. This power can be calculated as:

$$P = 3\frac{V^2}{R} = 3\frac{V^2}{k\rho}l \tag{1}$$

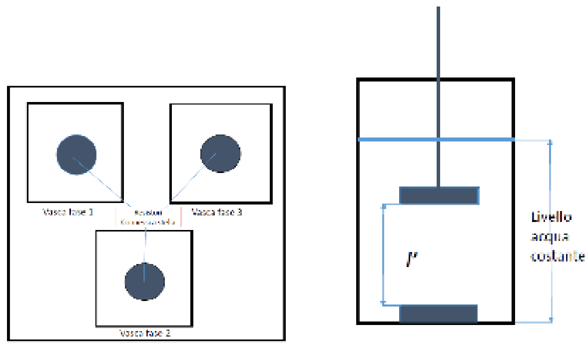
Fig. 3: New design of the power dissipation system.

where V is the line voltage, $R = k\rho/l$ is the delta equivalent resistance, l is the length of the electrode immersed in the water, ρ is the water resistivity and k is a parameter that depends on the geometry of the electrodes.

C. New design: description

As a result of the repowering of two turbines, that began in the late 1980s, the power plant is now equipped with four hydroelectric, vertical-axis, Kaplan-turbine units that can deliver under the most favorable conditions, $2 \times 18\ \mathrm{MW}$ (old turbines) and $2 \times 23\ \mathrm{MW}$ (new turbines).Due to the repowering, the rheostats were no longer able to act as a dump load with the new limits. In addition, the operating experience gained over the years has shown some critical issues related to the proper management of the regulation due to the variability of water resistivity in the Po River. Over time, interventions have been made with the aim of mitigating these issues, but with partial and non-resolving outcomes. Failing to achieve the expected improvement, a more radical solution was then opted for, which would intervene in the mode of operation, i.e., no longer regulation through sluice gates but direct handling of the electrodes, thus realizing a faster and more accurate system.

In the newly proposed solution the dump load consists of three insulating water tanks, one each electrical phase, where the inlet and outlet water flows keep the water level constant (see Fig. 3). In each tank there are two copper electrodes immersed in water: one is fixed at the bottom of the container, and one is movable. The three single-phase loads are star-connected with an appropriate connection between the three fixed electrodes (see Fig. 4). Power regulation is achieved by varying the distance between the electrodes. The control system adjusts this distance so that the dump load is always positioned at the value of the existing grid load so as not to create power transients.



(a) (b)

Fig. 4: Simplified sketch of the new dissipating system: (a) top view, (b) front view.

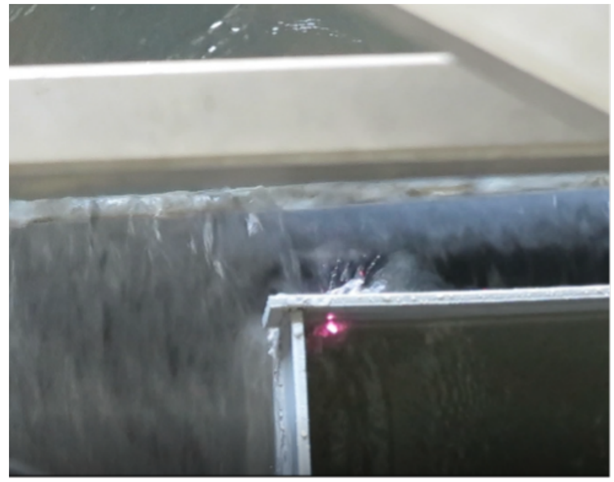
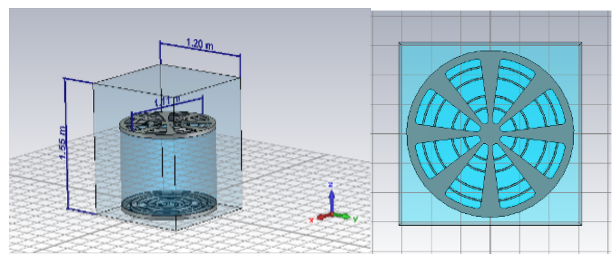


Fig. 5: Electrical sparks between the spilling water and the tank of another phase.



(a) (b)

Fig. 6: New design: (a) geometry, (b) detail of the electrode (top view).

D. New design: analysis

From the electrical point of view, the three resistances of the rheostat can dissipate the following power

$$P = 3\frac{E^2}{R'} = \frac{V^2}{k'\rho l'} \tag{2}$$

where $E = V/\sqrt{3}$ is the phase voltage, k' is the geometric parameter, ρ is the water resistivity, and l' is the distance between the electrodes.

The inspection of formula (2) indicates a substantial difference between this and the original solution represented in (1), In this last solution, in fact, the power dependence on the control parameter l' is nonlinear. This nonlinearity $1/l'$ makes controlling the power more difficult, especially when it is close to its maximum value corresponding to the minimum distance between the electrodes. In such a condition, the dP/dl' function is maximum and therefore the control system will have to compensate for this strong variability. Another critical issue is that the condition of maximum absorbed power is reached with the minimum distance of the electrodes, a condition that can create discharge phenomena between the electrodes due to excessive proximity.

During the experimental verification of this solution, an additional difficulty emerged: due to water runoff from all three containers, visible electrical discharges occurred on the water surface between the containers, as shown in Fig. 5. Due to the phase voltage of 10 kV applied, this situation caused the unwanted tripping of overcurrent protections. The most positive aspect of this solution is the expected improvement in dynamics because of electrode position control and no longer due to changing water levels.

III. Electrical Analysis of the New Design

A. Preliminaries

The structure studied consists of the two electrodes and the tank containing river water. The electrodes are considered as perfect conductors at the assigned potential, while the water has a resistivity of $\rho = 2960\ \Omega\mathrm{cm}$. The resistivity is assumed to be uniform and independent of the power dissipated and, therefore, of the temperature. With this assumption, results can be obtained for a reference applied voltage chosen to be 1 V and then appropriately scaled for different values of applied voltage.

The upper electrode has a position that varies between 0.3 m and 0.9 m with respect to the fixed lower electrode. Fig. 6 shows the geometry and the detail of the electrodes. The analysis is conducted using CST Studio Suite [6] and involves studying the current density field in the structure for various values of the electrode distance.

B. Electric potential

An example of the analysis of the electric potential in the structure corresponding to the maximum distance between the electrodes is shown in Fig. 7. It can be seen that the electric potential decreases almost linearly between the two electrodes in the case with the electrodes at maximum distance.The volume of water above the electrode assumes the potential of the upper electrode. This result is independent of the size of the water tank. For this reason, the voltage difference between the tanks is the line voltage. To prevent discharge between the tanks, the distance between them should be increased

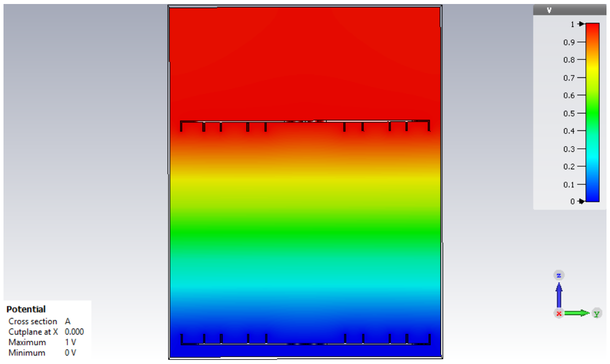


Fig. 7: Electrical potential (range $0-1$ V) with maximum electrode distance (0.9 m).

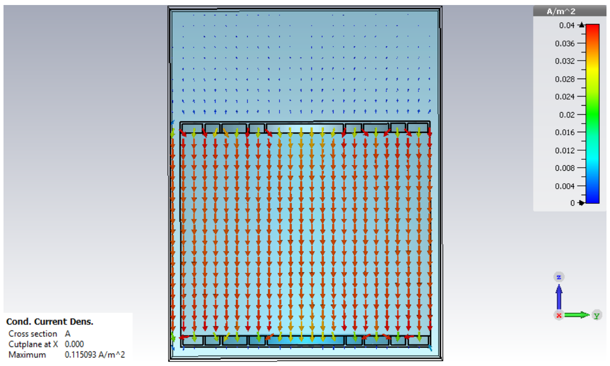


Fig. 8: Current density (range $0-0.4$ $\mathrm{A/m^2}$) with maximum electrode distance (0.9 m).

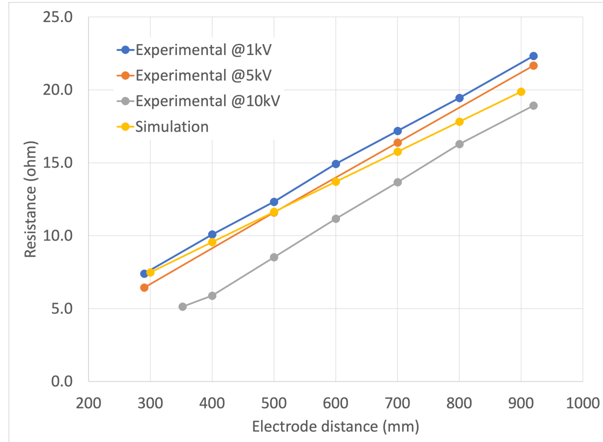


Fig. 9: Resistance as a function of electrode distance.

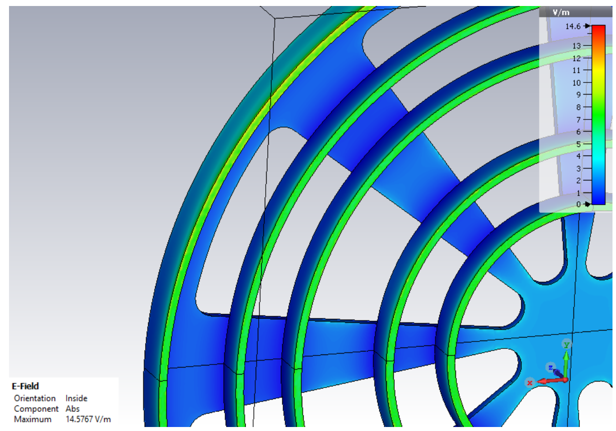


Fig. 10: Electric field on the surface of the upper electrode.

and, if necessary, alternative paths should be provided for the water overflowing from the different tanks. Fig. 8 shows the current density distribution for electrodes at maximum distance. Since the system operates at an imposed voltage, the current (and therefore the current density) is maximum when the resistance is minimum, i.e. when the distance between the electrodes is minimum. Given the proportionality between the current density and the electric field, it is concluded that the configuration with the highest dielectric stress occurs when the water, viewed this time as the dielectric constant, is under the greatest stress. Fig. 9 shows the resistance value as the distance changes, calculated and compared with the measurements. The calculated resistance curve lays between the measured values at the different voltages of $1-5-10$ kV. The different slope is attributed to the fact that the water resistivity was considered uniform and constant.

C. Electric field

Another critical point of the new design is the geometry of the electrodes. The disc that forms the base of the electrodes has sharp-edged details where the electric field is intensified. Fig. 10 shows the magnitude of the electric field on the surface of the top electrode when the distance between the two electrodes is 30 cm. It can be seen that the electric field is maximum at the outermost fin, where it takes the value of 14.6 $\mathrm{V/m}$ for each volt applied to the electrodes. Since the phase voltage is 5.8 kV, the maximum dielectric stress is 841 $\mathrm{V/cm}$, which locally exceeds the value of 250 $\mathrm{V/cm}$ assumed as the limit. However, the dynamics of any discharge are not easy to predict because local failure of the dielectric does not necessarily lead a discharge between the electrodes.

IV. Conclusions

In this paper, we analyzed and discussed the design features and experimental results of the design of a new power regulation system. An in-depth analysis of the proposed system was then developed using a finite element simulation program. The current field distribution was obtained taking into account the detailed geometry of the electrodes and their placement in the tank. The calculation was carried out by describing the three-dimensional geometry of the system, which was divided into elements of tetrahedral shape. The objective was to investigate the many critical and non-intuitive aspects such as the effect of the complex geometry of the tank, the electrodes and their distance on the power dissipation and the electric field produced in the liquid with possible ionization or electric discharge. Some simplifications were made in the field analysis and in particular water with homogeneous and linear electrical properties is assumed. The effects on the results of varying water resistivity can be evaluated immediately if they are attributed to unavoidable and well-known seasonal phenomena affecting the river waters. From the technical findings made and the theoretical nature assessments made, it is evident that the design of the new dissipation system has serious implicit flaws that prevent the achievement of the design targets, specifically a dissipated power of 8 MW per tank. The main reasons for the design failure can be summarized as follows:

1) Assuming temperature homogeneity in the various cross-sections of the water tank, a water flow rate of 200 l/s total (66.7 l/s for each electrode), and the need to dissipate 8 MW for each tank, the temperature rise is $\Delta T = 30\ °\text{C}$. Given an average river temperature of $15\ °\text{C}$, the water leaving the tank has a temperature $T_{out} = 45\ °\text{C}$, which should not result in consistent steam formation. It is also true that, under certain seasonal conditions, river temperatures can reach as high as (see Fig. 11), and with such values the average outlet temperature would reach $T_{out} = 55\ °\text{C}$, a rather high value that would certainly need to be mitigated, also in view of the direct return to the river flow. To reduce the average water outlet temperature, the water supply to the tank would have to be increased. This should be considered an initial design flaw. It should also be noted that the reduction in water temperature, however, would have resulted in an increase in the resistivity of the water itself, requiring a further reduction in the distance between the electrodes to achieve the value of power to be dissipated.
2) The proposal to change the size of the three caissons from 1200 mm to 2000 mm would not have improved the performance of the dissipation system because the cause of the malfunction was wrongly attributed to the reduced water passage section between the tank and the electrodes and not to the large variation in water temperature, between the inner and outer zones of the electrode, due to the recirculation zone. Therefore, the proposed new design solution would certainly not have been decisive unless it was coupled with a redesign and redistribution of the water access holes to the tank.
3) Another critical aspect of the new design is that the power dissipated is inversely proportional to the distance between the electrodes. Therefore, the maximum power occurs at the minimum distance between the electrodes. This aspect is critical because it increases the possibility of electrical discharge between the electrodes. The analysis of the electric field has made it possible to highlight that the electric field is maximum at the outermost part of the electrode, where it reaches a value of 841 V/cm for a supply voltage of 10 kV. This value locally exceeds the design value of 250 V/cm by more than 3 times. It is also true that the dynamics of a possible discharge is not easy to predict, since a local dielectric failure does not necessarily lead to a discharge between the electrodes, but this shortcoming must be taken into account during the design phase.
4) It should also be emphasized that the way the power output of the heat of the heat sinks in the new solution must also take into account the non-linearity between the control variable (distance between the electrodes) and the dissipated power. In particular, it was found that with the new geometry, small errors in system positioning can result in large variations in power dissipation. Simulations show that when the electrodes are 30 cm apart, a displacement error of 1 cm results in total power dissipation variations of more than 1 MW. It should be noted that the large size of the electrodes (diameter of 1100 mm), the small size of the handling rod, its considerable length, the unavoidable mechanical play and the high speed of the water that immerses the electrodes can cause oscillations of the plates and thus significant variations in the electrical power dissipated.
5) Finally, it has been experimentally verified during some preliminary tests that the water discharge from the three tanks causes electrical discharges between the phases with possible tripping of the automatic protections and

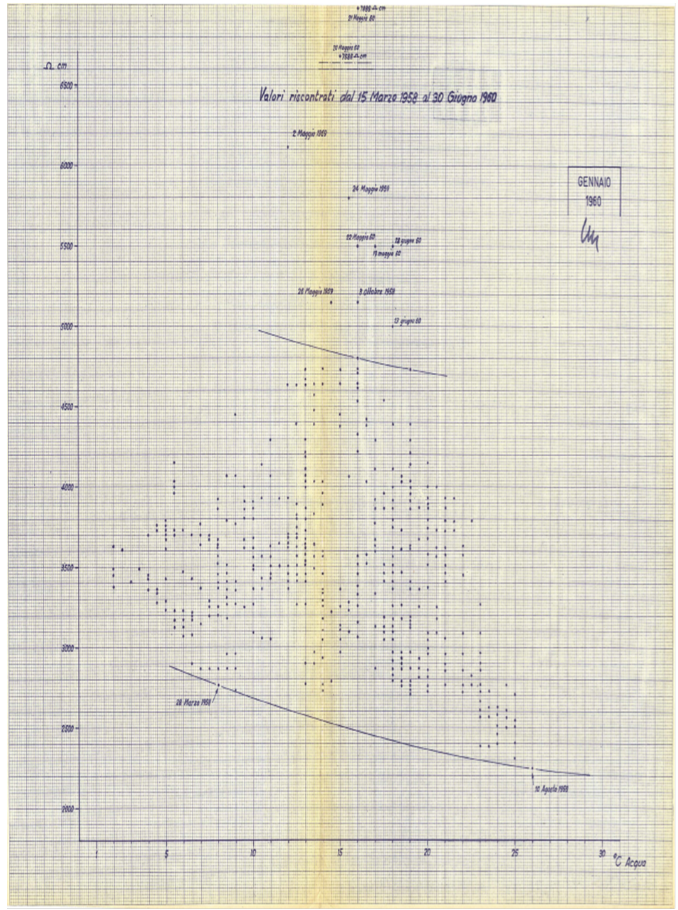


Fig. 11: Water temperature and resistivity measured between March 15, 1958 and June 30, 1960 (Courtesy of Enel Green Power S.p.A.).

with possible tripping of the automatic protection devices and consequent stoppage of the discharge system. This result must be considered an inherent design flaw of the solution adopted, since it is necessary to prevent the water coming from the different tanks at different potentials from joining.

V. Aknowledgements

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