CLASSIC ANALYTICAL METHOD APPLIED TO BLOWDOWN PROCESS OF A PUMP-TURBINE MOTOR-GENERATOR

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ABSTRACT

As a general practice the organization of compressed air blowdown schemes have always been conducted using a rule of thumb, based on previous operational experience, resulting to failure of blowdown schemes to depress draft-tube water and maintain it below the runner to allow synchronous compensator mode to be conducted. In this paper a classic analytical method has been applied to blowdown of pump-turbines using parameters chosen on the basis of the analytical approach made. The study has shown therefore that for the case of similar units for pumped storage plants at Wettingen, Gaston, Krasnoyarskii, and Dinorwig, the empirical approach is justified and the performance of the scheme is insensitive to the system parameters chosen. The blowdown period achieved compares fairly well with the period achieved in some of these plants.

Key words: Draft Tube Water Level Blowdown Method.

INTRODUCTION

One of the main operational problems in power transmission systems is to minimize the variations in voltage caused principally by transmission lines impedance losses in the form of reactive power Previous studies indicate that, a 500 kV overhead line generates about 100 Mvar of reactive power per 100 km of transmission line, a 750 kV overhead line generates more than 200 Mvar and a 1150 kV overhead line - about 600 Mvar [1]. As such, small changes of the load can result in system instability and a decrease in power transfer capability of the transmission network [2].

To enhance the stability of power transmission both the voltage and reactive power must be controlled. This may be achieved by switching pump - turbine motor -generator units of Pumped Storage Plants (PSP) to run in synchronous compensator(SC) mode [3,4] at times of off -peak load drawing reactive power from the grid with the runner spinning -in -air

To implement SC mode compressed air is pumped into the draft -tube after the turbine inlet guide vanes have been closed and the air will blowdown the water to a predetermined position below the runner to reduce resistance to rotation.

Use of motor -generator units in SC mode was reported byWettingen Power Plant operated by the city of Zurich Electricity Board, Pumped Storage Plants at Gaston (USA),Krasnoyarskii (Russia), Dinorwig (UK), etc. [5]. Some failed attempts to operate motor -generator machines in SC mode were reported at the Gaston Hydropower Station of the Virginia Electric and Power Company [6]. Since the problem at Gaston was reported, information has become available concerning difficulties in some stations to achieve draft -tube water depression and hence failure to attain SC mode, as the blowdown schemes have been designed using the rule of thumb,based on previous operational experience.

In this paper the author has introduced a classic analytical method that can be used to predict draft -tube water level position, a design requirement needed for a rational organization of new blowdown schemes.The method is based on the use of geometric relations of a physical plant in which a new blowdown scheme is to be installed. The results of the water level position predicted using this approach were verified by means of a simulation study made using a mathematical model developed for the blowdown process at Zagorskii Pumped Storage Plant (Russia) indicating that the empirical method used is justified because draft -tube water depression level predicted analytically compares well with the experimental results obtained using digital simulation technique. The time taken to achieve draft -tube water depression is also within the range of depression time at Wettingen, Gaston, Dinorwig and Krasnoyarskii Pumped Storage Plants.

PUMP-TURBINE OPERATION MODES

Pump -turbine motor -generator units can apart from SC mode operate in a number of other modes. To explain to the reader some of these modes a complete characteristics plot of pump turbine units has been presented in four quadrants representing the speed and capacity in reduced values [7]as can be seen in Fig.1.

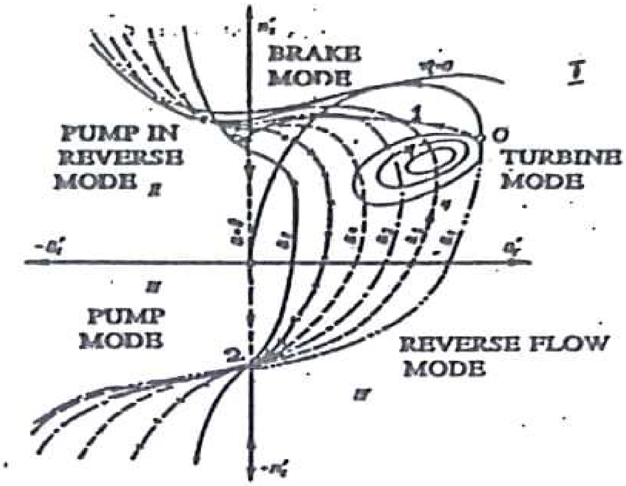

Fig. 1: Complete characteristics of pump-turbine showing diferent modes

Under given initial conditions: speed, capacity and inlet guide vanes opening law, the pump -turbine unit operates in a normal turbine mode corresponding to the first quadrant at optimum point O. To transfer the pump -turbine unit from turbine mode to SC mode, the motor -generator unit is unloaded with respect to active power This corresponds to path, 1 starting from point O as the turbine's inlet guide vanes start to close, reducing the discharge while the generator is still connected to the grid. The turbine speed remains higher than the optimum value until the dischage is reduced to zero, i.e. at a closing law a=0. After closing the inlet guide vanes a timing sequence signal from the station control panel will initiate the blowdown process and compressed air will depress draft-tube water below the runner, allowing the motor-generator unit to operate in SC mode while the runner is spinning-in-air.

When SC mode is no longer needed the pump-turbine unit may be returned back to generation mode, or stopped and its rotation reversed to operate in a pump mode. This mode corresponds to curves in the third quadrant starting from point 2. Pump mode is operated during off-peak hours to pump water from the lower reservoir (tailrace) to the upper reservoir for storage to be used latter in the generation mode during peak-load hours.

In the case of loss of power during operation in pump mode, the speed and discharge will change direction leading to a reverse flow mode represented in the fourth quadrant.

After the speed has been reduced to zero, the unit will start to rotate in the turbine direction and by inertia the pump-turbine will enter the speed-no-load (above $\eta=0$), corresponding to a break mode, as shown in quadrant one, and at zero discharge, the pump-turbine will rotate in a reverse pumping mode shown in the second quadrant. These two operations usually happen during emergency situations only.

The transition time between different modes depends on the individual process. To transfer pump-turbines from a generation mode to SC mode may take about 60 seconds [8]. A typical blowdown time achieved in some pump-turbine installations is given in Table 1.

Table 1. Typical parameters of blowdown schemes

No.	Name of plant	Country	No. of units	Receiver pressure (bar)	Blow time, (s)
1.	Wettingen power plant	Switzerland	3	2.0	30.0
2.	Gaston power plant	USA	4	8.0	40.0
3.	Krasnoyarskii power plant	Russia	8	8.0	45.0
4.	Dinorwig power plant	UK (North - Wales)	6	31.0	15.0

BLOWDOWN SCHEME LAYOUT

Several blowdown systems have been implemented [6,9] but they difer in their layout. The general configuration of a blowdown scheme used in this study as shown in Fig.2 consists of the air receiver, compressor installation unit, and a control system for automatic delivery of compressed air to the pump-turbine draft-tube. The pump-turbine unit 1, is normally embedded within the foundation concrete that is determined by the type of the turbine used. Limitation to cavitation damage requires that the runner's elevation for most vertical shaft turbine units be below the tailrace water level, thus having a negative suction head (-Hs). When the blowdown process is initiated an automatically controlled valve 4, is actuated by the action of a hydraulic drive 5, which is operated by a coil armature placed in a permanent magnet. The slide valve 6, will then open to admit air from a turbo-compressor installation of the existing hydropower plant designed specifically to implement SC mode. The compressor installation unit is fully instrumented for independent operation.

The air pressure in the receiver is usually maintained at 0.7-0.8 MPa, but use of higher pressure schemes has also been reported. The advantage of using higher pressure schemes is the small size of air receiver, but the permissible pressure variation within the air receiver is more restricted and the draft-tube water level indicator must be more sensitive, and the control scheme be more responsive to minimise water level fluctuations within the draft-tube, 7.

The compressed air delivered will depress draft-tube water to a predetermined level H_{max} below the runner. The water level is monitored by a pneumohydraulic regulator 8, installed in the draft-tube hatch. This is achieved by sensing draft-tube water level pressure $p_d(t)$ transduced back to the control loop in form of an electric signal $v_o(t)$ generated by a resistive potentiometer 10, via an operational amplifier for corrective measures to be taken.

ANALYTICAL DETERMINATION OF WATER LEVEL

Most of the design parameters of pumped storage plants (PSP) are unique because the topography of their installation sites is not the same. The blowdown schemes for these installations and their performance capability to realise synchronous compensation operation are usually adjusted to meet specific conditions. As such, to design new blowdown schemes the knowledge of the geometric dimensions of a physical plant is essential.

In this design study a classic analytical method has been applied to a blowdown process using design data for Zagorskii Pumped Storage Plant (ZPSP). The method demonstrates how the expected position of draft-tube water level could be predicted to facilitate the selection of parameters of new blowdown scheme designs. This is an essential feature, without consideration of which, a reduction in the magnitude of power consumed from the grid during SC operation will not be achieved if water level is not kept at this level below the runner.

In order to be able to determine the expected draft-tube water level the analytical method used incorporates geometric parameter relations of a draft-tube installation at (ZPSP) as shown schematically in Fig. 3. These design parameters are necessary and allow the prediction of water level position that has to be achieved to be made. This position should not exceed a permissible water level value within the vertical cone of the draft-tube so that air losses to the tailrace can be minimized during the blowdown process.

When the draft-tube water is depressed (see Fig.2), the turbine's head cover pressure rises until an effective water level is achieved leaving the runner to rotate in air. The compressed air pressure developed at the delivery point in the turbine head cover at the instant of the blowdown can be determined using the expression [8]

$$p_{do}(t) = |H_s| - \frac{B_o}{2} - p_o \tag{1}$$

where p_o is the standard atmospheric pressure which is equivalent to 10.34 meters of water column, B_0 is the inlet guide vanes height, H_s is the elevation of the runner. The corresponding head cover position is

$$H_O = \frac{(p_{do} - p_o)}{\gamma} \tag{2}$$

where γ is the specific weight of water.

After completing water depression process, the expected air pressure in the draft-tube can be determined by

$$p_d(t) = p_{do}(t) + (0.4xD_1 + \Delta h\ ) \tag{3}$$

where the design factor Δh can be selected between the values 1.0 to 2.0 [10], and D_1 is the inlet diameter of the runner. This pressure should be sufficient enough to maintain draft-tube water level at a position Hmax, during the entire operational period in SC mode. The corresponding expression for predicting this water level position is given as

$$H_{\max}(t) = \frac{p_d(t)}{\gamma} - \frac{p_o}{\gamma} \tag{4}$$

The predicted water level position should be compared with the draft-tube design geometry to ensure that Hmax value lies within the vertical cone of the draft-tube and should satisfy the condition [8]

$$H_{\max} < [H_{o+}B_o + H_d + H_t - h_5] \tag{5}$$

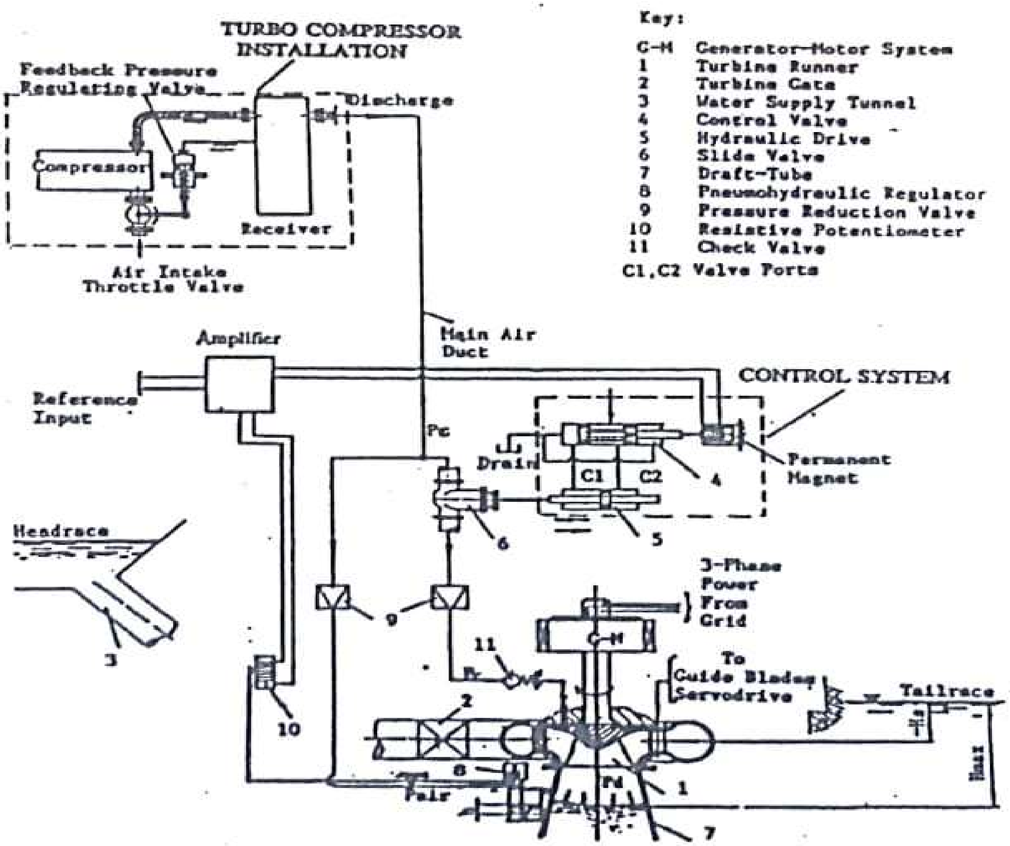

Fig. 2: Layout of scheme for draft-tube water depression

According to Fig. 3, the draft-tube exit parameters are computed as: $B_5=1.1D_1$, and $h_5=3.0D_1$. The draft-tube length $L_5=4.0D_1$, the vertical cone height $H_d=K_dD_1$, and the turbine runner chamber height $H_t=0.4D_1$, where the design factor K_d is selected in the range between 3.5 and 4.0 [8].

To make the analytical method relevant to industrial practice the author has made use of design data of Zagorskii Pumped Storage Plant (Russia) to allow nominal value of the expected draft-tube water level to be known. A comparison of this value can be made using a mathematical model of the blowdown process developed for (ZPSP) as will be described in the next section of this paper. The Francis turbine type was adopted for simplicity to operate and the design data used for the Zagorskii plant type-PO 115/697 are: Head, H= 80.0 m; Inlet diameter of the runner, D_1=4.5 m; speed, n=150 rpm; Power generation, N=200 MW; Runner's elevation H_s= -13.0 m; Inlet guide vanes height, B_o= 1.1 m; Runner's chamber height, H_t= 1.8 m [8].

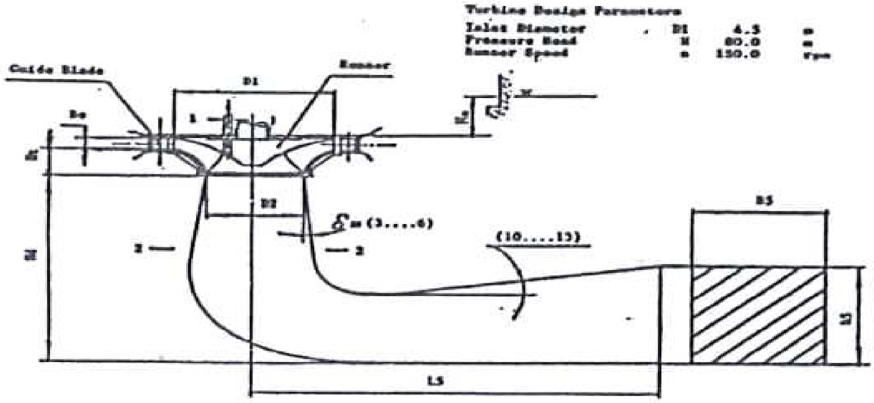

Fig. 3: Notation of turbine runner and draft-tube

WATER LEVEL PREDICTION MODEL

The analytical method described above provides only preliminary design data required for the design of new blowdown schemes , and as an essential design requirement the selection of parameters of the blowdown scheme tuned to a particular pump-turbine installation unit can be made. Draft-tube water depression is a composite process in which the constituent parameters require separate control to achieve the desired water level.The main parameters that need to be controlled during the blowdown process are the slide valve travel y(t) and the air supply pressure $p_t(t)$ delivered from a compressor installation unit which is fully instrumented for independent operation.

The delivery of compressed air into the draft-tube is implemented by opening a slide valve fitted in the supply pipe. To achieve an effective depression process compressed air must be dischaged at the correct pressure value. For most blowdown schemes the air supply pressure from the existing station compressor installation unit may require to be reduced before being discharged into the draft-tube. To facilitate for this, pressure reduction or a reduction valve may be included.

The expression that relates the slide valve opening and the supply pressure allowing to model the valve action is

$$p_r(t) = p_c B_4 y(t) \tag{6}$$

where $p_r(t)$ is the instantaneous pressure through the slide valve, B_4 is the pressure reduction valve constant of about 1.5 MPa used in this study and $y(t)$ is the air slide valve travel [11].

During the blowdown process draft-tube pressure rises by an amount sufficient to form a stable water level below the runner. Assuming the rate of pressure rise in the draft-tube to be directly proportional to the mass flow rate through the supply pipe the blowdown process can be modelled using the following expression

$$T_d \frac{dp_d(t)}{dt} + p_d(t) = p_r(t) \tag{7}$$

where $T_d = c_{ov}/\omega$ is the time constant, C_{ov} is the air carry over factor that allows air losses to be accounted for. Previous model studies show the value of carry over factor would be in the range from 1.2 to 1.3 for Kaplan turbines[6], but no data of similar tests has been reported for Francis turbines. For practical approximation purpose the air system carry over factor can be determined by $C_{ov} = (1+V_1 p_o/V_d/p_d)$. The amount of air loss is estimated by $V_1 = 1.4\text{x}10^{-4} D_2{}^2 H_t n T$; where $p_d(t)$ is the compressed air pressure occupying draft-tube space volume V_d, p_o is the standard atmospheric pressure, n is the speed of the runner, H_t the height of the runner. The flow velocity coefficient $\omega = [1+\lambda L/d)^{0.5}]^{-0.5}$; L and d are the length and diameter of supply pipe and λ a friction factor.

Solutions to Eq. 6 and Eq. 7 emulating the blowdown process may be obtained by using digital simulation method adopting Runge-Kutta numerical integration algorithm methods. The principal design data of air delivery system used in this study are: compressor's nominal pressure $p_s =$ 0.8 MPa, air mass discharge capacity $M_s = 4.8$ kg/s, and the supply pipe pressure was limited at the value $p_c = 0.9p_s$ [12], the total compressed air storage capacity of the receiver $V_r = 170.2\ m^3$ approximately.

For the blowdown process being investigated the air carry over factor for Francis turbine was estimated analytically to be $C_{ov} = 1.06$, and the flow velocity constant $\omega = 0.54$ [8]. The correct value of the air carry over factor would however require a special study to be conducted which is beyond the scope of this study.

CASE STUDY RESULTS

Analytical Results

By making use of Eq. 1 through Eq. 4 the design data for the type of turbine used, draft-tube water level has been computed to reach a maximum value $H_{max} = 15.9$ m below the tailrace water level. After cross checking this value using the Zagorskii turbine installation parameters it was found that the draft-tube water level would have to be maintained at about 1.6 m, below the runner's outlet blades periphery at an elevation of 14.3 m below tailrace water level.

Applying the turbine's draft-tube outlet design relationships described in previous section, the estimated values for the geometric dimensions of the draft-tube are: $H_o = 12.5$ m; $B_o = 1.1$ m; h_5 - 13.5 m; $H_d = 16.83$ m; $H_t =$ 1.8 m, showing that the draft-tube water level value predicted using the analytical approach satisfies the design conditions given in Eq. 5.

Model Simulation Results

As a design requirement the expected draft-tube water level to be achieved for this turbine installation was predicted analytically. Comparison of this value with the results obtained from simulation study of blowdown process developed for (ZPSP) indicate that the model configuration chosen was capable to emulate draft-tube water depression reaching a level of 16 m below the tailrace water in about 23 seconds. This blowdown time achieved compares well with data in the other installations as given in Table 1. A typical plot indicating draft-tube water level achieved in absolute value is shown in Fig. 4, suggesting that draft-tube water depression process was insensitive to the blowdown model parameter changes made by varying the compressor capacity using suction angles variations between 20 and

30 degrees.

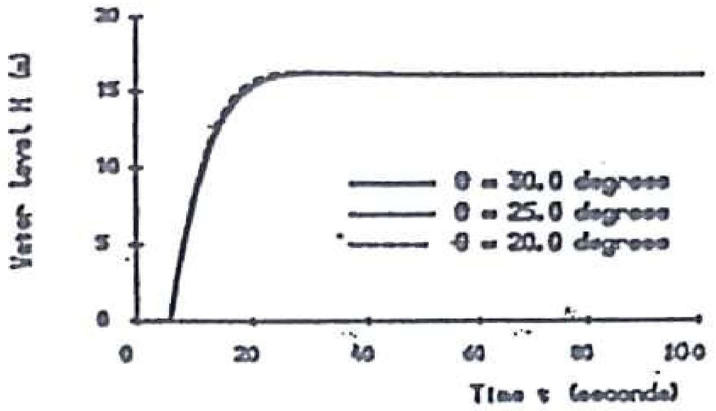

Fig. 4: Draft-tube water depression curves at different compressor suction vane angles

CONCLUSION

It has been shown in this study that the analytical method presented is adequate for a preliminary selection and design of nominal parameters of a blowdown scheme. Simulation results obtained give an indication that the blowdown model parameters chosen using the proposed approach can yield fairly good performance behaviour as could be expected from an actual installation. However, it is important to note that the blowdown scheme configuration developed and employed in this study contains only fundamental terms and may require further development.

Francis type turbine was adopted in this work for its simplicity to operate, but many other installations employ Kaplan type turbines as well. To develop a blowdown model including such machines would require an additional knowledge on turbine performance with changing turbine blade angles which is a typical feature of Kaplan turbines. Information to be gathered from simulation studies that relate draft-tube water depression to Kaplan turbines would be invaluable to the industry.

NOMENCLATURE

P_{do}	turbine's head cover delivered pressure, (N/m^2)
P_o	standard atmospheric pressure, (N/m^2)

P_d	draft tube compressed air pressure, (N/m^2)
H_{max}	draft tube water level position, (m)
P_r	instantaneous air pressure through the valve, (N/m^2)
T_d	a time constant
Y	air slide valve travel, (m)

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