IOP Conf. Series: Earth and Environmental Science **163** (2018) 012081 doi:10.1088/1755-1315/163/1/012081

1-D MOC simulation software for hydraulic transients: TOPsys

J B Yang and J D Yang

The State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, 430072, China

Jbyang830212@whu.edu.cn

Abstract. The development of hydropower in China has entered the gold period nowadays. Numerous challenging hydropower projects have been presented to researchers and scholars. In order to adapt to this trend and the need of the nation, TOPsys, an one dimensional simulation software based on the method of characteristics (MOC) for hydraulic transients, has been developed in State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University recently. This software has been employed for transient flow simulations of more than thirty hydropower stations in China and overseas. The whole paper is organized as follows: first, basic mathematical theory of the software was introduced. Subsequently, several typical engineering applications, including conventional power stations and pumped storage power stations, were given for validation. Finally, the versatility as well as the expandability of this software was shown with several special engineering examples.

1. Introduction

The development of hydropower in China has been continuously growing Since 2000, as is shown in figure 1. According to IEA2016 report [1], China accounted for 26.7% of the world's hydropower generating capacity in 2014, far more than any country in the world. To ensure the energy supply, pumped storage units and conventional hydraulic turbines are of key importance. However, the units have to undergo frequent transition processes, such as start-ups, load acceptance and rejection, and even emergency load rejection. In these transient scenarios, the hydropower station will experience significant vibration and pressure pulsations, which could be a threat for the units. Therefore, the precise simulation of typical transition process is essential for the design and refurbishment of power station. In addition, hydropower units have an important role in stabilizing the grid system, which means it is necessary to optimize the selection of the governor parameters according to the operating conditions of the power station. In order to simulate these conditions, a software which has fast calculation speed and high precision as well as the versatility to expand is necessary. TOPsys, an one dimensional simulation software based on the method of characteristics (MOC) for hydraulic transients, has been developed in State Key Laboratory of Water Resources and Hydropower Engineering Science. This software has been used in more than 30 projects of hydropower station in China, from low head units to high head units. In the following paper, a brief introduction of its theory was given first. Then, case studies including transient flow analysis for conventional hydropower stations and pumped hydro units were shown.

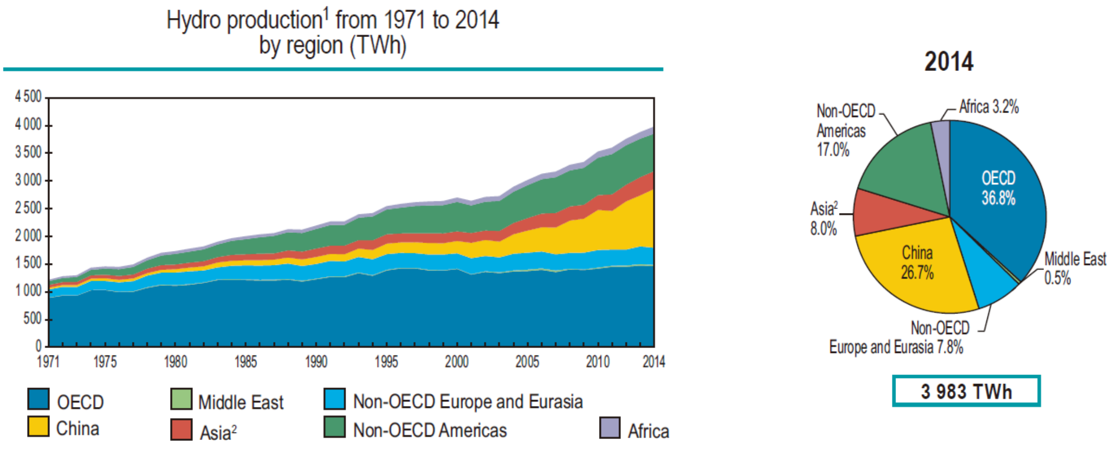

Figure 1. Hydro production from 1971 to 2014 [1]

2. Mathematical model

In review of simulation for fluid transients, the MOC [2] and electrical analogy [3] were most well-known method as on one-dimensional transient flow simulation. They could be used to not only for parameter study for the design of the power plant [4], but also to investigation complex hydrodynamic phenomena such as Rotor-Stator-Interaction [5] and water column separation [6,7]. Since the equation and boundary conditions have been sufficiently discussed in the classic publications, they are briefly introduced in this paper.

The continuity equation and momentum equation was described as

$$VH_x + H_t + \frac{c^2}{g}V_x + \frac{c^2}{g}\frac{A_x}{A}V - \sin\theta \cdot V = 0 \tag{1}$$

$$gH_x + VV_x + V_t + \frac{fV|V|}{2D} = 0 \tag{2}$$

where the subscripts x and t denote differential operations with respect to distance and time, respectively.

These equations could be further expressed as two groups of characteristic equations along the characteristic line as equation (3) and equation (4) to calculate transient pressure and flow discharge.

$$C^+: \quad Q_P = QCP - CQP \cdot H_P \tag{3}$$

$$C^-: \quad Q_P = QCM + CQM \cdot H_P \tag{4}$$

3. Case validation

3.1. Case 1: conventional power stations

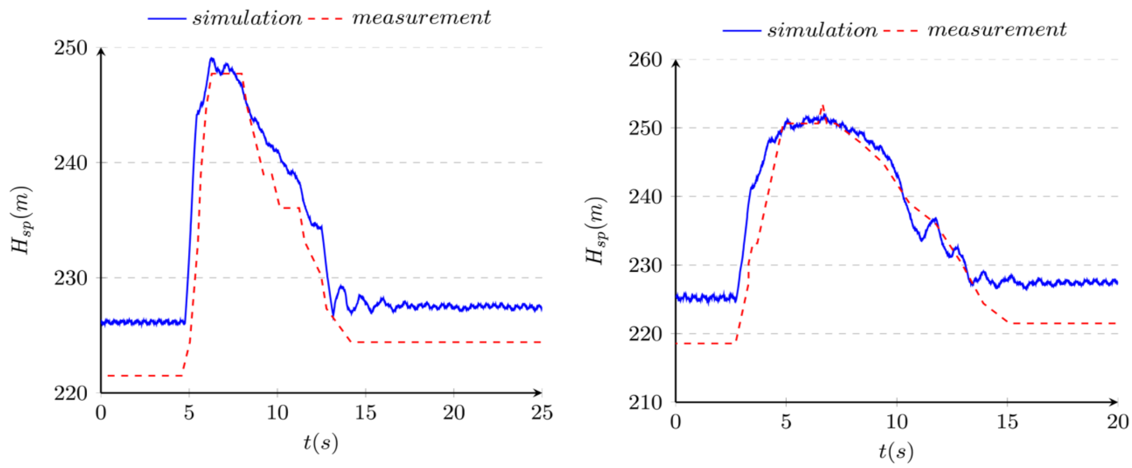

Figure 2. Simulation and measurement for pressure in spiral case from emergency load rejection, 700MW (left) and 500MW (right)

There are a large number of hydropower stations located in the southwest of china. The example given here is Xiaowan Hydropower Station which is in the middle reaches of the Lancang River. This power station has two set of hydraulic units, each of which has three conventional Francis turbines. The rated output of the turbine is 700MW. To ensure the safety of the unit, the prototype load rejection test was carried out. The turbine operated with 700MW and 500MW in steady state at first. Then, the load of the unit was totally rejected. In the prototype experiment, only the data of pressure in the spiral case were provided due to the confidentiality constraints. According to the layout of the power plant, the characteristic curves of the turbine and the closing law of the guide vane, simulation for total load rejection of the turbine was conducted. Figure 2 displays the results from measured data and one-dimensional simulation. It was observed that, despite the deviation of the initial value, the trend of variation and maximum value of the volute pressure during the load rejection were simulated with a satisfactory accuracy.

3.2. Case 2：Pumped hydro

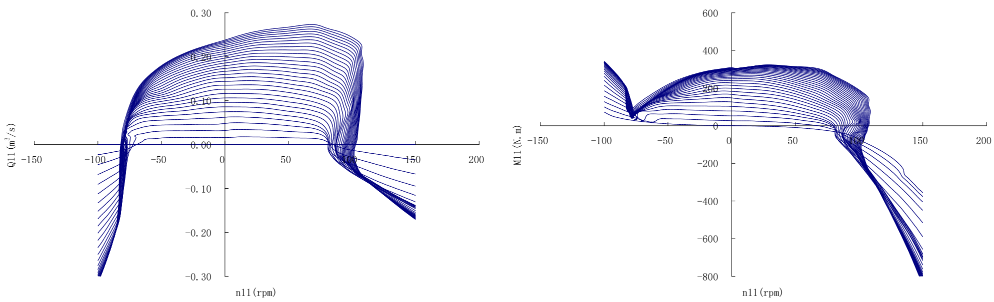

Figure 3. S-shape characteristic curves

Pumped hydro units have the ability to operate in both pump mode and turbine mode. This flexibility makes it quickly to respond to the grid. However, in the turbine brake mode, significant difference between pumping hydro units and conventional Francis turbines occurs [8], which is S-shaped characteristics. Figure 3 shows typical 4-quadrant characteristic curves of a pump-turbine. In order to simulate transient operation of pump hydro units, the transformation of characteristic curve was proposed by Suter [9]. In TOPsys, a B-spline space curved surface in coordinate system is constructed for the representation of the complete characteristics of pump-turbine by Yang [10].

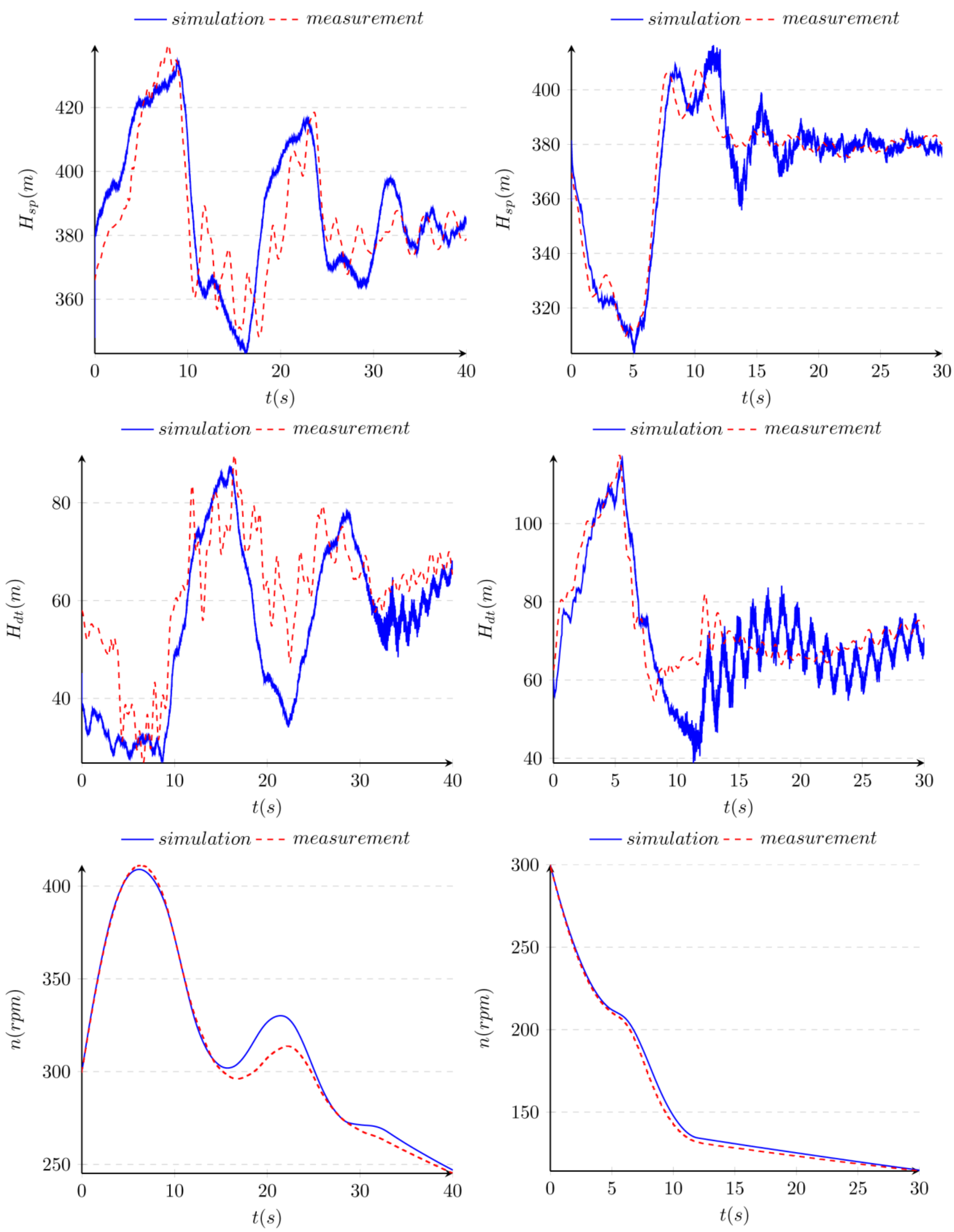

Figure 4. Results from simulation and measurement of emergency Load rejection (left) and power failure (right) from a prototype Francis pump-turbine, including pressure in spiral case, pressure in draft tube and rotational speed

Figure 4 shows comparison of results from simulation and field test data of prototype pumped storage power plant. Two typical transient scenarios of the pump hydro units, emergency load rejection and power failure, were included. The measured pressure in spiral case and draft tube were processed with time-averaged low-pass filter, since the focus of one-dimensional simulation was transient water hammer pressure rather than pulsating pressure with high frequency.

In general, the error of simulation for power failure in pump mode was lower emergency load rejection conditions. The reason was that, on the one hand, the characteristic curves provided by the manufacturer were statically measured, which was difficult to be accurate in the S-shaped zone. On the other hand, in simulation, the S-shaped characteristics curves cause the difficulty of simulation, resulting in the deviation between simulation results and measured data.

3.3. Versatility and expandability

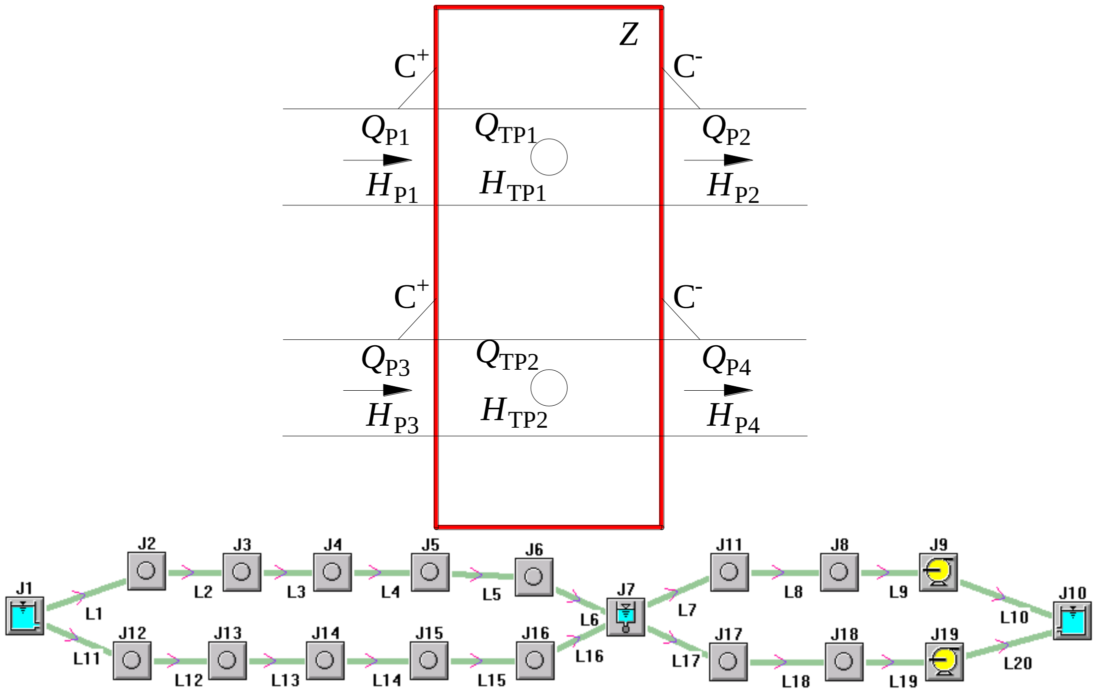

Figure 5. layout of a conventional hydropower station with a shared surge tank

To show the diversity of the software, this case presents the analysis of a conventional hydropower station. The power station is currently in design. The layout of the pipeline was shown in the figure 5. Due to the limitation of geography, two pipes were designed to share a surge tank. In order to simulate the transition process of the power station, the software is reprogrammed to supplement the special boundary conditions. Simulations for load rejection, load acceptance and hydraulic interactions were realized. Results of simultaneous emergency load rejection for two turbines were shown in Figure 6, including the variation of rotational speed and the water level of pressure tank. Finally, the simulation helped to determine the design of surge tank as well as the parameters of the penstock.

IOP Conf. Series: Earth and Environmental Science **163** (2018) 012081 doi:10.1088/1755-1315/163/1/012081

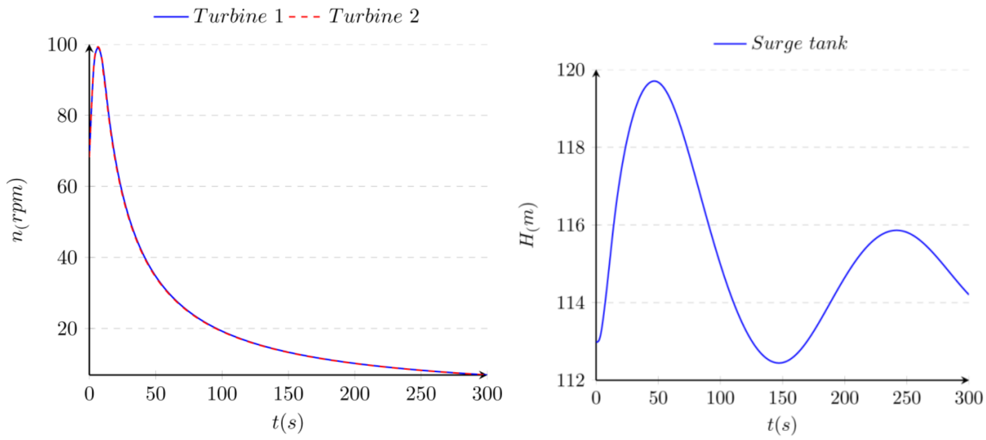

Figure 6. simulation of simultaneous emergency load rejection for two turbines, rotational speed (left) and water level in the surge tank (right)

4. Conclusions

In this paper, one-dimensional simulation software for transient flow, TOPsys, was introduced with several engineering cases. The main concern of this paper was not about the basic equations, but the application of the software in hydropower stations in China. As was discussed, the software was not only able for simulation of the traditional operation in conventional hydropower stations, but also qualified for pumped hydro units. In addition, this software can be reprogrammed to simulate the transition process of a hydropower station with complex design. In the future, complicated hydraulic systems would be constructed in China, such as cascade power stations and high-head hydropower stations with extremely long pipes. To adapt to this demand, the software would be revised and updated.

References

[1] International Energy Agency. Key world energy statistics 2016. 2016.

[2] Wylie, E. B., and Streeter, V. L., 1993, Fluid Transients in Systems, Prentice Hall, Englewood Cliffs, NJ.

[3] Nicolet C. Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems[J]. Epfl, 2007.

[4] Rezghi A, Riasi A. Sensitivity analysis of transient flow of two parallel pump-turbines operating at runaway[J]. Renewable Energy, 2016, 86:611-622.

[5] Nicolet C, Ruchonnet N, Alligné S, et al. Hydroacoustic simulation of rotor-stator interaction in resonance conditions in Francis pump-turbine[C]// Iop Conference Series: Earth & Environmental Science. OAI, 2010:793-798.

[6] Pejovic, S., Zhang, Q. F., Karney, B., and Gajic, A., 2011, "Analysis of pump-turbine "S" instability and reverse water hammer incidents in hydropower systems," In 4th International Meeting on Cavitation and Dynamic Problems in Hydraulic Machinery Systems, Belgrade, Serbia.

[7] Nicolet C, Alligne S, Bergant A, et al. Simulation of water column separation in Francis pump-turbine draft tube[C]// 2012:2002.

[8] Zuo, Z., Fan, H., Liu, S., and Wu, Y., 2016, "S-shaped characteristics on the performance curves of pump-turbines in turbine mode–A review," Renewable and Sustainable Energy Reviews, 60, pp.836-851.

[9] Suter, P., 1966, "Representation of Pump Characteristics for Calculation of Water Hammer," Sulzer Tech. Rev., 4, pp. 45-48.

[10] Yang, J. B., and Yang, J. D., 2012, "B-Spline Surface Construction for the Complete Characteristics of Pump-Turbine," IEEE 2012 Asia-Pacific Power and Energy Engineering

Conference, Shanghai, China, pp. 1–5.