Time response of frequency of the hydro-turbine governing system under the coupled action of surge tank and power grid

Z Y Peng[1], J D Yang[1], W C Guo [1,2]

[1] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, 430072, China
[2] Maha Fluid Power Research Center, Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, 47907, USA

Corresponding author's e-mail:pengzy@whu.edu.cn (Z Y Peng)

Abstract. For grid connected hydropower plants with surge tanks, the time response of frequency of the hydro-turbine governing system under the coupled action of surge tank and power grid with load disturbance have been examined. On the basis of a mathematical model of a hydro-turbine governing system operating in an isolated grid with a surge tank, a power grid model of the hydro-turbine governing system connected to a grid has been developed. Using Laplace transformation, a comprehensive transfer function, taking the disturbance of the hydro-turbine as the input signal and the speed of the hydro-turbine as the output signal, has been developed for the mathematical model. Finally, by using MATLAB-Simulink to numerically simulate the time response of frequency of the system under the coupled action of the grid at different scales and the surge tank with different sectional areas, the mechanism of the coupled action of the surge tank and the power grid and the effect of grid scale on time response of frequency of system has been analysed. It is concluded that surge tank only affects the tail wave of the time response of frequency, and for surge tanks with large sectional area, the fluctuations in the tail wave are gentler. Hence, the system is easier to become steady. The power grid has an inhibiting effect, which becomes greater for larger grid scale, on both the head wave and the tail wave of the time response of frequency in which the head wave is separated into several wavelets and the tail wave become gentler.

1. Introduction

In modern hydropower system, hydropower plant due to its flexible operation characteristics undertakes the primary task of peak and frequency modulation. In the hydropower system, the turbine regulating system is the core component of load frequency control (LFC) [1]. The hydro-turbine generating unit can operate in a grid-connected mode or in an isolated network operation mode. The former is the main operation mode while the latter is an accidental and temporary operation mode. Hence, it is of vital importance to study the time response of frequency of the hydro-turbine regulating system under the grid-connected operation mode [2-5].

Researchers have carried out a lot of work in this field [2-5]. For time response of frequency regulation quality problems, in literature [2], WEI Shou-ping had studied the theory, and carried out experiment and numerical simulation of hydropower plant without surge tank. He also analysed the governor parameter set and its influence on the time response of frequency. However, for hydropower plant with surge tank, there are less research results. Surge tank is a crucial flat pressure measure for the hydropower plant, and the unit time response of frequency is affected by the fluctuation of water level in the tank, which generates both main wave and tail wave [3]. These waves are significantly different from the one in a hydropower plant without surge tank. Using a numerical simulation method in literature [4], Zou Jin analysed the influence of different order generator model on the time response of frequency of hydraulic turbine. By using another numerical simulation method in literature [5], WEI Shou-ping analysed the influence of governor power regulation on the regulation quality under secondary frequency modulation. He also compared the differences between the hydropower and thermal power governor systems connected with grid. However, it could be found in literatures [2-5] that the models used were incomplete; some considered the influence of surge tank without a power grid while others had taken the effect of the power grid into account but without a surge tank. In both cases, they failed to consider the influence of the coupled effect of the surge tank and the power grid comprehensively.

To overcome the aforementioned deficiencies, in this study, the influence of coupled action of surge tank of different sectional areas and power grid of different scales on the time response of frequency[6] of hydro-turbine governing system have been examined by adding a grid model. Further, on the basis of a mathematical model of hydro-turbine governing system [7] operating in an isolated grid with a surge tank, whose stability was analysed [8], six groups of different parameters were set to describe six grids of different scales. In this way, a complete mathematical model of the hydro-turbine governing system, which is close to the real situation, has been developed. Then, taking the disturbance of a hydro-turbine as the input signal and the speed of a hydro-turbine as the output signal, a comprehensive transfer function has been developed using Laplace transform of the complete mathematical model. Further, the mathematical model of a diversion power system has been developed using MATLAB-Simulink to simulate numerically the time response of frequency of the system under the coupled action of the grid of different scales and the surge tank of different sectional areas. Horizontally, this study has compared the differences of the time response of frequency of the system with surge tank, connected with power grid and the system without surge tank, connected with isolated grid. The mechanism of the coupled action of surge tank and power grid was analysed. Vertically, the influence of the surge tank section area and the power grid scale on the time response of frequency of the system under coupled action of surge tank and power grid was also analysed. Finally, conclusions are drawn based on the results of the analyses.

2. Mathematical model

Fig. 1 shows a mathematical model of a complete diversion power system [9]. It consists of a hydraulic system model, a model of hydro-turbine control system [10], a governor system model [11], a generator model [12-13] and a power grid model.

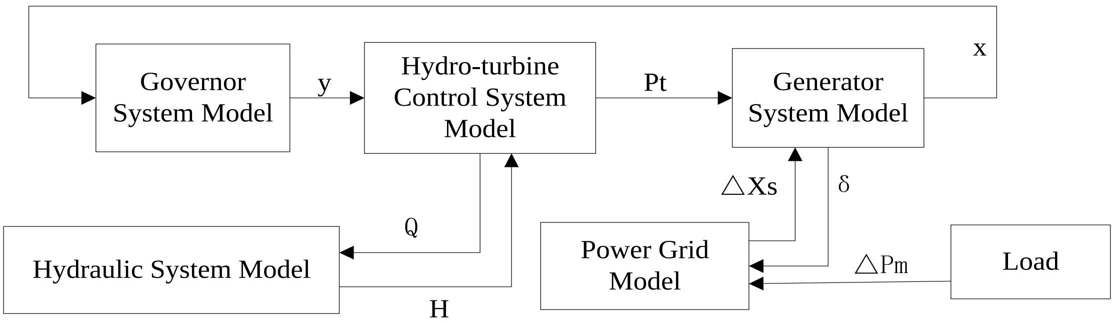


Figure 1. Model of diversion power system

2.1 Basic equations of hydraulic system model [14]

The hydraulic system simulates the relationship between work head and work flow. In this study, a rigid water hammer model is used, whose basic equations are:

Momentum equation of flow in diversion tunnel:
$$z = T_{wy}\frac{dq_y}{dt} + \frac{2h_{y0}}{H_0}q_y \tag{1}$$

Continuity equation of flow in surge tank:
$$q_y = -T_F\frac{dz}{dt} + q_t \tag{2}$$

Momentum equation of flow in pressure pipeline:
$$h = -T_{wt}\frac{dq_t}{dt} - \frac{2h_{t0}}{H_0}q_t - z \tag{3}$$

2.2 Basic equations of hydro-turbine control system model [1][6]

Moment equation：
$$m_t = e_h h + e_x x + e_y y \tag{4}$$

Discharge equation：
$$q_t = e_{qh} h + e_{qx} x + e_{qy} y \tag{5}$$

2.3 Basic equation of governor system model [1][6]

Governor usually operates in three regulation modes: (1) frequency regulation, (2) power regulation, and (3) opening regulation. This study examined the frequency regulation mode only, without considering factors such as characteristics of dead zone and saturation in the electro-hydraulic servo system. Assuming that the governor system is a linear element, the basic equation is:

$$b_t T_d\frac{dy}{dt} = -(x + T_d\frac{dx}{dt}) \tag{6}$$

2.4 Basic equations of generator model

In this study, the first order model of a generator is used and the basic equation [6] is:

$$T_a\frac{dx}{dt} = m_t - (m_g + e_g x) \tag{7}$$

In which, m_g can be expressed as follows [6]:

$$m_g = K_a\int xdt + D_a x + \Delta P_{em} \tag{8}$$

2.5 Power grid model

In this study, the power grid has been substituted by an equivalent generator unit [15][16], as shown in Fig. 2.

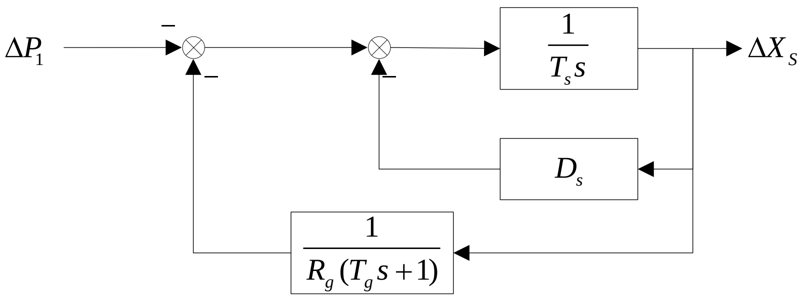


Figure 2. Block diagram of power grid model

In Fig. 2, T_s includes the rotation inertia effect of all the units in the grid, whose value has accounted for the grid scale. D_s account for the damping characteristics about the grid load and frequency and determine the corresponding power change for a certain degree of frequency deviation. Usually, it is difficult to measure D_s accurately. However, it has a positive correlation with the scale of the grid [17]. Furthermore, $\frac{1}{R_g(T_g s+1)}$ denotes the equivalent speed regulating system of the grid, accounting for the dynamic characteristics of the speed regulating system of all the units in the grid. R_g is determined by e_{pi} of all the units in the grid jointly, satisfying the relation $R_g = \frac{1}{\sum_i e_{pi}}$. Due to the difference between the rated power base value of the generator and that of the grid system, it is necessary to use B to link them.

2.6 Overall model of system
Fig. 3 shows a block diagram of the system model.

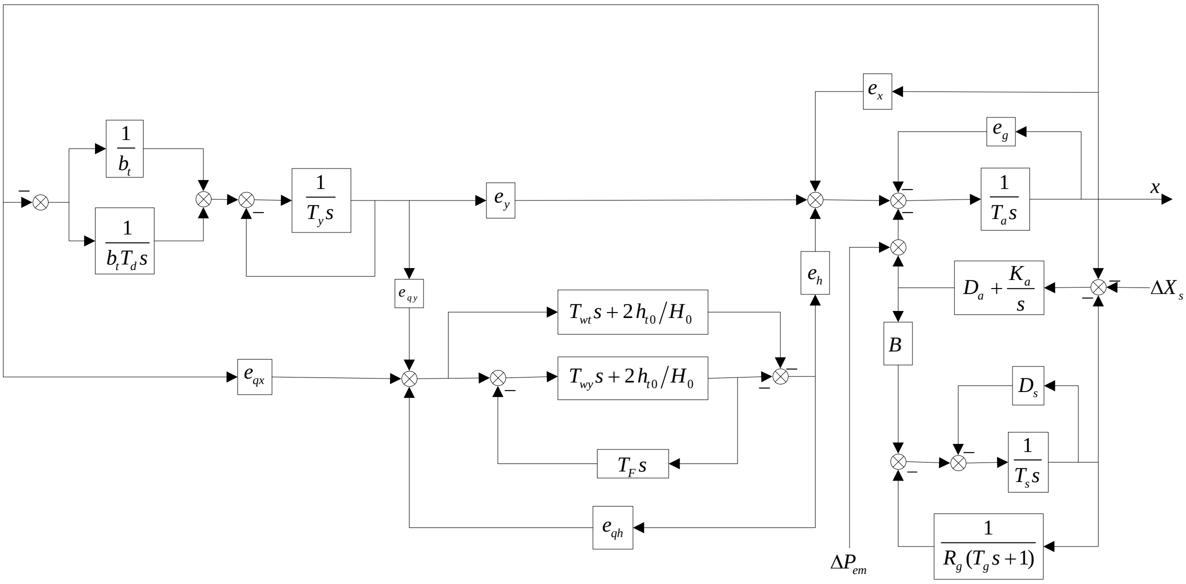
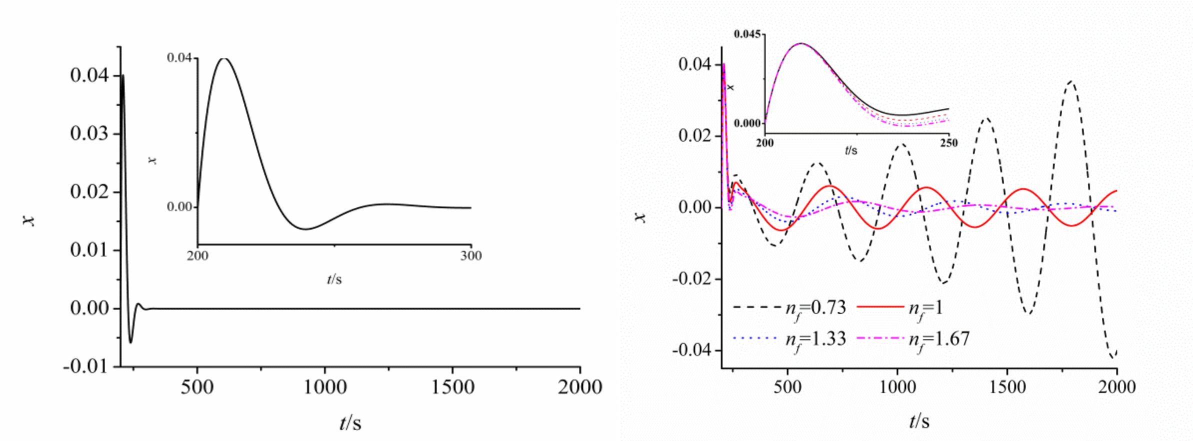


Figure 3. Block diagram of system model

3. The time response of frequency of system under the coupled action of surge tank and power grid

In this study, a relatively complete model of the diversion power system has been developed by using MATLAB-Simulink. Combining this model with the models of hydraulic system, generator and power grid, in which the hydraulic system uses the rigid water hammer model; the hydro-turbine uses the ideal model; and the generator uses the first order model. In this study, by setting the basic parameter as follows: e_h=1.5, e_x=-1, e_y=1, e_{qh}=0.5, e_{qx}=0, e_{qy}=1,b_t=0.5,T_d=10s,T_a=10s,e_g=1,e_n=0.2, T_{wt}=2.33s, T_{wy}=2.33s, T_{wy}=23.84s, T_y=10s, h_{t0}=5.53, h_{y0}=7.57, H_0=89m, the time response of frequency of the system under single action of surge tank and coupled action of the surge tank and the power grid have been analysed.

3.1 Time response of frequency of system under single action of surge tank
Under step load disturbance m_{g0}=-0.1, n_f are 0.73, 1, 1.33, and 1.67 for the time response of frequency, showed in Fig.4, of both systems, in isolated grid, without surge tank and with surge tank separately.



(a) without surge tank (b) with surge tank

Figure 4. Time response of frequency of systems under single action of surge tank

Based on Fig. 4, under the step load disturbance, the transient characteristic of the system without surge tank rise rapidly and then decays rapidly, forming a head wave. On the other hand, for the system with surge tank, it also forms a head wave but there is also a tail wave of low frequency, which is due to the presence of the surge tank. Further, n_f has no effect on the head wave, but has enormous impact on the tail wave. The bigger the n_f, the more gentle are the tail wave fluctuates, and easier for the system to become steady. The converse is true for smaller n_f.

3.2 The time response of frequency of system under coupling action of surge tank and power grid

3.2.1 Establishment and analysis of space state equation of power grid model

In the power grid model, the disturbance of unit frequency x and the load M_{g0} are taken as the input signal. $\triangle P_{em}$ and $\triangle X_s$ are taken as the output signal. Further, Fig. 5 shows the spatial state parameters X_1, X_2, X_3.

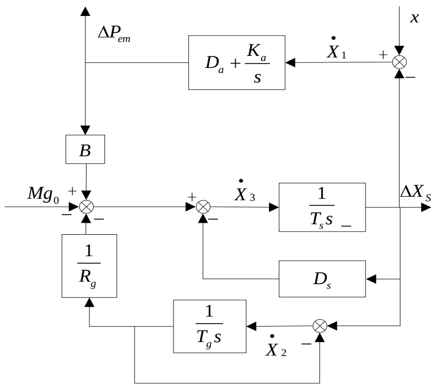


Figure 5. Schematic diagram of spatial state parameters of power grid model

The space state equations of the power grid model are:

$$\begin{cases} \begin{pmatrix} \dot{X}_1 \\ \dot{X}_2 \\ \dot{X}_3 \end{pmatrix} = \begin{bmatrix} 0 & 0 & -\frac{1}{T_s} \\ 0 & -\frac{1}{T_g} & \frac{1}{T_s} \\ BK_a & -\frac{1}{R_g T_g} & -\frac{D_a B + D_s}{T_s} \end{bmatrix} \begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} + \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ D_a B & -1 & 0 \end{bmatrix} \begin{pmatrix} x \\ Mg_0 \\ 0 \end{pmatrix} & (9) \\ \begin{pmatrix} \Delta P_{em} \\ \Delta X_s \end{pmatrix} = \begin{bmatrix} K_a & 0 & -\frac{D_a}{T_s} \\ 0 & 0 & \frac{1}{T_s} \end{bmatrix} \begin{pmatrix} X_1 \\ X_2 \\ X_3 \end{pmatrix} + \begin{bmatrix} D_a & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{pmatrix} x \\ Mg_0 \\ 0 \end{pmatrix} & (10) \end{cases}$$

The system matrix is denoted as A and it accounts for the characteristics of the system [18]:

$$A = \begin{bmatrix} 0 & 0 & -\frac{1}{T_s} \\ 0 & -\frac{1}{T_g} & \frac{1}{T_s} \\ BK_a & -\frac{1}{R_g T_g} & -\frac{D_a B + D_s}{T_s} \end{bmatrix} \quad (11)$$

Without pole zero cancellation in the transfer function of the grid system model, the state stability is consistent with the output stability. So, the characteristics equation of matrix A is the characteristics equation of the system and the characteristics root of the system matrix A is the pole of the system transfer function. According to equation $|A-\lambda I|=0$, the characteristics equation of the transfer function of grid system model is:

$$T_s R_g T_g \lambda^3 + (R_g T_g D_a B + R_g T_g D_s + R_g T_s)\lambda^2 + (R_g D_s + BK_a R_g T_g + R_g D_a B + 1)\lambda + BK_a R_g = 0 \quad (12)$$

Further, as $T_s R_g T_g > 0$, $R_g T_g D_a B + R_g T_g D_s + R_g T_s > 0$, $R_g D_s + BK_a R_g T_g + R_g D_a B + 1 > 0$, $BK_a R_g > 0$, and $-\frac{1}{R_g T_g D_a B + R_g T_g D_s + R_g T_s}\begin{vmatrix} T_s R_g T_g & R_g D_s + BK_a R_g T_g + R_g D_a B + 1 \\ R_g T_g D_a B + R_g T_g D_s + R_g T_s & BK_a R_g \end{vmatrix} > 0$, the grid system model is steady according to the Routh criterion.

In this study, six power grids of different scales have been examined: (1) small grid, (2) medium grid Ⅰ, (3) medium grid Ⅱ, (4) large grid Ⅰ, (5) large grid Ⅱ, (6) infinite grid. Table 1 shows their basic parameters:

Table 1. Values of grid parameters at six different scales

	B	Ts	Ds	Rg	Tg
small grid	1	8	0.1	1	8
medium grid Ⅰ	0.2	20	0.2	0.3	20
medium grid Ⅱ	0.1	40	0.4	0.2	40
large grid Ⅰ	0.01	400	4	0.1	400
large grid Ⅱ	0.001	4000	40	0.02	4000
infinite grid	$\varepsilon \to 0^+$	∞	1000	$\varepsilon \to 0^+$	∞

In order to simplify the model, equating D_a=0.073. Further, Table 2 shows the poles of transfer function of the grid model at six different scales.

Table 2. Poles of transfer function of grid model at six different scales

	λ_1	λ_2	λ_3
small grid	-0.014338+0.51453i	-0.014338-0.51453i	-0.11795
medium grid I	-0.012493+0.1668i	-0.012493-0.1668i	-0.035744
medium grid II	-0.0098509 +0.089317i	-0.0098509 -0.089317i	-0.015481
large grid I	-0.0057553+0.0096421i	-0.0057553-0.0096421i	-0.00099132
large grid II	-0.0000212	-0.00061456	-0.0096143
infinite grid	$-\varepsilon \to 0^-$	$-\varepsilon \to 0^-$	$-\varepsilon \to 0^-$

It is apparent all the poles of transfer function of the grid model system at different scales have negative real part, which indicates that the grid model system developed in this study is stable. With larger grid scale, both the absolute value of imaginary part and real part become smaller. In fact, the absolute value of the imaginary part becomes smaller faster than the real part. This means that for power grids of larger scale, the oscillation period of the time response of frequency becomes longer. In fact, for grids larger than Grid II, the oscillations under the external disturbance were extremely slow. It could even be considered to have achieved a new stable state after a certain period of time.

Figs. 6 show the fluctuation of $\triangle P_{em}$ of the grid model system at different scales under the load disturbance M_{g0}=-0.1.

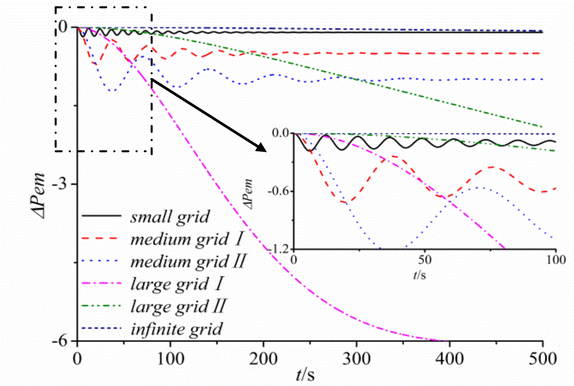


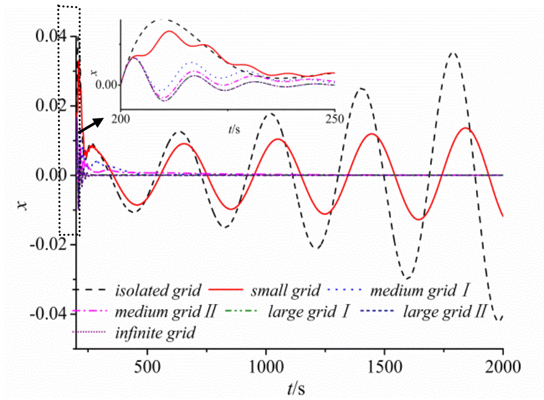
Figure 6. Fluctuation of $\triangle P_{em}$ of grid model system under load disturbance

In view of the preceding results, the grid model can simulate the performance of real-life power grid system. For power grids of larger scale, the greater the grid system inertia, the more robust is the system. Moreover, the electromagnetic effect of the load disturbance on the generator set is amplified by the power grid. For larger grids, the amplification effect is more significant.

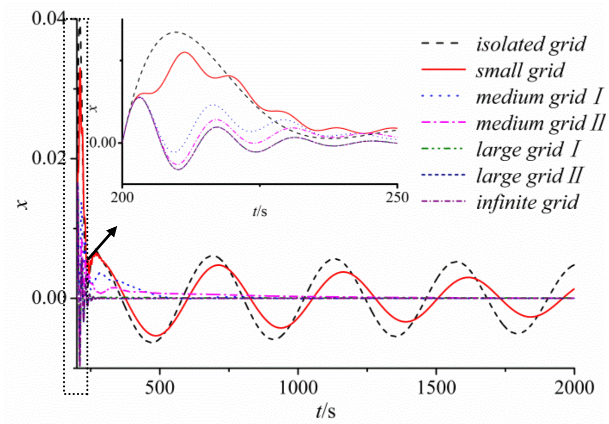
3.2.2 The time response of frequency of system under the coupled action of power grid and surge tank

The influences of the coupled action of the surge tank and the power grid on the time response of frequency of system have been analysed. It has been carried out under the disturbance of $\triangle P_{em}$ =-0.1 with different n_f for four groups of time response of frequency when the system was connected to the power grid of different scales and one isolated grid.

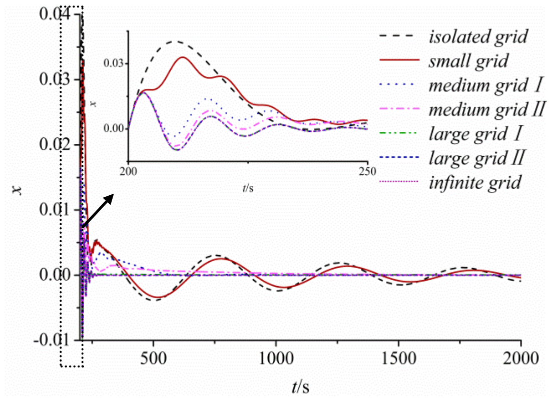
Fig. 7 shows the time response of frequency of the system under the coupled action of the surge tank and the power grid.



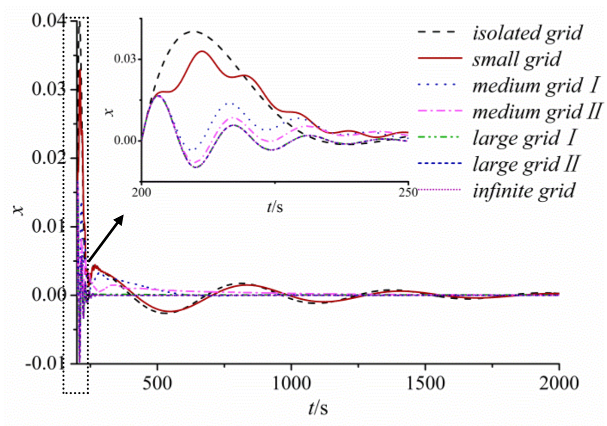
(a) n_f =0.73



(b) n_f =1



(c) n_f =1.33



(d) n_f =1.67

Figure 7. Time response of frequency of system under the coupled action of surge tank and power grid

It is apparent that the surge tank affects the tail wave only, while the power grid has a significant effect on both the head wave and the tail wave. The head wave is affected by the grid generating high frequency harmonics, and disperses into several wavelets, whose peak gradually decreases with increasing grid scale. While the tail wave is suppressed by the grid: under action of the small grid, the tail wave is similar to the one under the action of the isolated grid but it is easier for the former to become steady, which is consistent with the practical case. The time response of frequency of the system under the action of the small grid is quite close to those in the isolated grid when n_f exceeds a certain value. Under this condition, the isolated grid can be simulated by the small grid: tail wave almost disappears when the grid scale increases to medium or large scale. This shows that the influence of surge tank on the tail wave almost disappears when the system is connected to a large grid. Further, for the grid is close to the infinite grid, after a quick oscillation, the time responses of frequency almost remain constant. This shows that it is acceptable to assume the speed of the generator connected to the infinite power grid is almost constant.

4. Conclusions

1) The time response of frequency of hydro-turbine regulation system consists of the head wave and the tail wave, and the surge tank affects the tail wave only. The bigger the n_f, there are less fluctuations in the tail wave. As such, it is easier for the system to become steady.
2) The grid model developed in this study can simulate a real-life power grid system. For power grids of larger scale, the grid system inertia is greater, the system becomes more robust. Moreover, the electromagnetic effect of the load disturbance on the generator set is amplified by the power grid. For larger grids, the amplification effect is more significant.

3) The power grid has a significant effect on both the head wave and the tail wave. The head wave is affected by the grid dispersing into several wavelets, whose peak gradually decreases with increasing grid scale. While the tail wave is suppressed by the grid, when n_f exceeds a certain value, the isolated grid can be simulated by a small grid. The influence of the surge tank on the tail wave almost disappears when system is connected to a large grid.

Acknowledgements
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Nomenclature

b_t:	Transient transfer coefficient	n:	Speed of hydro-turbine
B:	Power conversion factor	n_f:	Section amplification coefficients of surge tank, and $n_f = F/F_{th}$
D_a:	Equivalent damping coefficient	$\triangle P_{em}$:	Electromagnetic power variation
D_s:	Self-regulating coefficient of the equivalent load of a power grid	$\triangle P_l$:	Power disturbance of the grid
e_g:	Load self-regulation coefficient	Q_y, Q_t:	Diversion tunnel flow, pressure pipe flow
e_y,e_x,e_h:	Moment transfer coefficients of turbine	R_g:	Equivalent permanent difference coefficient of the grid
e_{qy},e_{qx}, e_{qh}:	Discharge transfer coefficients of turbine	T_F:	Time constant of surge tank, and $T_F = FH_0/Q_0$
e_{pi}:	Permanent difference coefficient of all the units in the grid	T_{wt}, h_{t0}:	Flow inertia time constant of pressure pipe and its head loss, and $T_{wt} = L_t Q_0 / g f_t H_0$
E:	Generator potential	T_{wy},h_{y0}:	Flow inertia time constant of diversion tunnel and its head loss, and $T_{wy} = L_y Q_0 / g f_y H_0$
F:	Actual sectional area of surge tank	T_a:	Unit inertia time constant
F_{th}:	The critical stable sectional area of surge tank	T_s:	Inertia time constant of the grid equivalent unit
f_t,f_y:	Sectional area of pressure pipe, diversion tunnel	T_g:	Inertia time constant of the servomotor of grid equivalent
H:	Work head of unit	$\triangle X_s$:	Frequency fluctuation of unit
K_a:	Equivalent synchronization coefficient	Y :	Gate opening
L_t, L_y:	Length of pressure pipe, diversion tunnel	z, h, q_y, q_t, m_t, x, y:	Deviation relative value of $Z, H, Q_y, Q_t, M_t, n, Y$
m_e:	Electromagnetic torque	Z:	Change of surge tank water level (positive direction is downward)
M_t:	Torque of hydro-turbine		

References

[1] CHENG Y C, ZHANG J B 2009 *Automatic Regulation of Hydro-turbine* (Beijing:China Water&Power Press)
[2] WEI S P 2009 Analysis and Simulation on the Primary Frequency Regulation and Isolated Grid Operation Characteristics of Hydraulic Turbine Regulating Systems J. *Hydropower Automation and Dam Monitoring* **33(6)** 27-33(in Chinese)
[3] Zhao G L, Yang J D, Yang A L 2007 The influence of electric transient process on speed

regulation quality J. *Journal of Hydroelectric Engineering* **01** 135-138(in Chinese)
[4] Zou J, Lai X, Zong X 2013 Effects of generator electromagnetic processes on transient process of hydropower station with islanoled load J. *Engineering Journal of Wuhan University* **46(1)** 109-112, 116(in Chinese)
[5] WEI S P, WU Y G, LIN J H 2006 Hydro-turbine Governor and Grid Load Frequency Control Part Two Simulation of Grid Load Frequency Control J. *Hydropower Automation and Dam Mnitoring* **01** 18-22(in Chinese)
[6] WEI S P 2009 *Regulation of Hydro-turbine* (Wuhan:Huazhong University of science and technology Press)
[7] Guo W C, Yang J D, Yang W J, Chen J P, Teng Y 2015 Regulation quality for time response of frequency of turbine regulating system of isolated hydroelectric power plant with surge tank J. *International Journal of Electrical Power and Energy Systems* **73** 528-538
[8] Guo W C, Yang J D, Chen J P, Teng Y 2014 Study on the Stability of Waterpower-speed Control System for Hydropower Station with Air Cushion Surge Chamber *27th IAHR Symposium on Hydraulic Machinery and Systems* (Montreal, Quebec, Canada, 22-26 September)
[9] LIU Q Z, HU M, MA J M 2008 *Hydropower Station* (Beijing: China Water&Power Press)
[10] ZHEN Y, CHEN D X 2009 *Hydraulic Turbine* (Beijing: China Water&Power Press)
[11] Jing L, Ye L Q, O.P. Malik, Zeng Y 1998 An Intelligent Discontinuous Control Strategy for Hydroelectric Generating Unit *IEEE Transactions on Energy Conversion vol.* 13 No.1 pp 84-89 March
[12] Wozniak L 1975 Load Level Tuning of Governor Gains for Suboptimal Speed Control of Hydroelectric Installations J *Journal of Fluids Engineering* **97(1)** 67-70.
[13] Vilanova R, Visioli A 2012 *PID control in the third millennium* (London: Springer)
[14] LIU Q Z, Peng S Z 1993 *Surge Tank of Hydropower Station* (Beijing:Water Resources and Electric Power Press)
[15] Thorne D.H, Hill E.F 1975 Extensions of stability boundaries of a hydraulic turbine generating unit *Power Apparatus and Systems, IEEE Transactions on* **94(4)** 1401-1409
[16] Phi D.T, Bourque E.J, Thorne D.H, et al. 1981 Analysis and application of the stability limits of a hydro-generating unit *IEEE Transactions on Power Apparatus and Systems* **7** 3203-3212
[17] Inoue T, Taniguchi H, Ikeguchi Y, et al. 1997 Estimation of power system inertia constant and capacity of spinning-reserve support generators using measured frequency transients *IEEE Transactions on Power Systems* **12(1)** 136-143
[18] Katsuhiko Ogata 2003 *Morden Control Engineering(Fifth Edition)* (Beijing:Pearson Education North Asia Limited, Publishing House of Electronics Insdustry)