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Sensitivity of Transient Phenomena Analysis of the Francis Turbine Power Plants

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ABSTRACT
The accurate definition of the transient phenomena of the hydroelectric power plant (HPP) and its units, taking into account various aspects of operation is an essential requirement for design, performances and control of HPPs. Numerical analysis of transient phenomena, such as increase of the rotational speed (runaway) of the units, increase of the pressure (turbine inlet head) in the hydraulic system (water hammer) and water level oscillation in the surge tank is presented. The results of transient phenomena analyses are relied upon for very costly engineering decisions. Because of this, it is important that the researcher understands the effect unknown modeling parameters on the result of transient analysis. Usually, different researchers may choose alternate values for an unknown modeling parameter and this can have significant effects on the results. The main aim in this paper is to investigate of the sensitivity of transient phenomena analysis with variation in modeling parameters such as pipeline friction factor, wave speed, turbine guide vanes closing law, surge tank throttling coefficient and generator inertia.

Keywords - Hydropower plant, transient phenomena, water hammer, runaway, sensitivity.

I. INTRODUCTION

Study the dynamic behavior of a hydropower plant (HPP) is a necessary prerequisite for ensuring safety and defining the transient phenomena such as increase of the rotational speed (runaway) of the units, increase of the pressure (head) in the hydraulic system (water hammer) and water level oscillation in the surge tank. Transient phenomena in HPP occurs during unit shutdown or startup, switching from one operation regime of HPP to another, load rejection, emergency shutdown, out of phase of synchronization etc.

The accurate definition of the transient phenomena of the HPP and its units, taking into account various aspects of operation is an essential requirement for the design, performances and control of HPP. The numerical results of transient phenomena analyses are relied upon for very costly engineering decisions. Because of this, it is important that the researcher understands the effect unknown modeling parameters on the result of transient analysis. Usually, different researchers may choose alternate values for an unknown modeling parameter and this can have significant effects on the results.

II. CASE STUDY

The case study of the HPP operation presented here investigates two units with vertical Francis turbines each with rated capacity of 40 MW and flow rate of 50 m3/s. A complete model of the hydropower plant with all corresponding elements is shown in Figure 1.

The HPP consists of the following hydraulic components: upstream reservoir (accumulation), gallery, surge tank, penstock(pipeline), valve, Francis turbine(s) and downstream reservoir (tailrace). Technical characteristics of the hydropower plant are given in Table 1.

The sensitivity of transient phenomena for emergency shutdown scenario of two unit(simultaneously) was investigated by variation in the following modeling parameters:

- ♣ pipeline friction factor,
- ♣ wave speed,
- ♣ surge tank throttling coefficient,
- ♣ turbine guide vanes closing law and
- ♣ generator inertia.

These parameters used in sensitivity transient analyses are often the subject of estimates or assumption based on the available designs, and thus are likely to contribute to a high portion of the error in the analysis. . Parameters such as pipe length and diameter, acceleration due to gravity and the density of water would also likely, have an impact on the transient analysis if they were to vary, but these are well known and nearly constant parameters. The limit of the sensitivity analysis was based on the maximum and minimum likely value for each modeling parameter. This parameters for different transient simulation scenarios (B,C,D,E,F) are presented in Table 2. The software package WHAMO is used for all numerical computations.

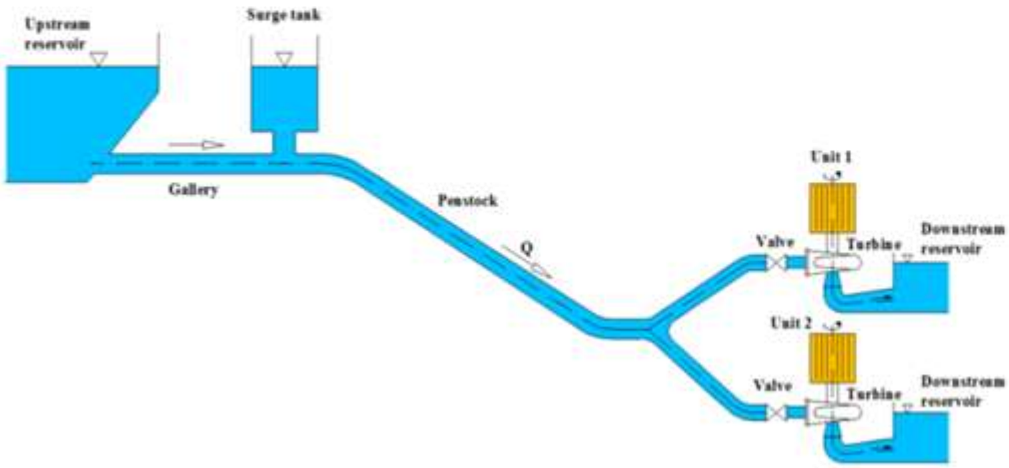

Fig.1 Layout of the hydropower plant with Francis turbines

Table 1 Characteristics of HPP (rated values)

Upstream reservoir	**Gallery**	**Surge tank**	**Penstock**	**Turbine**	**Generator**
H_{max}=109 [m]	L=98 [m] D=5.0 [m] λ=0.02 a=1050 [m/s]	A_S =19.60 [m^2] A_t =8.44 [m^2] H_{max}=40 [m]	L =220 [m] D=5.0/3.12 [m] λ=0.02 a=1020 [m/s]	H_0=92 [m] n_0=300 [min^{-1}] Q_0=50 [m^3/s] P_0=40 [MW] J_T = 30 [tm^2]	J_G=1500 tm^2

Table 2 Values of modeling parameters for different scenarios

	Scenario						
	B		**C**	**D**	**E**	**F**	
	$\mathbf{a}_{(gallery)}$ [m/s]	$\mathbf{a}_{(penstock)}$ [m/s]	**J** [tm^2]	**gv** [s]	$\mathbf{A}_{st}$ [m^2]	$\lambda_{(gallery)}$ [-]	$\lambda_{(penstock)}$ [-]
1 (min)	1245	1323	1200	6	2.6	0.005	0.0045
2 (max)	1481	1481	1800	8	14.2	0.025	0.02
3	/	/	/	14	/	/	/
Base case (scenario A)	1317	1410	1500	12.5	8.44	0.015	0.012

III. VALIDATION OF THE NUMERICAL MODEL

The The numerical modeling and results from simulation of the transient phenomena for emergency shutdown(simultaneously) of two Francis turbine for scenario A (base case) is shown in Fig.2 an Fig.3-left.

The guide vanes closing law (12.5 seconds linearly) after emergency shutdown is shown in Fig.3-right. The time step of iterations (Δt=0.001 [s]) is determined according Lewy-Courant criteria [1].

The reliability of the numerical computation is confirmed by verification using experimental data [2] obtained with field measurements. The comparison of the results is presented in Table 3. By comparing the results can be concluded that the maximum amplitudes of the pressure (water hammer) and maximum increase of the turbine rotational speed (runaway) in a very good agreement (the error is 1%).

Table 3 The comparison of the results

	Measurements		**Simulation**		**Error**	
	$\mathbf{n_{max}}$ **[min^{-1}]**	$\mathbf{H_{max}}$ **[m]**	$\mathbf{n_{max}}$ **[min^{-1}]**	$\mathbf{H_{max}}$ **[m]**	$\mathbf{n_{max}}$ **[%]**	$\mathbf{H_{max}}$ **[%]**
Base case A	427.5	145.1	430.9	146.7	0.79	1.1

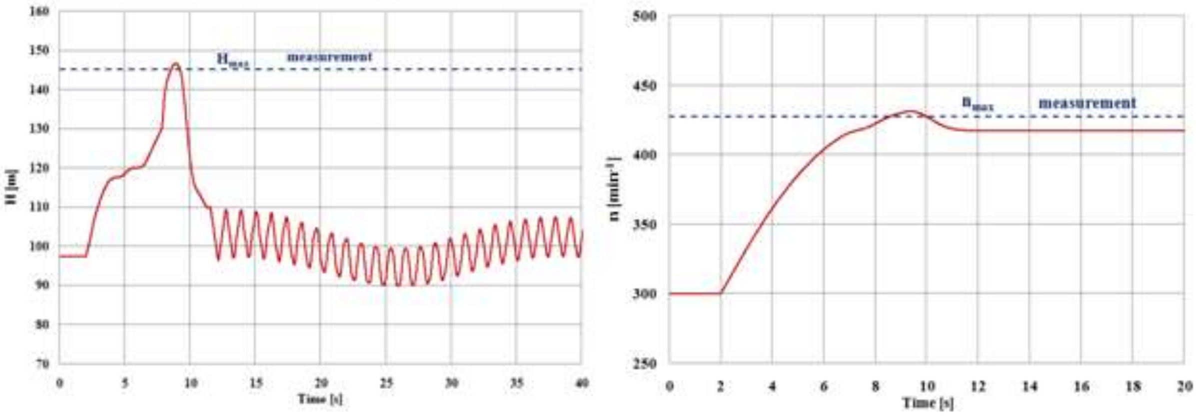

Fig. 2 Results of the simulation for scenario A (base case)

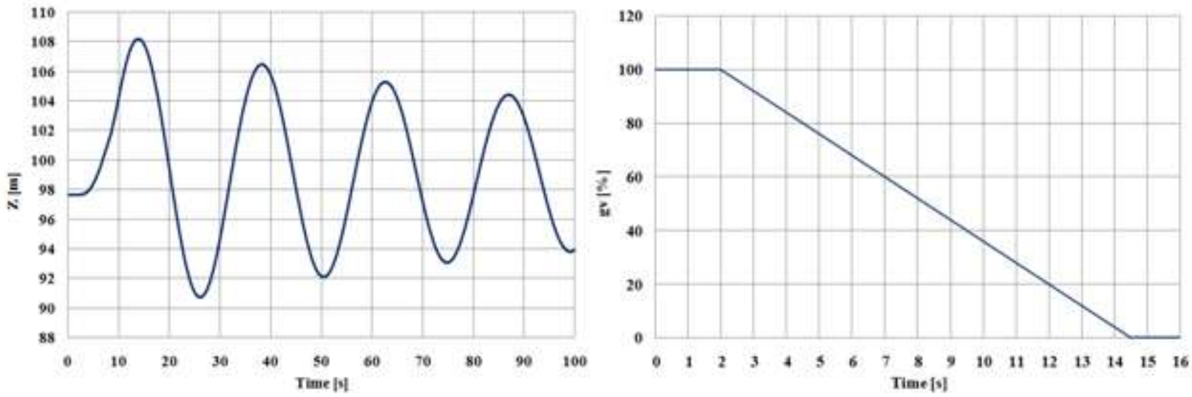

Fig. 3 Results of the simulation for scenario A (base case)

IV. VALIDATION OF THE NUMERICAL MODEL

After validation of the numerical model, the following transient computation scenarios for emergency shutdown of hydroelectric power plant are analyzed (Table 2):

- Scenario B: variation o the wave speed
- Scenario C: variation of the generator inertia
- Scenario D: variation of the turbine guide vanes closing law
- Scenario E: variation of the surge tank throttling coefficient
- Scenario F: variation of the pipeline friction factor

The wave speed for base case A is calculated according to following equation:

$$a^2 = \frac{K/\rho}{1+\left[\left(\frac{K}{E}\right)\left(\frac{D}{\delta}\right)\right]c_1}$$

In this equation K represents bulk modulus of elasticity of the liquid in the pipe, ρ is density of the fluid, E is young's modulus of material that pipes are made of, δ is pipe equivalent wall thickness, c_1 is a coefficient that takes in consideration the type of the pipeline stiffening i.e., [3]:

Case 1: For pipeline that is stiffened on one end only, $c_1 = 1\text{-}\mu/2$
Case 2: For pipeline that is stiffened on two ends; $c_1 = 1\text{-}\mu^2$
Case 3: For pipeline that is not stiffened $c_1 = 1$

In c_1 expressions, μ represents Poison's ratio that depends on material that pipes are made of.

The maximum wave speed is calculated by equation (1), which is the wave speed in a perfectly rigid pipeline (bulk modulus of water assumed 2.15 GPa). The lower limit for the wave speed is based on a 10% reduction of the bulk fluid modulus (due to reduced water temperature and/or air entrainment), and a 50% reduction in the gallery rigidity (representing an underestimation of the elasticity of the surrounding rock).

The upper and lower limits for generator inertia are based on a 20% increase and reduction in the inertia, corresponding to incorrect estimation of the generator inertia in the early stages of a project.

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The turbine guide vanes closing law is defining for different case of linearly closing time (fast and slowly). The inlet head loss in the surge tank are based on throttling of the surge tank through variation of cross section area in the junction or throttling coefficient k_t. The variation of the friction factor are based on the range of roughness values for concrete (gallery) and steel (penstock).

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V. RESULTS FROM SENSITIVITY ANALYSIS

Sensitivity was analysis by investigating the output turbine conditions (transient phenomena) for each case study (water hammer (turbine inlet head), unit rotational speed and oscillation (head) in the surge tank) in comparison to results obtained for the base case A. For the case study with scenario A,B,C,E,F the turbine guide vanes closing law is 12.5 seconds linearly (Fig.3-right) after emergency shutdown (simultaneously) of the turbine, while scenario D (Table.2) have a different time(linearly) of closing law.

5.1 Variation of the Wave Speed (scenario B)

The sensitivity of transient phenomena with variation of the wave speed is shown in Fig.4 and Fig.5.

The turbine inlet head(water hammer) are shown in Fig.4, while Fig.5 shows the turbine rotational speed. The water level oscillation in the surge tank is shown in Fig.6.

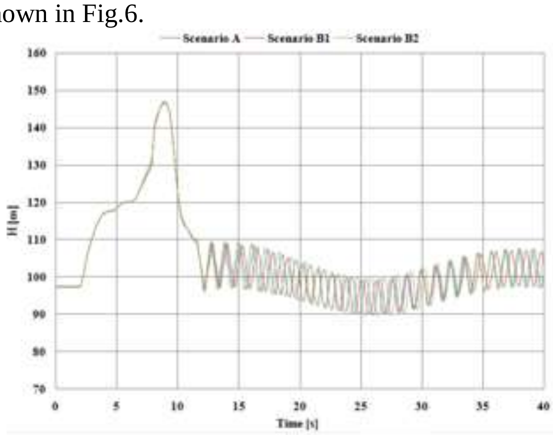

Fig. 4 Results for turbine inlet head (scenario B)

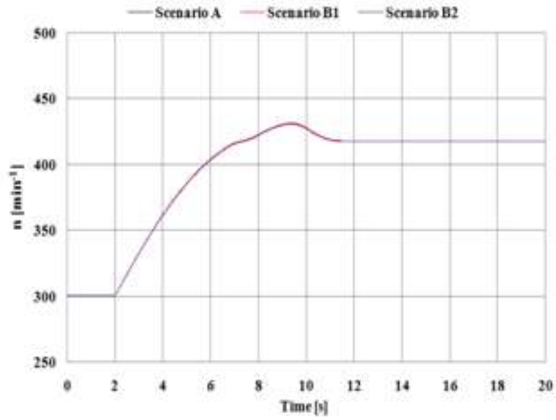

Fig. 5 Results for rotational speed (scenario B)

5.2 Variation of the Generator Inertia (Scenario C)

The sensitivity of transient phenomena with variation of the generator inertia is shown in Fig.7, Fig 8 and Fig.9. The turbine inlet head(water hammer) are shown in Fig.7, while Fig.8 shows the turbine rotational speed. The water level oscillation in the surge tank is shown in Fig.9.

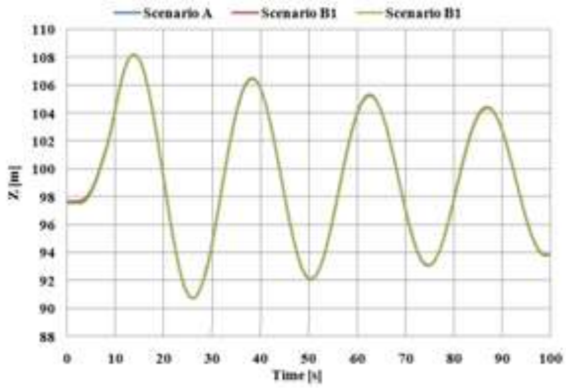

Fig. 6 Results for water level oscillation in the surge tank (scenario B)

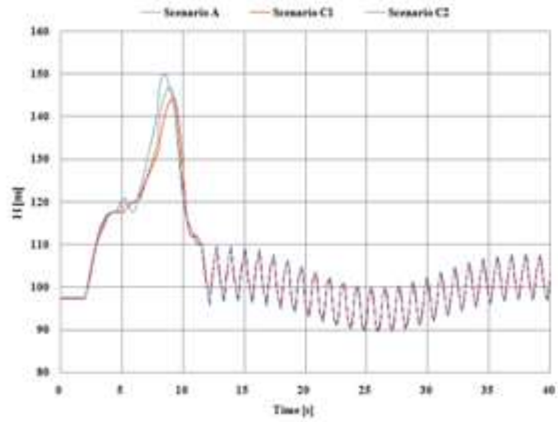

Fig. 7 Results for turbine inlet head (scenario C)

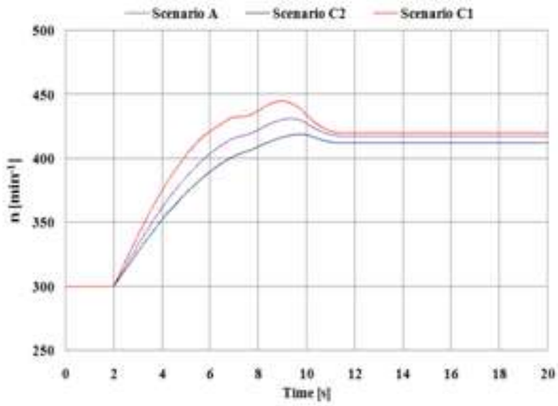

Fig. 8 Results for rotational speed (scenario C)

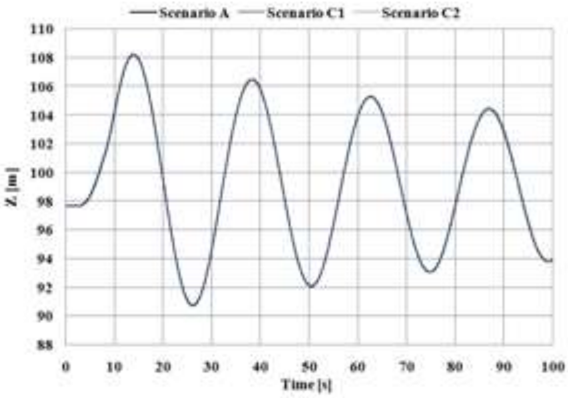

Fig. 9 Results for water level oscillation in the surge tank (scenario C)

5.3 Variation of the Turbine Guide Vanes Closing Law (Scenario D)

The sensitivity of transient phenomena with variation of the turbine guide vanes closing law is shown in Fig.10 to Fig. 13. The turbine inlet head (water hammer) are shown in Fig.10, while Fig.11 shows the turbine rotational speed. The water level oscillation in the surge tank is shown in Fig.12 and Fig.13 shows the turbine guide vanes closing law (gv [%]).

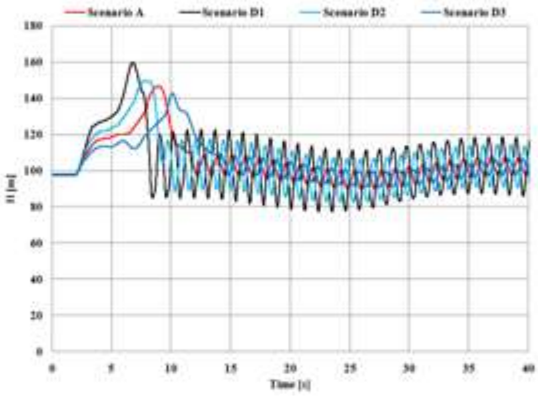

Fig. 10 Results for turbine inlet head (scenario D)

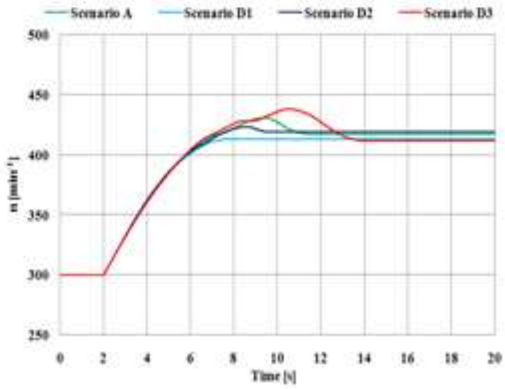

Fig. 11. Results for rotational speed (scenario D)

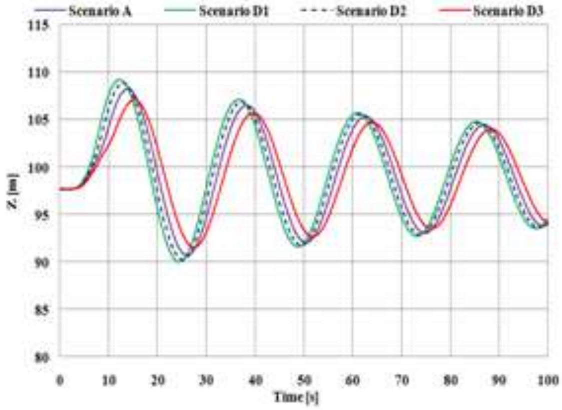

Fig. 12 Results for water level oscillation in the surge tank (scenario D)

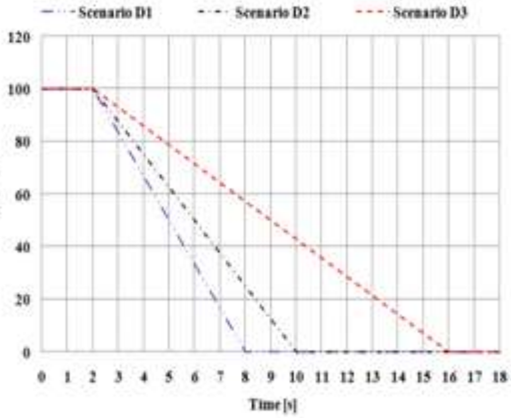

Fig. 13 Turbine guide vanes closing law

5.4 Variation of the Surge Tank Throttling Coefficient (Scenario E)

The sensitivity of transient phenomena with variation of the surge tank throttling coefficient is shown in Fig.14, Fig. 15 and Fig.11. The turbine inlet head are shown in Fig.14, while Fig.15 shows the turbine rotational speed. The water level oscillation in the surge tank is shown in Fig.16.

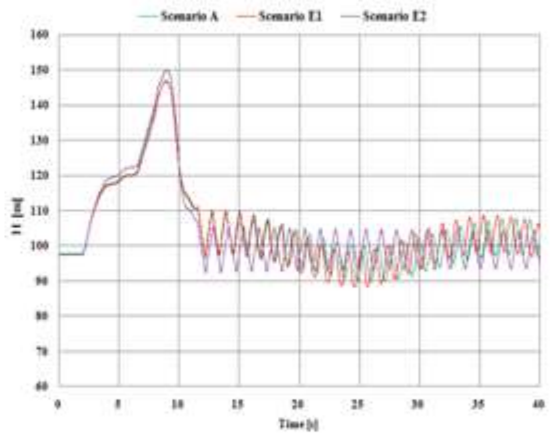

Fig. 14. Results for turbine inlet head (scenario E)

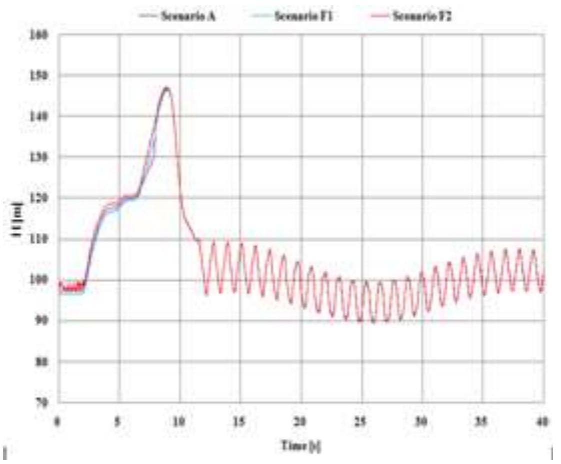

Fig. 17. Results for turbine inlet head (scenario F)

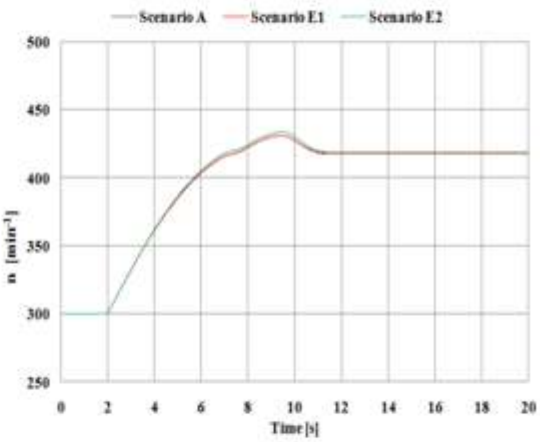

Fig. 15 Results for rotational speed (scenario E)

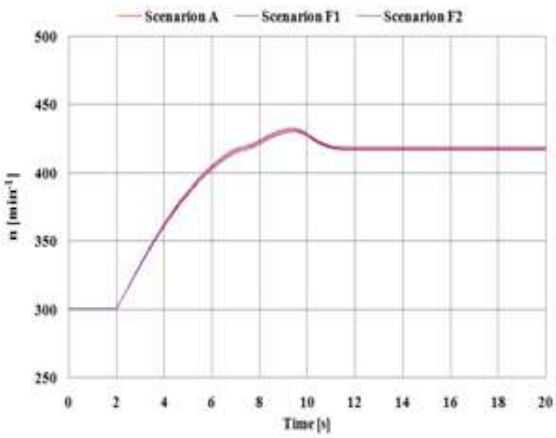

Fig. 18 Results for rotational speed (scenario F)

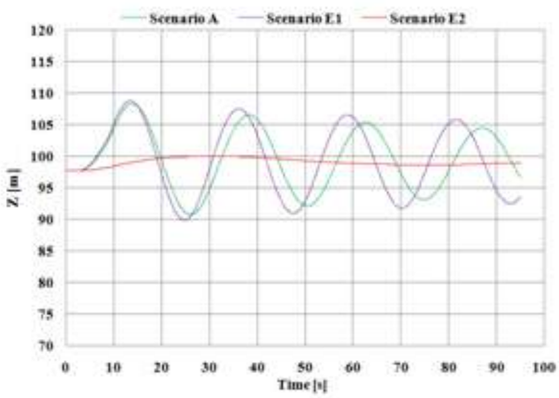

Fig. 16 Results for water level oscillation in the surge tank (scenario E)

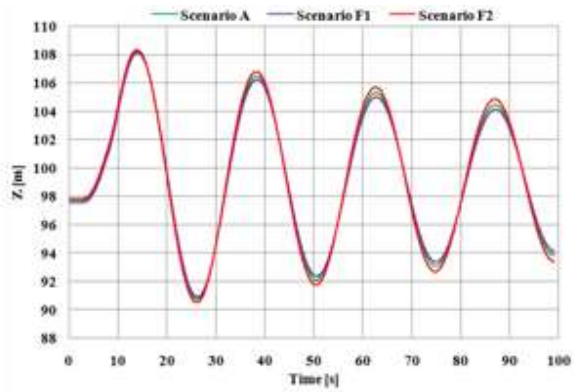

Fig. 19 Results for water level oscillation in the surge tank (scenario F)

5.5 Variation of the Pipeline Friction Factor (Scenario F)

The sensitivity of transient phenomena with variation of the pipeline friction factor is shown in Fig.17, Fig. 18 and Fig.19. The turbine inlet head(water hammer) are shown in Fig.17, while Fig.18 shows the turbine rotational speed. The water level oscillation in the surge tank is shown in Fig.19.

5.6 Summary, Comparison and Explanation of the Results

The variation of the turbine rotational speed for each modeling parameters (different scenarios) is shown in Fig. 20, while Fig. 21 shows the variation of the maximum turbine inlet head.

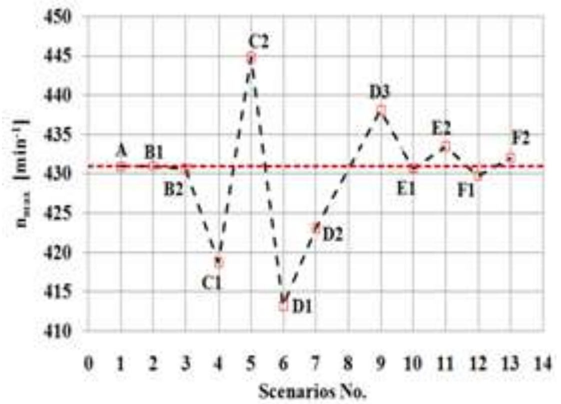

Fig. 20 Results for rotational speed

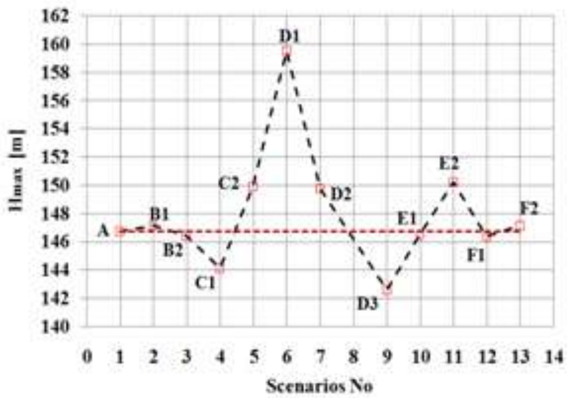

Fig. 21 Results for maximum turbine inlet head

The variation of the minimum turbine inlet head turbine for each modeling parameters (different scenarios) is shown in Fig. 22, while Fig. 23 shows the variation of the maximum water level oscillation in the surge tank.

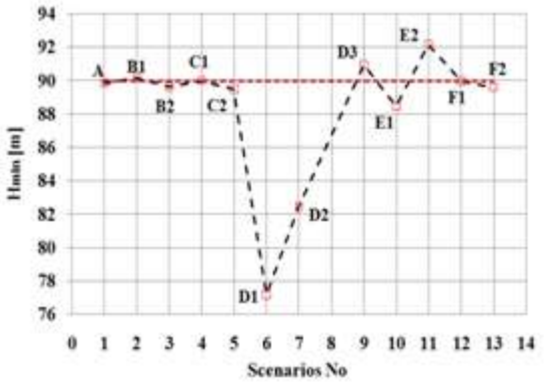

Fig. 22 Results for minimum turbine inlet head

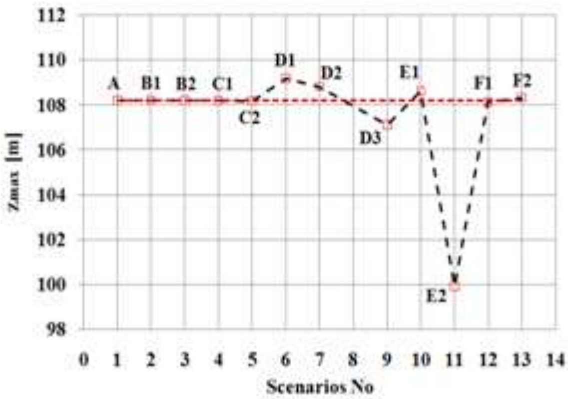

Fig. 23 Results for maximum water level oscillation in the surge tank

The variation of the minimum water level oscillation in the surge tank for each modeling parameters (different scenarios) is shown in Fig. 24.

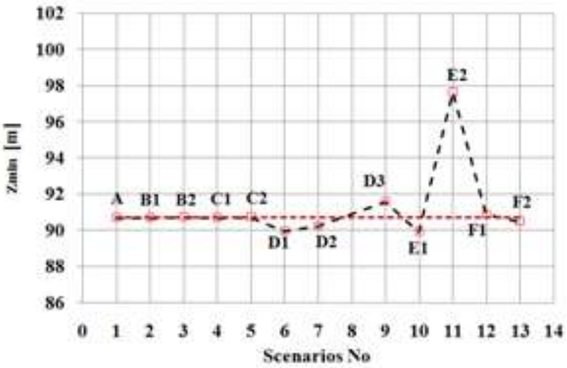

Fig. 24 Results for minimum water level oscillation in the surge tank

The sensitivity of output turbine conditions for variation of each modeling parameters is summarized in Table 4.

By comparing the simulation results can be concluded that the variation of the wave speed there is not effect to the amplitudes (max/min) of the turbine inlet head (Table 4) and time of occurrence of the head peaks. By examining Fig.4 can be concluded that there is small discrepancies in the time evolution of the turbine inlet head after guide vanes closure. These are probably due to the water hammer reflections and differ in frequency due to the difference in wave speed.

Scenario No.		Rotational speed n_{max} (min^{-1})	Maximum head H_{max} (m)	Minimum head H_{min} (m)	Maximum oscillation Z_{max} (m)	Minimum oscillation Z_{min} (m)
1	**A (Base case)**	430.90	146.70	89.86	108.20	90.71
2	**B1**	431.00	147.10	90.19	108.20	90.71
3	**B2**	430.60	146.43	89.64	108.20	90.74
4	**C1**	444.80	144.10	90.00	108.20	90.71
5	**C2**	418.70	149.91	89.49	108.17	90.74
6	**D1**	413.20	159.53	77.18	109.18	89.98
7	**D2**	423.10	149.75	82.48	108.81	90.25
8	**D3**	438.10	142.55	90.95	107.11	91.59
9	**E1**	430.70	146.46	88.48	108.69	89.82
10	**E2**	433.50	150.20	92.17	99.91	97.66
11	**F1**	429.80	146.33	89.98	108.11	90.89
12	**F2**	432.10	147.13	89.61	108.33	90.50

Table 4. Summary of the results

Varying the generator inertia had a significant variation in the turbine rotational speed (Fig.8) and turbine inlet head (Fig.7), although there is negligible effect on the water level oscillation in the surge tank. By comparing the results it is apparent that for increased generator inertia, the head (water hammer) rise while turbine speed (runaway) reduce, else the head reduce while the turbine speed rise. With variation of the generator inertia (±20%) that was examined, the head rise and turbine speed rise both vary by cca.10%. Before a turbine manufacturer has been contracted, the generator inertia often has to be assumed. Because of this, it is important to investigate the sensitivity of the analysis results to variations in inertia.

For the different guide vanes closing time investigated, there was a significant variation in the all output conditions for the turbine. This modeling parameter is main criteria which directly affect to the so-called guaranteed control values of the HPP, allowed increase of the head (water hammer) and allowed increase of the rotational speed (runaway). Therefore, it is necessary to define the guide vanes minimum closing time, so that the maximum value of the pressure(head) at the turbine and the maximum value of the turbine's rotational speed be within permissible limits i.e. not exceed the guaranteed control values. To evaluate the influence of the guide vanes closing time on the guaranteed control values, it's necessary to perform series of computations for different values of the guide vanes closing time. For example (see Table 4), if the guide vanes closing time is 6 [s] (linearly closing-Scenario D1) then the increase of the head (water hammer) at the turbine is cca.63% (H_{max}=159.53 [m]) higher compared to the hydrostatic head H_0 = 98 [m], while the increase of the turbine rotational speed (runaway) is cca.38% higher (n_{max}=413.20 [min^{-1}]) compared to the rated value of the rotational speed (n_0=300 [min^{-1}]). These values for the increase the head and rotational speed must be (limited) smaller than the guarantee control values (H_{max}<$H_{guar.}$, n_{max}<$n_{guar.}$). Thus, shortest possible guide vanes closing time can be determined.

With variation the throttling coefficient (or cross section area in the junction) of the surge tank significant variation in water level oscillation is obtained. The maximum and minimum water level oscillation varying by over 10%. By examining Fig.16 and Table 4 can be concluded that the higher throttling coefficient reduce the variation of water level oscillation in the surge tank. Varying the throttling coefficient had a negligible effect on the turbine rotational speed, while turbine inlet head(max/min) varied by approximately 2%.

In this case study the variations in pipe friction factor resulted in notable changes in all turbine outputs. Of additional interest is the possible variation in turbine head from the initially(steady state) estimated "base case A". According Fig.17, Fig. 18 and Fig . 19 can be concluded that the lower pipe friction is likely to lead to higher pressure peaks at the turbine inlet, turbine speed increase, and variation of water level in the surge tank.

VI. CONCLUSION

In this paper, sensitivity of transient phenomena analysis of the HPP with variation in modeling parameters such as pipeline friction factor, wave speed, surge tank throttling coefficient, turbine guide vanes closing and generator inertia is presented. Numerical modeling and computation of transient phenomena of the HPP during emergency shutdown for base case was first investigated. The reliability of the numerical simulation is confirmed by comparison of the computation results with experimental data obtained. Each modeling input parameters have been based on the maximum and minimum values. In the base case each modeling parameters have a best estimate values. By transient phenomena analysis can be concluded that some modeling parameters are likely to have a significant impact on the computation results of a transient analysis than others. Future research may be seen in investigated of the influence of others parameters of the analysis. These parameters can be following: time step iteration of the computation, unit characteristics(hill chart), the effect of discrete loss (junctions, bends) etc.

REFERENCES

[1] S. Mario *"Pipeline hydro-dynamics" (Croatian)*, Faculty of Mechanical Engineering and Naval Architecture, Zagreb, 2005.

[2] V. Iliev *"Analysis of the influence of the unsteady phenomena in the intake structures, penstocks and units of the hydro power plants during transient regimes"*, Master Thesis, Faculty of Mechanical Engineering, Skopje-Macedonia, 2011.

[3] A. B. Almeida, E. Koelle (1992): *Fluid Transients in Pipe Networks*, C. M. P., Elsevier.

[4] M. Hanif Chaudry *"Applied Hydraulic Transients"*, British Columbia Hydro and Power Authority Vancouver, Canada, 1979.

[5] E. B. Wylie, Victor L. Streeter "*Fluid Transients*", University of Michigan, 2001.

[6] Charles Jaeger *"Fluid Transients in Hydro-Electric Engineering Practise"*, University of Glasgow, 1977.

[7] Christophe Nicolet "*Hydroacoustic modelling and numerical simulation of unsteady operation of hydroelectric systems*" A La Faculte Sciences Et Techniques De Lingenieur, Labaratoire de machines hydrauliques, Thesis No 3751, Lausanne 2007.