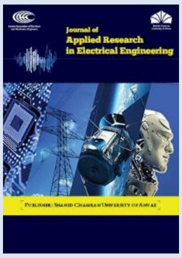
J. Appl. Res. Electr. Eng., Vol. 1, No. 1, pp. 79-85, 2022 DOI: 10.22055/jaree.2021.33523.1009

Shahid Chamran University of Ahvaz

Iranian Association of Electrical and Electronics Engineers

Journal of Applied Research in Electrical Engineering

E-ISSN: 2783-2864
P-ISSN: 2717-414X
Homepage: https://jaree.scu.ac.ir/



Research Article

A Novel Method of Modeling for Dynamic Behavior of Hydro-Electric Turbines During Load Rejection

Saman Ghahghahzadeh[1,*], and Mohammad Reza Afsharnia[2]

[1] *Department of Electrical* Engineering, *Masjed-Soleiman Branch, Islamic Azad University, Masjed-Soleiman, Iran*

[2] *Sama Technical and Vocational* Training *College, Islamic Azad University, Masjed-Soleiman Branch, Masjed-Soleiman, Iran*

[*] *Corresponding* Author*:* *samanghahghahzadeh@yahoo.com*

Abstract: This work proposes a new model for dynamic behavior of hydro-electric turbines on the basis of inlet mechanical power with different loads together with reactions of wicket gates and governor during load rejection. Then, practical experiments are investigated, and their results are compared with simulated results developed in SIMULINK. The results show that proposed modeling satisfies practical behavior of real systems.

Keywords: Modeling, hydroelectric turbine, load rejection, regression.

Article history
Received 26 May 2020; Revised 23 May 2021; Accepted 02 June 2021; Published online 29 June 2021.

How to cite this article
S. Ghahghahzadeh, and M. R. Afsharnia, "A novel method of modeling for dynamic behavior of hydro-electric turbines during load rejection," *J. Appl. Res. Electr. Eng.*, vol. 1, no. 1, pp. 79-85, 2022. DOI: 10.22055/jaree.2021.33523.1009

1. Introduction

Hydroelectric plants demonstrate particular behaviors during power generation due to their physical construction. Sudden changes in the load are an example of situations that may influence plant parameters. Hence, the load rejection test is prevalent to investigate the reaction of turbine-generator combination reaction, which examines the robustness of plant units. However, the results may differ based on the percent of nominal power delivered by the hydroelectric unit before the load rejection test. Turbine speed, wicket gate position, pressure head in the spiral case, and so on are generally investigated during the load rejection process. Regarding these quantities, the governor design and parameters are to be attended. In [1], the results of the simulation indicate that the higher the power level, the greater the disturbance caused by the load rejection. The nuclear power plant operating with full load is necessary to be equipped with the protection system for load rejection. In practice, load rejection may occur in special cases, such as short circuits in network. In [2], an experimental study has been conducted to estimate synchronous generator parameters through a sudden short circuit in the laboratory.

In [3], a complete analysis is investigated with a focus on the electrical aspects of load rejection and the variations of generator voltages and currents. Also, transient processes of load rejection caused by different accident conditions and elaborating the characteristics of different types of load rejection are studied in [4] in which a numerical simulation method of different types of load rejection is then established.

Amazing models for load rejection of thermal power plants, which helped and guided us through this work, are applied in [5]. Paper [6] presents a nonlinear mathematical model of the Francis turbine in a hydropower plant evaluated by full-scale field tests involving steady and transient operations that use a conventional turbine model developed by IEEE [7]. Besides several field tests have globally been performed although most of them may not be released to the public, such as [8] and [9].

Regarding these strong researches and other works such as [10-14], our study numerically evaluates turbine behavior in which mechanical aspects are considered with a newly developed model processed in SIMULINK®.

Section 2 reviews the theory of modeling according to [15], which is a famous reference. In Section 3, the experimental results of mechanical parameters related to the Masjed-Soleiman hydropower plant are presented. The new model is developed and the results are presented in Section 4.

In Section 5, the results are applied to regression and formulation. Finally, some conclusions are made in Section 6.

2. Modeling

When there is an unbalance between the torques acting on a rotor, the net torque causing acceleration is

$$T_a = T_m - T_e \tag{1}$$

in which T_e, T_a, and T_m are the electromagnetic torque, accelerating torque, and mechanical torque, respectively. In (1), T_e and T_m are positive for a generator, and the prime mover is accelerated by the unbalance in the applied torques. Hence, the main equation of motion is

$$J\frac{d\omega_m}{dt} = T_a \tag{2}$$

where J is combined moment of inertia of generator and turbine in kg.m2, ω_m is angular velocity of the rotor, in rad/s, and t is time in sec.

Equation (2) can be normalized in terms of per unit inertia constant H, defined as the kinetic energy in watt-seconds at rated speed divided by the VA base. Using ω_{0m} to denote the rated angular velocity in mechanical radians per second, the inertia constant is

$$H = \frac{J\omega_m^2}{2VA_{base}} \tag{3}$$

Then, the moment of inertia J will be as below:

$$J = \frac{2H}{\omega_{0m}^2}VA_{base} \tag{4}$$

Substituting the above relation in (2) gives

$$\frac{2H}{\omega_{0m}^2}VA_{base}\frac{d\omega_m}{dt} = T_m - T_e \tag{5}$$

Rearranging yields

$$2H\frac{d}{dt}\left[\frac{\omega_m}{\omega_{0m}}\right] = \frac{T_m - T_e}{VA_{base}/\omega_{0m}} \tag{6}$$

Regarding the relation $T_{\text{base}} = {VA_{base}}/{\omega_{0m}}$, the equation of motion in form of per unit is

$$2H\frac{d\overline{\omega_r}}{dt} = \bar{T}_m - \bar{T}_e \tag{7}$$

In (7), we have

$$\overline{\omega_r} = \frac{\omega_r}{\omega_0} \tag{8}$$

in which ω_0 is its rated value of rotor velocity and ω_{r} is the angular velocity of the rotor in electrical rad/s.

On the other hand, supposing δ is the angular position of the rotor in electrical radians with respect to a synchronously rotating reference and δ_0 is its initial value,

$$\delta = \omega_r t - \omega_r t + \delta_0 \tag{9}$$

Taking the time derivative, we have

$$\frac{d\delta}{dt} = \Delta\omega_r \tag{10}$$

$$\frac{d^2\delta}{dt^2} = \omega_0\frac{d(\Delta\overline{\omega_r})}{dt} \tag{11}$$

Substituting for $\frac{d(\Delta\overline{\omega_r})}{dt}$ given by the above equation in (7), we get

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = \overline{T_m} - \overline{T_a} \tag{12}$$

It is often desirable to include a component of damping torque, not accounted for in the calculation of T_e, separately. This is accomplished by adding a proportional to speed deviation in the above equation as follows.

$$\frac{2H}{\omega_0}\frac{d^2\delta}{dt^2} = \overline{T_m} - \overline{T_a} - K_D\Delta\overline{\omega_r} \tag{13}$$

The swing equation, expressed as two first-order differential equations, will become

$$\frac{d\Delta\overline{\omega_r}}{dt} = \frac{\overline{T_m} - \overline{T_a} - K_D\Delta\overline{\omega_r}}{2H} \tag{14}$$

$$\frac{d\delta}{dt} = \omega_0\Delta\overline{\omega_r} \tag{15}$$

in which time is in seconds, δ is in electrical radians, and ω_0 is equal to 2πf. The block diagram form of the above two equations is shown in Fig. 1.

3. Experimental Tests

In this work, we have examined several load rejection tests individually and together on units 5 and 6 of the Masjed-Soleiman hydroelectric plant. The tests were conducted at different states when the units were generating 25%, 50%, 75%, and 100% of their rated power. Figs. 2 to 5 depict the result curves of the above tests. The variations are in terms of time.

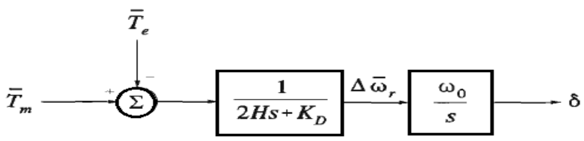


Fig. 1: Block diagram of above equations.

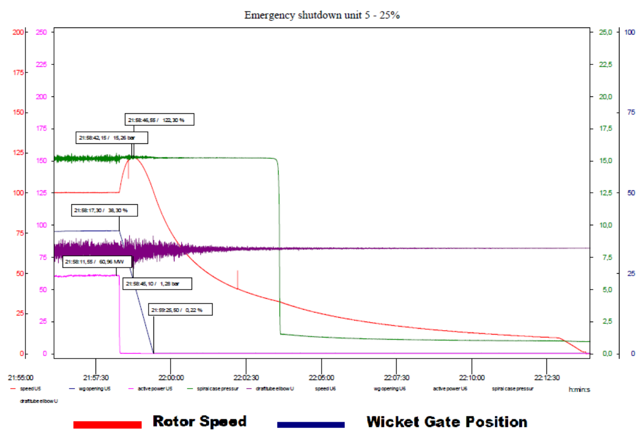


Fig. 2: The results of load rejection on unit 5 of the Masjed-Soleiman plant while delivering 25% of rated power.

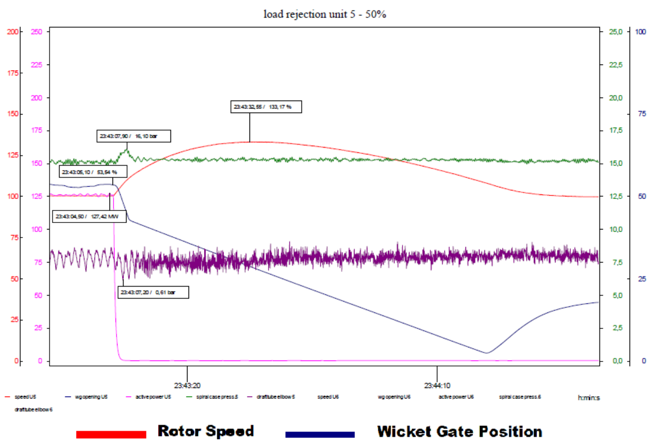


Fig. 3: The results of load rejection on unit 5 of the Masjed-Soleiman plant while delivering 50% of rated power.

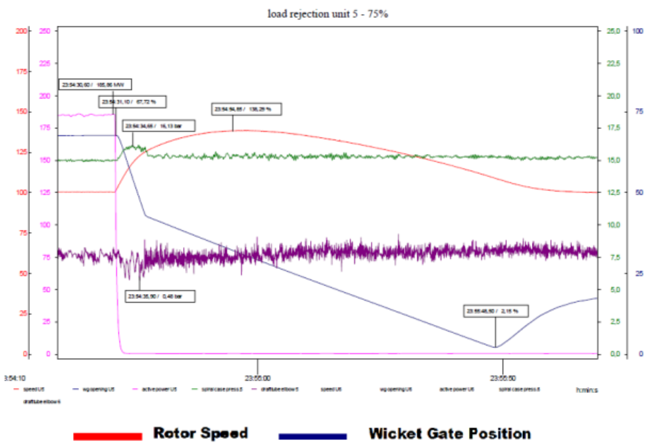


Fig. 4: The results of the load rejection on unit 5 of the Masjed-Soleiman plant while delivering 75% of rated power.

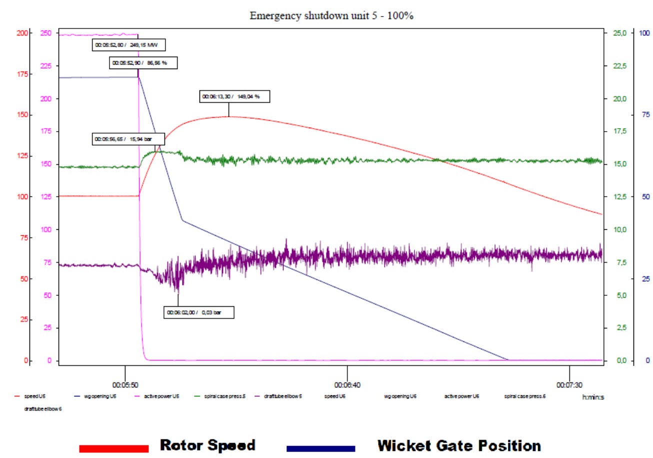


Fig. 5: The results of the load rejection on unit 5 of the Masjed-Soleiman plant while delivering 100% of rated power.

4. Simulation and Results

According to the equations mentioned in Section 2, the mechanical behavior of turbine-generator combination can generally be stated by

$$T_m - T_e - K\,\omega = J\frac{d\omega}{dt} \qquad (16)$$

Multiplying both sides of (16) with ω, we have

$$P_m - P_e - K\,\omega^2 = J\omega\frac{d\omega}{dt} \qquad (17)$$

Fig. 6 shows a new block diagram of turbine- generator combination operation, which should be attended to during the load rejection process.

This new block diagram can be implemented in the SIMULINK® environment. Hence, the mechanical braking system is operating after load rejection. Phrase $K_B\omega^2$ will be added to the diagram shown in Fig. 6, which will cause speed reduction together with the governing system.

Consequently, the rotor will get started to reduce speed reaching zero. Fig. 7 shows the implemented diagram in the SIMULINK® environment.

The simulation was executed when the system served different loads before load rejection. In this simulating work, the power delivered by the studied system was 50%, 75%, 80%, and 100% of the rated power. Figs. 8 to 11 depict the behavior of the system by presenting rotor speed variations and wicket gate position during the process in terms of time in Table 1, significant parameters are being collected which will affect design considerations.

5. Formulating and Regression

According to Table 1, two significant functions are to be attended by variations of the percent of rated power delivered before load rejection: percentage of maximum over speed (F1) and time to reach maximum over speed (F2). Functions F1 and F2 are fitted by regression with two following polynomials.

Fig. 12 shows the points on the basis of Table 1 and its related fitness function F1, and Table 2 presents coefficients of function F2 as it is derived from Fig. 13.

$$f_1(l) = -0.0004l^3 - 0.09\,l^2 - 5.74l - 115 \qquad (18)$$

$$f_2(l) = 1.9 * 10^{-5}l^3 - 0.0057\,l^2 + 0.5633l - 13 \qquad (19)$$

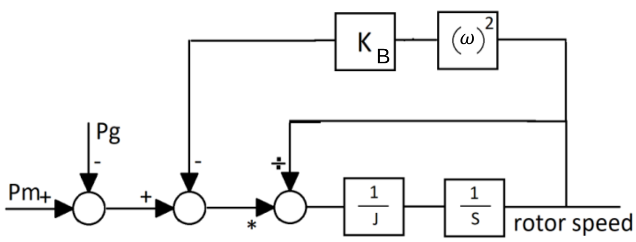


Fig. 6: The block diagram of turbine-generator during load rejection.

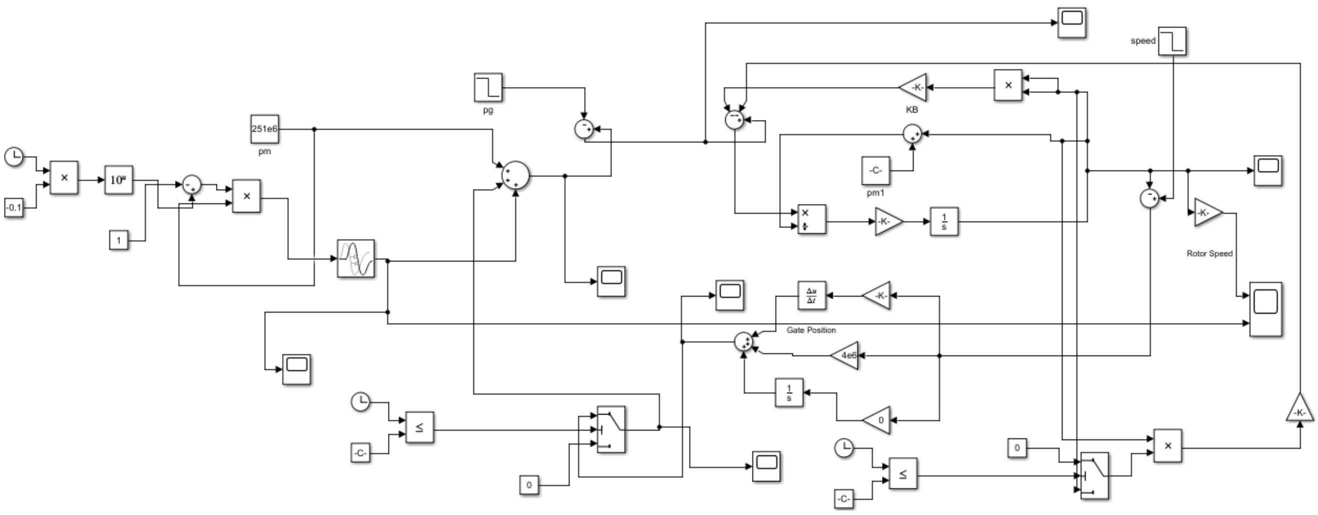
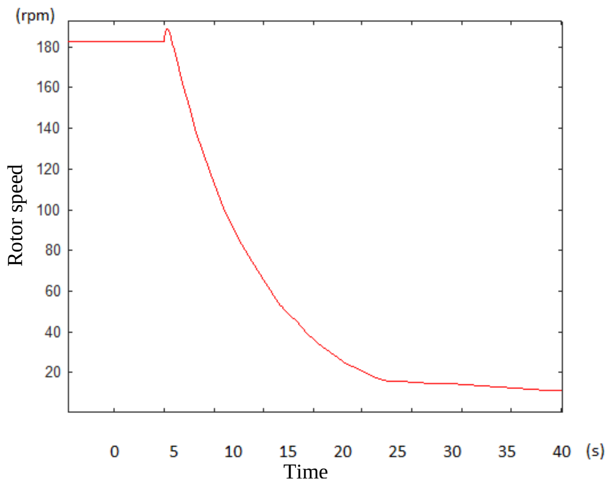
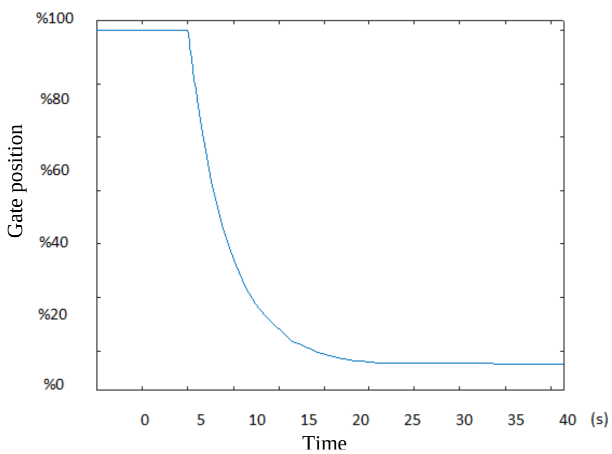


Fig. 7: Implemented diagram in SIMULINK environment.

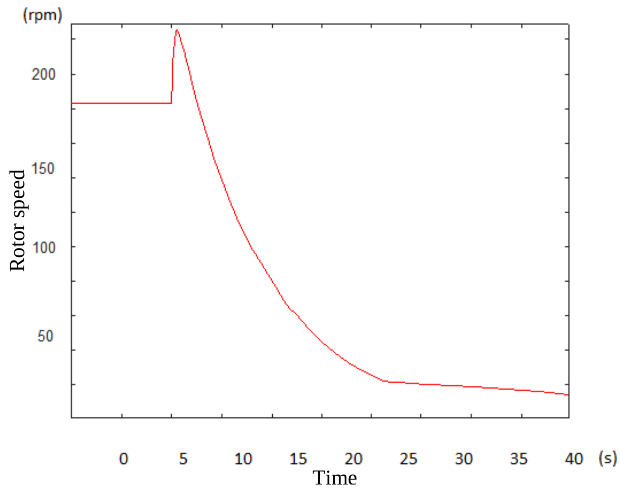


(a)

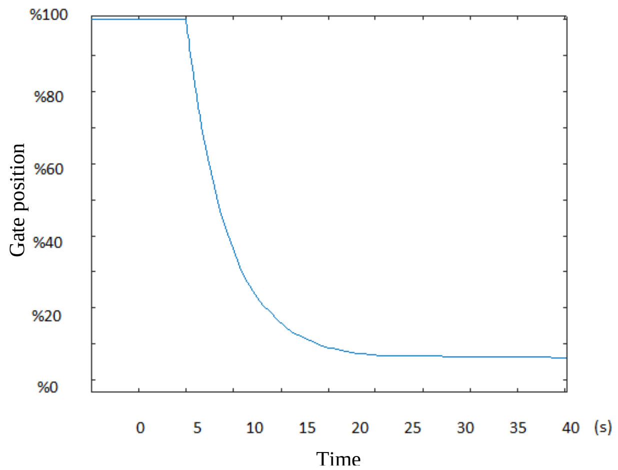


(b)

Fig. 8: Variations of (a) rotor speed, and (b) wicket gate position when delivering 50% of the rated power before load rejection.



(a)



(b)

Fig. 9: Variations of (a) rotor speed, and (b) wicket gate position when delivering 75% of the rated power before load rejection.

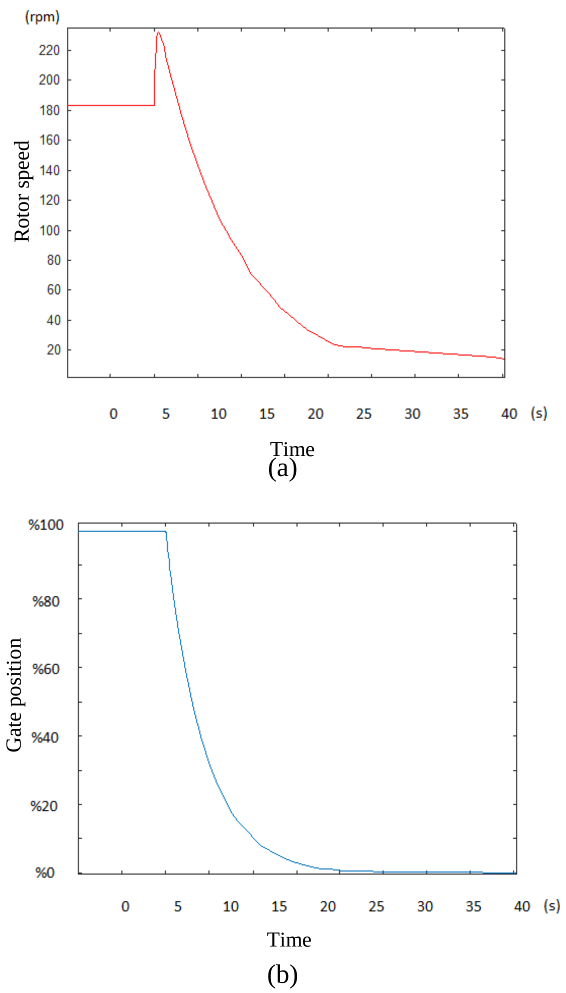


Fig. 10: Variations of (a) rotor speed, and (b) wicket gate position when delivering 80% of the rated power before load rejection.

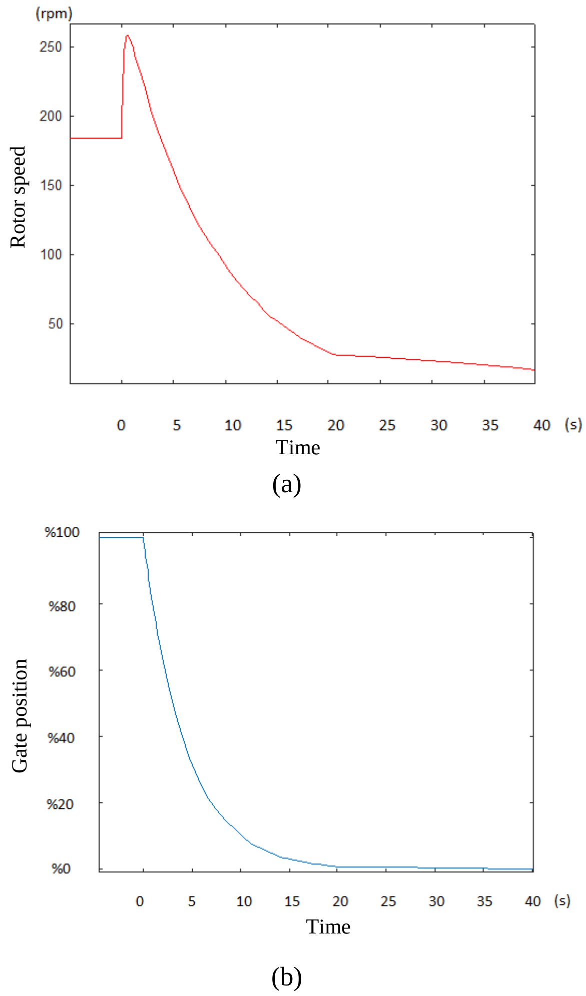


Fig. 11: Variations of (a) rotor speed, and (b) wicket gate position when delivering 100% of rated power before load rejection.

Table 1: The results of the load rejection at different cases.

Power delivered before load rejection (MW)	Rotor speed before load rejection (RPM)	Maximum speed after load rejection	Percentage of over speed	Time to reach over speed (s)
250 (%100)	184	259	%41	5.58
200 (%80)	183	232	%27	5.48
187 (%75)	184	225	%22	5.35
125 (%50)	183	189	%3	3.36

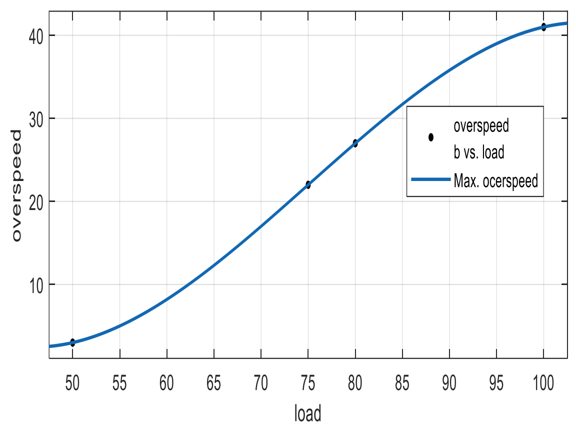


Fig. 12: Fitted function F1 as over speed vs. load percent.

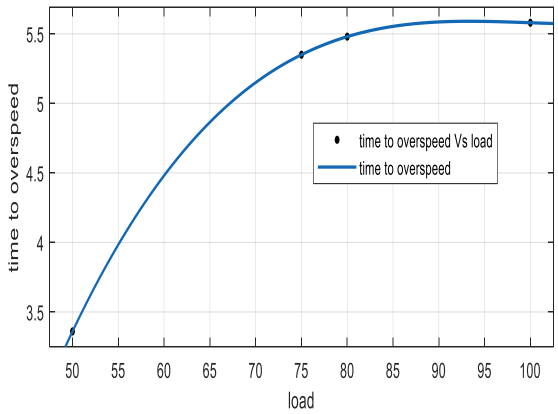


Fig. 13: Fitted function F2 as time to reach over speed vs. load percent.

Table 2: Regression parameters of fitted function F1.

Linear model polynomial f(x) = p1*x^2 + p2*x + p3
p1 = -0.0004
p2 = 0.09
p3 = -5.74
p4 = 115
Goodness of fit
SSE: 9.37e-26

6. Conclusion

After executing the above works and attaining the related results, the following conclusions can be made:

1- Experimental results show that modeling is qualified and can be trusted.

2- Maximum over speed will be increased if the power delivered before load rejection increases.

3- If the power delivered increases, the time of reaching maximum over speed after load rejection will decrease.

Acknowledgement

The first writer would like to thank Sama Technical and Vocational Training College at Islamic Azad University, Masjed-Soleiman branch for their financial support through the contract of "Modeling of Dynamic Behavior of Hydro-Electric Turbines During Load Rejection", contract of 96-25-6196. Also, the writers appreciate Khouzestan Water and Power Authority (KWPA), especially Mr. Pishva, Mr. Jelodar, and Mr. Gholipour for their cooperation in this project.

CRediT Authorship Contribution Statement

Saman Ghahghahzadeh: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Resources, Software, Roles/Writing - original draft, Writing - review & editing. **Mohammad Reza Afsharnia:** Data curation, Project administration, supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The ethical issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, redundancy has been completely observed by the authors.

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Biography

Saman Ghahghahzadeh has been with Islamic Azad University as academic staff since 2010. For more than 24 years, he has worked in different sections of power industry as researcher, technical advisor, and project manager. He has executed more than 20 research projects for several clients where he is also distinguished as a senior technical trainer. His main research interests are high-voltage engineering and tests, power transformers, generators, insulation, and power system components. Over the past years, Dr. Ghahghahzadeh has authored and coauthored more than 15 conference and journal scientific papers.

Mohammad Reza Afsharnia received his M.Sc. in electrical engineering from Islamic Azad University, Zanjan Branch of Sciences and Research. He has worked in a Masjed-Soleiman hydropower plant as an electrical engineer since 2010 besides his several experiences in technical design and advisory to the power industry.