

A COMPREHENSIVE SIMULATION FRAMEWORK FOR SMALL HYDROPOWER PLANT MODELLING

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This paper presents a simulation framework for modeling and analysis of small hydropower plants (SHPPs), focusing on the interaction between hydraulic, mechanical, and electrical subsystems. The proposed model integrates a hydraulic turbine, servo-drive actuator, governor control system, and an induction generator described by both simplified and complete dynamic models. Special attention is given to transient electromagnetic phenomena during start-up, grid connection, and power control. A comparative analysis shows that simplified models fail to capture fast transients such as current peaks and torque oscillations. The model is validated using real operational data, confirming its accuracy in both steady-state and transient conditions. Furthermore, a sensitivity analysis demonstrates the robustness of the proposed model with respect to variations of key hydromechanical parameters. The results highlight the importance of detailed modeling for proper design and dimensioning of electrical and mechanical components in SHPP systems.

KEYWORDS

Small hydropower plant, induction generator, electromagnetic transients, hydraulic turbine, grid connection

1 INTRODUCTION

The global energy sector is undergoing a significant transformation driven by the increasing demand for sustainable and low-emission energy sources. Renewable energy technologies, including solar, wind, and hydropower, are becoming essential components of modern power systems. Among these, hydropower remains one of the most reliable and efficient means of electricity generation. However, the construction of large hydropower plants is often constrained by environmental, geographical, and socio-economic factors. Consequently, attention has shifted toward small hydropower plants (SHPPs), which provide a decentralized, environmentally friendly, and economically viable solution for electricity generation, particularly in remote and rural areas.

Small hydropower plants typically operate with installed capacities up to several megawatts and are frequently implemented as run-of-river systems with minimal environmental impact. These systems utilize the potential and kinetic energy of water to drive hydraulic turbines coupled with electric generators. Due to their relatively simple construction and modular nature, SHPPs are well suited for integration into distributed energy systems, microgrids, and hybrid renewable configurations. Despite their smaller scale, SHPPs exhibit complex dynamic behavior resulting from strong coupling between hydraulic, mechanical, and electrical subsystems.

Accurate modeling of SHPPs is therefore essential for understanding system dynamics, optimizing control strategies,

and ensuring reliable operation under various operating conditions. In particular transient phenomena occurring during start-up, grid connection, and switching between control modes can significantly influence both the electrical and mechanical performance of the system. These effects include current surges, torque oscillations, and variations in turbine speed, which may lead to increased mechanical stress or improper dimensioning of electrical infrastructure.

Previous research has proposed a wide range of hydropower plant models with varying levels of complexity. While simplified models are often sufficient for analyzing steady-state operation or slow hydromechanical dynamics, they typically fail to capture fast electromagnetic transients associated with the electric generator. This limitation is especially critical in SHPPs equipped with induction generators, where transient processes such as magnetization, slip variation, and electromagnetic torque oscillations play a significant role during grid interaction. In many existing studies, the focus is placed either on the hydraulic subsystem or on the electrical generator separately, without considering their mutual interaction in a unified framework. Moreover, simplified torque-slip representations of induction machines are frequently used, which may lead to inaccurate prediction of transient phenomena. For practical engineering applications, however, precise modeling of these effects is essential, as it directly influences the design and dimensioning of electrical components such as cables, circuit breakers, and protection systems, as well as the mechanical integrity of the turbine-generator shaft.

The present study addresses these limitations by developing a comprehensive and modular simulation model of a small hydropower plant that integrates hydraulic, mechanical, and electrical subsystems within a unified framework. The model includes a detailed representation of the hydraulic turbine, servo-drive actuator, governor control system, and an induction generator described by both simplified and complete dynamic models.

The primary objectives of this research are therefore as follows:

- To develop a comprehensive simulation model of a small hydropower plant capable of accurately representing both slow hydromechanical processes and fast electromagnetic transients.
- To analyze and compare the behavior of simplified and complete dynamic models of the induction generator, with particular emphasis on their ability to capture transient phenomena during key operating modes such as start-up, grid connection, and power control.
- To validate the proposed model using real operational data from the real SHPP Krompachy in Slovakia and to demonstrate its applicability for analyzing transient effects relevant to the design and dimensioning of electrical and mechanical components in SHPP systems.
- To evaluate the sensitivity of the proposed model with respect to key hydromechanical parameters and to assess its robustness for application to different SHPP configurations.

By combining experimentally validated data with advanced modeling techniques, the proposed simulation framework provides a reliable tool for analyzing dynamic phenomena in SHPPs. The results contribute to a deeper understanding of the interaction between hydraulic and electromagnetic processes and support the development of more efficient and robust renewable energy systems.

2 BACKGROUND AND RELATED WORK

The modeling and control of hydropower plants have been extensively studied over several decades, reflecting the

inherently multidisciplinary nature of these systems, which involve hydraulic, mechanical, and electrical domains. One of the earliest systematic approaches was introduced by the IEEE Working Group on Prime Mover and Energy Supply Models [IEEE 1992], providing standardized representations of turbines and governors for dynamic studies of power systems. Since then, advances in computational tools and numerical methods have enabled the development of increasingly sophisticated and flexible simulation models.

Hydropower systems can generally be categorized into large-scale installations connected to national transmission networks and small or micro-hydropower plants designed for local or decentralized operation. While the fundamental principles of energy conversion remain the same, their dynamic characteristics differ significantly. Large hydropower plants are dominated by complex hydraulic phenomena such as long penstocks, surge tanks, and water hammer effects. In contrast, small hydropower plants (SHPPs) typically feature shorter water conduits and simpler configurations, resulting in faster system dynamics and stronger coupling between hydraulic and electrical subsystems.

Numerous studies have addressed the modeling of hydro-turbine and governor systems. Authors in [Malik 1991, Choo 2007] investigated the dynamic behavior of turbine-governor systems under varying grid conditions, highlighting the importance of accurate speed and frequency control. Naghizadeh et al. [Naghizadeh 2012] proposed educational models for hydro governor tuning, while Acakpovi et al. [Acakpovi 2014] provided a comprehensive classification of hydropower plant models ranging from simplified analytical approaches to detailed nonlinear dynamic representations.

In recent years, MATLAB/Simulink has become a widely used platform for hydropower system modeling due to its flexibility in combining mathematical descriptions with control algorithms. [Sattouf 2014]. Authors in [Usman 2015] demonstrated the applicability of such environments for analyzing both transient and steady-state behavior of hydropower systems. These tools enable efficient integration of mechanical and electrical subsystems, which is particularly important in SHPP applications.

A key aspect in SHPP modeling is the type of electric generator employed. While large hydropower plants predominantly use synchronous generators due to their controllability and efficiency, small-scale systems increasingly rely on induction (asynchronous) generators because of their simpler construction, lower cost, and reduced maintenance requirements. The behavior of induction generators in hydropower applications has been investigated in [Xu 2021, Koltsaklis 2023] who focused on reliability and energy availability aspects.

Recent research has also explored advanced modeling and control approaches, including intelligent and data-driven methods. Authors in [Fedor 2015] applied fuzzy control and dynamic identification techniques to induction machines, demonstrating their effectiveness in handling nonlinear system behavior. Similarly, Salhi et al. [Salhi 2010] proposed fuzzy-based control strategies for micro-hydropower plants, improving robustness under varying operating conditions.

Despite these developments, many existing studies either focus on individual subsystems or employ simplified generator models that do not fully capture the dynamic interaction between hydraulic and electrical components. Commonly used simplified torque-slip models of induction generators are unable to accurately represent fast electromagnetic transients occurring during critical operating states such as grid connection, switching events, or voltage disturbances. This

limitation becomes especially significant in SHPPs, where faster system dynamics and tighter coupling between subsystems amplify the impact of such transient phenomena.

As a result, the interaction between hydromechanical processes and electromagnetic dynamics is often not represented with sufficient accuracy, which may lead to incorrect prediction of current peaks, torque oscillations, and their impact on both electrical and mechanical components.

This limitation motivates the development of a comprehensive SHPP model capable of accurately representing both slow hydromechanical processes and fast electromagnetic phenomena, which constitutes the main objective of this work.

3 STRUCTURE OF THE PROPOSED SIMULATION MODEL

The SHPP model consists of four interconnected subsystems: the governor, servo-drive, hydraulic turbine, and electric generator. Each subsystem was modeled as a nonlinear dynamic system with normalized variables in per-unit (p.u.) values to ensure scalability and compatibility across configurations. All angular speed variables are expressed in normalized (per-unit) form with respect to the electrical angular speed of the grid ω_e , i.e. $\omega_m^* = \omega_m / \omega_e$. This normalization ensures consistent interpretation of the turbine operating regimes, including sub-synchronous, synchronous, and super-synchronous operation. The interconnections between the mechanical and electrical parts were modeled on a common shaft, reflecting the real coupling of the turbine and generator. The individual subsystems of the resulting SHPP simulation model are described in the following subsections.

3.1 Governor Subsystem

The governor subsystem represents the fundamental control unit of a small hydropower plant, ensuring stable operation under both isolated and grid-connected conditions. Its principal task is to control the turbine speed and the generated power by adjusting the water flow through the turbine via the servo drive. The accuracy and robustness of the governor directly determine the quality of frequency and power control, especially in systems with fast transient responses, such as small or micro-hydropower installations.

In a conventional SHPP configuration, the control process is divided into two operational modes: speed control and power control [Munoz-Hernandez 2013, Kishor 2017]. During the start-up phase, when the turbine operates without grid connection, the governor maintains a reference mechanical speed corresponding to the synchronous frequency of the grid. This prevents excessive overshoot and ensures a smooth transition to the synchronization state. Once the generator is successfully synchronized and connected to the electrical network, the governor switches to the power control mode, where it maintains the desired power output according to predefined setpoints or external grid demands.

To achieve satisfactory control performance across both modes, a proportional-integral (PI) controller is adopted. The proportional component (K_p) ensures fast error correction, while the integral term (K_i) eliminates steady-state deviations in turbine speed or power. The derivative term (K_d) was intentionally omitted in this configuration, as rapid variations in the control signal could induce instability or water hammer effects in the hydraulic circuit. Nevertheless, the control structure allows for future expansion into a full PID scheme if required for specific applications.

A switching logic block is implemented within the control structure to determine the active mode of control. The logical condition, typically based on the ratio of mechanical angular

speed of the shaft ω_m [rads⁻¹] to grid angular speed ω_1 [rads⁻¹], i.e. $d_{ref} = \omega_m/\omega_1$, defines whether the system is governed by speed or by power control. During the transition between these modes, a first-order low-pass filter with time constant T_f is introduced to smooth reference changes, thereby preventing abrupt actuator motion or oscillations in the turbine response. These features are crucial in small hydropower systems, where the inertia of the turbine-generator shaft is relatively low, and even small fluctuations in gate opening can significantly affect the output power.

The PI controller parameters K_p and K_i were obtained using a parametric optimization procedure implemented in MATLAB. The optimization criterion minimized the integral of the squared error between the reference and actual mechanical angular speed of the shaft

$$J = \int_0^T [\omega_{ref}(t) - \omega_m(t)]^2 dt \quad (1)$$

The performance index was evaluated over a discrete grid of controller gains, and the optimal pair (K_p, K_i) was selected at the minimum of criterion J .

The same procedure was applied to tune the PI power controller. The resulting parameters ensure stable dynamic performance under variable load and hydraulic conditions. The final controller gains are provided in the Appendix. The resulting simulation model of the Governor subsystem is shown in Fig. 1, where the meaning of the individual variables is as follows: P_{ref} - turbine reference power [W], P_e - electrical power of the generator [W], G_{ref} - guide vane opening position reference value [%].

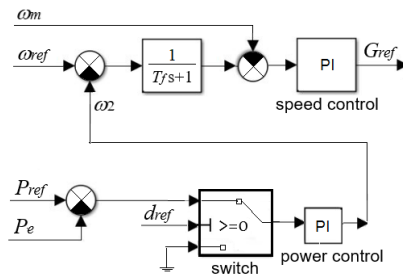


Figure 1. Governor subsystem model

3.2 Servo Drive Subsystem

In small hydropower installations, the servo drive is typically realized as a hydraulic or electromechanical actuator that controls the position of guide vanes. These elements determine the flow rate through the turbine, and therefore the generated mechanical torque. The precise positioning of the guide vanes is essential—both to achieve optimal power output and to prevent hydraulic shocks or cavitation phenomena that may occur due to excessive rate of change in water flow.

From a modeling perspective, the servo drive can be represented as a second-order dynamic system characterized by two state variables: the actuator speed and its position [Sattouf 2014]. The block diagram of this subsystem is shown in Fig. 2, where G and G_{ref} denote the actual and reference guide vane opening positions [%], respectively, K_a represents the actuator gain, T_a is the time constant of the servo mechanism. These parameters depend on the actuator's design, hydraulic fluid properties, and mechanical constraints of the guide vane system.

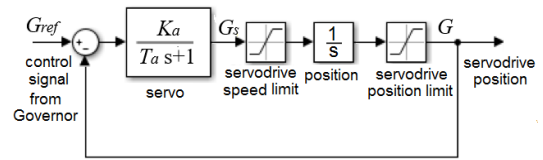


Figure 2. Servo Drive subsystem

To ensure stable operation and protect the mechanical structure, the servo subsystem includes saturation blocks that constrain both the maximum and minimum allowable gate opening and the rate of its change. The saturation limits, typically expressed in per-unit (p.u.) form, define the physical boundary of the actuator stroke—commonly in the range from 0 (fully closed) to about 1.0 (fully open). The rate limiters prevent excessive speed of motion, which could generate undesirable water hammer effects or induce oscillations in the turbine torque. These nonlinear elements are especially important in small-scale systems, where water column inertia is relatively low and pressure variations propagate rapidly [Tsuanyo 2023]. Figure 3 shows the response illustrating the effect of the servo speed and position limitation blocks (valve opening) for a step change in the input variable G_{ref} at $t=10$ seconds.

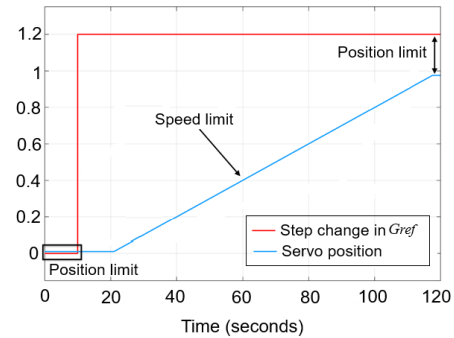


Figure 3. Response of the servo drive subsystem to a step change in the input variable G_{ref}

During the control process, the servo drive receives the desired gate position signal G_{ref} from the governor subsystem. The difference between the reference and actual gate position forms an error signal that drives the actuator until the equilibrium condition is achieved. In the case of a proportional-integral control structure, the actuator operates to minimize this deviation while respecting mechanical constraints and the rate of valve movement.

The servo dynamics play a dominant role in defining the overall time constant of the hydropower plant, since the water flow through the turbine cannot instantaneously follow control commands. Therefore, accurate representation of the servo drive behavior is essential for achieving a realistic simulation of transient processes such as start-up, synchronization, or load changes. In the MATLAB/Simulink model, these dynamics are captured using differential equations implemented as state-space blocks, enabling seamless coupling with both the hydraulic turbine and governor models.

3.3 Hydraulic Turbine Subsystem

The hydraulic turbine subsystem represents the core energy conversion unit of a small hydropower plant, transforming the potential and kinetic energy of water into mechanical power delivered to the generator shaft. The dynamic behavior of this subsystem strongly influences the overall system response, efficiency, and stability. Therefore, precise mathematical

modeling of the turbine is essential for both design optimization and control system development. The proposed model is based on the description of water flow through the turbine under no-load conditions, as presented in [Kishor 2017] and [Munoz-Hernandez 2013]. The modeling approach assumes the presence of a penstock (water conduit) and either a very large or no surge chamber.

A) Penstock Modeling

The penstock is modeled under the assumption that water is incompressible, and the pipe is sufficiently rigid, characterized by its length L and cross-sectional area A . Due to the relatively short penstocks typically used in small hydropower plants, head losses along the conduit are neglected. The flow dynamics can be expressed as

$$\frac{dq}{dt} = \frac{gA}{L}(H - H_l) \quad (2)$$

Where q is the turbine flow rate, H is the water head at the turbine inlet, H_l represents head losses, g is gravitational acceleration.

After normalization, the equation can be expressed as:

$$T_w \frac{dq}{dt} = h - h_l \quad (3)$$

where $q = Q/Q_{max}$ and $h = H/H_{max}$ and T_w denotes the water starting time (water time constant), defined as

$$T_w = \frac{Lq_{base}}{Ag h_{base}} \quad (4)$$

Here, q_{base} represents the maximum turbine flow (fully open guide vanes, $G=1$), and h_{base} is the maximum available water head.

B) Flow Characteristics

The turbine flow q is a nonlinear function of the guide vane opening G and the available water head h , as follows

$$q = G\sqrt{h} \quad (5)$$

The water flow at full servo opening ($G=1$) is then given by

$$q_{base} = 1\sqrt{h_{base}} \quad (6)$$

This relationship reflects the physical behavior of the turbine, where the flow increases with both vane opening and water head.

C) Mechanical Power and Efficiency Representation

Under ideal conditions, the turbine mechanical power would be proportional to the product of flow and head

$$P_m^* = qh \quad (7)$$

However, real turbines operate with efficiency lower than unity. Therefore, it is necessary to include efficiency effects in the model.

A commonly used approach is to introduce the no-load flow q_{nl} , which represents the flow required to overcome internal losses. The effective flow contributing to power generation is then

$$q_{eff} = q - q_{nl} \quad (8)$$

The resulting mechanical power is expressed as:

$$P_m = A_t(q - q_{nl})h - DG\Delta\omega \quad (9)$$

where A_t is the turbine gain coefficient.

The second term in Eq. (9) represents the turbine damping component, accounting for hydraulic losses and mechanical interactions in the system. This term can be generally expressed as a nonlinear function

$$M_d = f(G, \Delta\omega, D) \quad (10)$$

where G denotes the guide vane opening, $\Delta\omega$ is the angular speed deviation ($\omega_m - \omega_e$), and D represents the penstock diameter. The damping torque M_d contributes to the overall turbine dynamics by opposing rapid variations in rotational speed, thereby stabilizing the turbine response during transient operating conditions.

D) Turbine gain

The turbine gain A_t is calculated using rated operating conditions

$$A_t = \frac{P_r}{(q_r - q_{nl})h_r} \quad (11)$$

Where P_r is the rated turbine power, q_r is the rated flow, h_r is the rated head.

These parameters are typically obtained from technical documentation of the hydropower plant.

E) Resulting hydraulic turbine model

The resulting hydraulic turbine model captures the dominant nonlinear relationships between flow, head, and mechanical power, while incorporating the most significant effects influencing turbine behavior. Minor damping effects associated with hydraulic losses are neglected due to their limited impact in small hydropower plant configurations. This simplification does not significantly affect the accuracy of the model and allows efficient integration with the remaining subsystems of the SHPP.

The resulting block diagram of the turbine subsystem, derived from its mathematical formulation, is shown in Fig. 4. The parameters of the simulation model are provided in the Appendix.

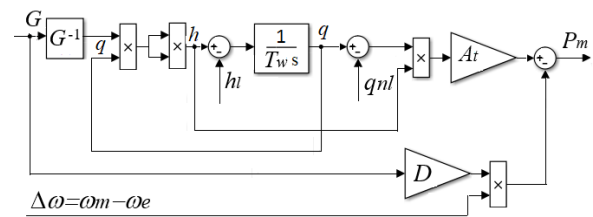


Figure 4. The resulting block diagram of the turbine model

3.4 Electromechanical Subsystem Model

The electromechanical subsystem forms the interface between the hydraulic energy conversion stage and the electrical grid. Its purpose is to describe the transfer of mechanical power from the turbine shaft to the electrical network through the generator, while simultaneously capturing the dynamic interaction between electromagnetic and mechanical quantities.

In small hydropower plants equipped with an induction generator, the subsystem can be divided into two mutually coupled parts:

1. The mechanical coupling between turbine and generator,
2. The electrical model of the induction generator.

Because electromagnetic processes occur on a millisecond time scale, whereas hydraulic dynamics evolve over seconds, careful

modeling is required to correctly capture both slow and fast phenomena.

A) Mechanical Coupling of Turbine and Generator

The hydraulic turbine and the induction generator are rigidly connected via a common shaft. The mechanical interaction between them is governed by the rotational motion equation derived from Newton's second law for rotational systems

$$J_c \frac{d\omega_m}{dt} = T_m - T_e - T_f \quad (12)$$

Where J_c represents the total inertia of the rotating system (turbine+shaft+generator), T_m is the turbine mechanical torque, T_e is the electromagnetic torque of the generator, T_f accounts for mechanical losses (friction and damping effects).

This equation expresses the dynamic balance between driving torque produced by the turbine and opposing torques generated by electromagnetic conversion and mechanical friction.

In steady-state operation, when $d\omega_m/dt = 0$, the turbine torque equals the sum of electromagnetic and friction torques. During transient events—such as start-up or grid connection—this balance is temporarily disturbed, leading to acceleration or deceleration of the shaft.

The resulting block diagram of this mechanical subsystem is shown in Fig.5, where T_r represents the induction generator rotor time constant, reflecting the dynamic effect of the rotor resistance on the electromagnetic response [Sattouf 2014].

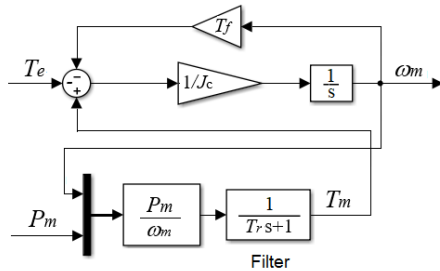


Figure 5. Mechanical subsystem block diagram

B) Induction Generator Model

For SHPP applications, induction generators are widely used due to their structural simplicity and robustness. Depending on the purpose of the analysis, two different modeling approaches can be adopted:

- a simplified quasi-static torque–slip representation,
- a complete dynamic electromagnetic model.

B1) Simplified Torque–Slip Representation

For general electromechanical behavior studies, the generator torque may be approximated using the Kloss-type torque characteristic [Perdukova 2020]

$$T_e = \frac{2U_1 s s_{max}}{s^2 + s_{max}^2} \quad (13)$$

The corresponding block diagram of this simplified model is illustrated in Fig.6, where s denotes the instantaneous slip of the induction machine (IM), s_{max} represents the breakdown (maximum) slip, and n_p is the number of pole pairs. The electrical output power P_e is determined as the product of the electromagnetic torque T_e and the mechanical angular speed of the shaft ω_m .

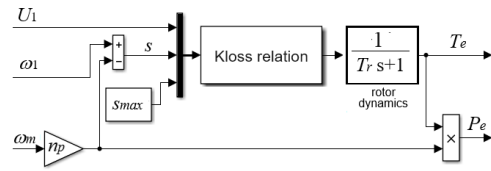


Figure 6. Block diagram of the simplified induction machine model motor system

This simplified model is computationally efficient and sufficient for analyzing steady-state transitions or slow electromechanical interactions. However, it does not accurately reproduce short-term torque peaks or current surges during grid connection.

B2) Complete Dynamic Model of Induction generator

To investigate fast electromagnetic phenomena—such as stator current peaks or torque pulsations—a full dynamic model of the induction machine is required.

In the adopted approach, the generator is modeled using a state-space formulation in an orthogonal coordinate system $\{x, y\}$ rotating with respect to the stator at the angular speed of the stator magnetic field ω_1 . The state variables typically include components of stator current vector I_1 (i_{1x} , i_{1y}) and rotor magnetic flux components ψ (ψ_{2x} , ψ_{2y}). The dynamic equations represent a current–flux model of a three-phase squirrel-cage induction machine and describe the coupling between electrical and mechanical quantities [Tran 2022].

$$\begin{bmatrix} \frac{di_{1x}}{dt} \\ \frac{di_{1y}}{dt} \\ \frac{d\psi_{2x}}{dt} \\ \frac{d\psi_{2y}}{dt} \end{bmatrix} = \begin{bmatrix} -K_3 & \omega_1 & -K_2 K_4 & -K_2 \omega_m n_p \\ -\omega_1 & K_3 & K_2 \omega_m n_p & -K_2 K_4 \\ 0 & MK_4 & -\omega_2 & K_4 \end{bmatrix} \begin{bmatrix} i_{1x} \\ i_{1y} \\ \psi_{2x} \\ \psi_{2y} \end{bmatrix} + \begin{bmatrix} K_1 & 0 \\ 0 & K_2 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_{1x} \\ u_{1y} \end{bmatrix} \quad (14)$$

$$n_p \frac{M}{L_2} (\psi_{2x} i_{1y} - \psi_{2y} i_{1x}) - T_{load} = J \frac{d\omega_m}{dt} \quad (15)$$

where the meaning of the individual variables is as follows: u_{1x} , u_{1y} - components of stator voltage vector U_1 , ω_m -motor mechanical angular speed, ω_1 -angular speed of the stator voltage ($\omega_1 = 2\pi f_1$), ω_2 -slip angular speed ($\omega_2 = \omega_1 - \omega_m$), R_1 , R_2 -stator/rotor phase resistance, L_1 , L_2 -leakage inductances, T_m -motor mechanical torque, T_{load} -load torque, n_p -number of pole pairs, J -moment of inertia, L_m -main inductance, M -mutual inductance $M = 2/3 L_m$, $K_1 = 3/2 (L_1 + L_2 L_m / (L_m + L_2))^{-1}$, $K_2 = -3/2 (L_1 + L_2 + L_1 L_2 / L_m)^{-1}$, $K_3 = K_1 (R_1 + (M/L_2)^2 R_2)$, $K_4 = R_2 / L_2$

Figure 7 shows the block diagram representation of the induction machine model derived from Eqs. (14) and (15).

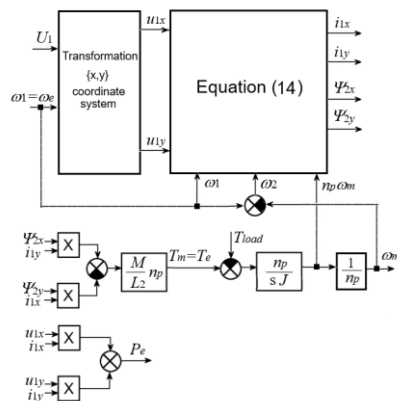


Figure 7. The block diagram of IM complete model

Figure 8 illustrates the mutual interconnection of the individual subsystems.

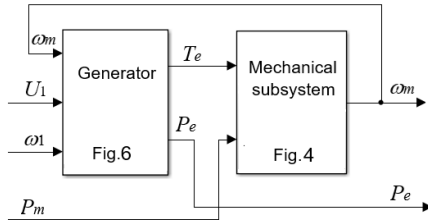


Figure 8. The block diagram of the electromechanical subsystem

4 MODEL VALIDATION AND TRANSIENT ANALYSIS OF THE SHPP

Based on the models of the fundamental SHPP subsystems presented in Chapter III, the complete SHPP model according to Fig. 9 was implemented in the MATLAB environment.

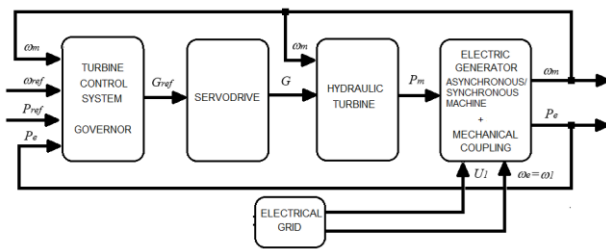


Figure 9. The structural diagram of the SHPP simulation model

To provide a rigorous validation of the proposed simulation model, it is necessary to define the assumed operational sequence of the SHPP and to describe the corresponding verification methodology in detail. The verification procedure was based on reproducing the typical operational states of the SHPP under controlled simulation conditions.

Within the developed model, the *start-up* process is initiated by an external command signal representing the operator's intervention. This signal activates the control subsystem, which accelerates the hydraulic turbine toward a predefined reference angular speed corresponding to the electrical grid frequency intended for connection. During this phase, the generator operates in an isolated condition, and the objective of control is to achieve stable quasi-synchronous mechanical speed while minimizing oscillations.

After reaching steady-state conditions, defined by the convergence of the turbine angular speed to the grid angular frequency, the generator is automatically connected to the electrical grid. At this stage, the reference active power is set to $P_{ref} = 0$, meaning that the generator remains synchronized but does not intentionally supply electrical power to the network.

In the subsequent phase, a non-zero reference power value is introduced via an input control signal. This command triggers the transition from speed control to power control mode. The SHPP then begins delivering electrical power to the grid by adjusting the slip speed through the additive control mechanism implemented in the governor subsystem. This operating sequence during *start-up* process enables systematic evaluation of the model's dynamic response during three operating states:

Run-up to grid speed, $t = \langle 0, 50 \rangle$ seconds,

grid connection, $t = \langle 50, 100 \rangle$ seconds,

power switching, $t = \langle 100, 200 \rangle$ seconds

thereby providing a comprehensive basis for validating the accuracy and robustness of the proposed simulation framework.

The complete SHPP model was validated using operational data obtained from the Slovakia SHPP Krompachy. The corresponding parameters are summarized in the Appendix.

4.1 Comparative analysis of the SHPP model characteristics with the complete and simplified induction generator representations

For the three defined operating states first the properties of the complete SHPP model were verified using both the simplified and the full dynamic model of the induction generator.

Figure 10 shows a comparison of the electromagnetic torques T_e and electrical powers P_e of the complete and simplified induction generator models under the fundamental operating states of the SHPP.

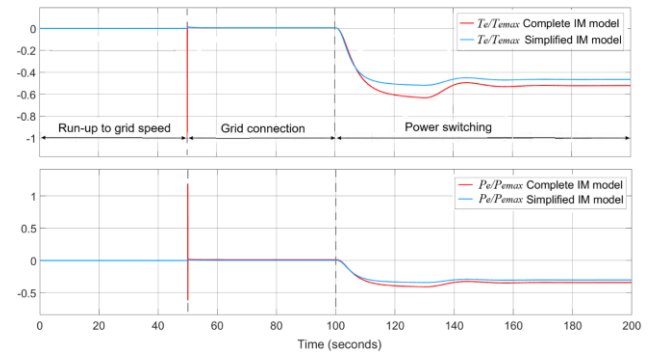


Figure 10. Comparison of torques and powers of the complete and simplified generator models.

During the start-up phase of the SHPP toward the electrical angular speed of the grid ω_e , the generator produces only the passive inertia torque and friction torque on the turbine shaft; therefore, its electromagnetic torque T_e and the electrical power P_e delivered to the grid are zero.

In the operating mode corresponding to the transition of turbine control from speed regulation to power regulation at $t=100$ seconds, the dynamic processes within the turbine are significantly slower. Under these conditions, the difference between the complete and simplified generator models becomes evident primarily in the steady-state values of the electromagnetic torque T_e and the generated electrical power P_e , as illustrated in Fig. 10.

The most significant difference between the two models occurs after the generator is connected to the electrical grid (Grid connection) at $t=50$ seconds. While the simplified induction machine model exhibits virtually no dynamic electromagnetic torque T_e on the common turbine-generator shaft, the complete model reveals short-term torque T_e and power P_e peaks. These peaks may approach the maximum permissible limits from the standpoint of torsional stress in the turbine shaft and can consequently induce undesirable vibrations in its bearings. A detailed view of the generator synchronization with the electrical grid is provided in Fig. 11.

The observed discrepancy stems from the fact that the simplified model neglects the fast electromagnetic transients occurring within the stator and rotor circuits. In contrast, the complete dynamic model captures millisecond-scale phenomena associated with magnetic flux establishment and current redistribution, which directly generate torque oscillations on the shaft. This highlights the inherent difference between the rapid electromagnetic dynamics and the

comparatively slower mechanical response of the turbine–shaft system.

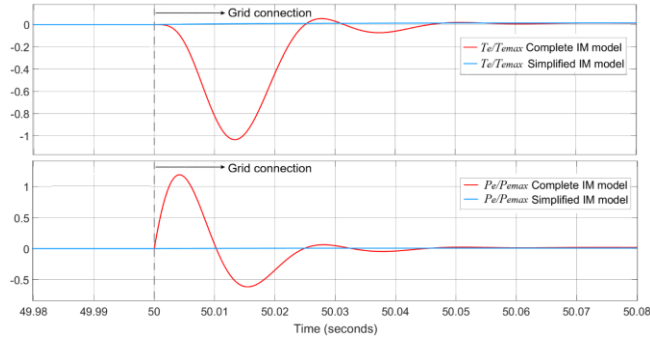


Figure 11. Detailed representation of the generator connection to the electrical grid

These observations clearly demonstrate that the simplified torque–slip model is insufficient for accurate analysis of fast electromagnetic phenomena. Therefore, the complete dynamic induction generator model is more appropriate for investigating transient events such as synchronization, voltage disturbances, or short-term outages.

From a practical engineering perspective, precise modeling of these phenomena is essential for proper dimensioning of electrical infrastructure components, including cables, contactors, circuit breakers, and protection devices, as well as for ensuring mechanical reliability of the turbine–generator shaft assembly. Consequently, the adoption of the complete induction machine model significantly enhances the predictive capability and applicability of the proposed SHPP simulation framework.

4.2 Simulation of the SHPP start-up

As previously stated, the start-up of the SHPP consists of three fundamental phases: turbine acceleration to grid speed, generator connection to the electrical grid, and transition to power control mode. The start-up simulation of the SHPP employing the complete induction machine model is presented in Fig.12.

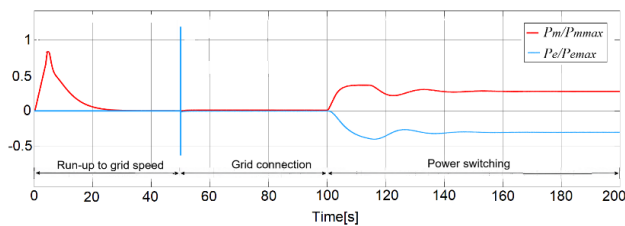


Figure 12. Power-based analysis of the SHPP start-up process

In the first start-up phase ($t=0 \div 50$ seconds), the turbine delivers mechanical power to the shaft P_m , accelerating the rotating assembly toward the electrical angular speed of the grid ω_e . At $t=50$ seconds, the induction generator is connected to the electrical grid.

At the instant of connection, the generator is not yet magnetized and must draw a transient magnetizing current from the grid to establish the air-gap magnetic flux. From the grid perspective, the stator circuit initially behaves as a low-impedance load, which gives rise to short-duration inrush currents. These current peaks are accompanied by electromagnetic torque oscillations acting on the common turbine–generator shaft.

After the electromagnetic transients' decay (approximately at $t=100$ seconds), the generator reaches steady operating conditions and enters the generating regime. At this stage, the

turbine control is switched to power regulation mode. As shown in Fig.12, the mechanical power supplied by the turbine P_m is converted into electrical power and delivered to the grid as active power P_e .

In steady generating operation, the turbine drives the rotor at a supersynchronous mechanical angular speed ω_m , slightly higher than the synchronous speed corresponding to the grid frequency (see Fig.13). In terms of induction machine theory, this corresponds to a negative slip condition

$$s = \frac{\omega_e - \omega_m}{\omega_e} < 0 \quad (16)$$

Under negative slip, the direction of electromagnetic torque reverses relative to motoring operation, and mechanical power is converted into electrical power supplied to the grid. The magnitude of the supersynchronous speed deviation is proportional to the required reference power P_{ref} , ensuring controlled and stable energy transfer.

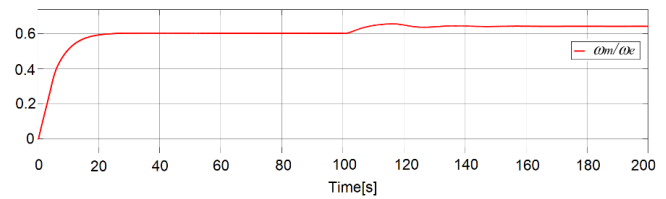


Figure 13. Analysis of the SHPP start-up based on the shaft mechanical angular speed ω_m

When the generator is directly connected to the grid at $t=50$ seconds, its stator currents exhibit peaks reaching approximately five times the nominal current value, as shown in Fig. 14.

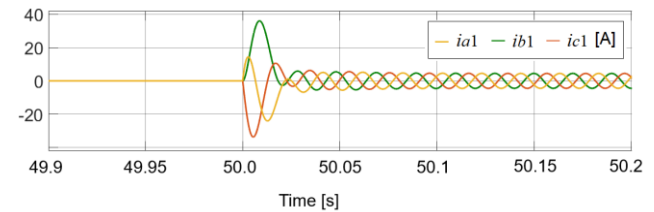


Figure 14. Waveforms of the individual components of the generator stator current during connection to the electrical grid

The stator winding resistance of the generator R_1 remains constant during grid connection and is equal to its nominal value (see parameters in Appendix). After the generator is connected to the electrical grid, the mechanical angular speed of the shaft ω_m temporarily decreases, as shown in Fig.15.

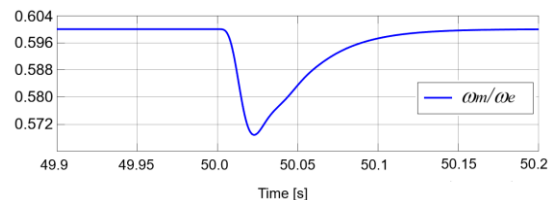


Figure 15. Mechanical angular speed ω_m of the shaft during generator grid connection

Current peaks represent an undesirable phenomenon in the electrical grid, as they may cause operational disturbances such as circuit breaker tripping or increased economic costs due to the need for oversized grid components and higher charges imposed by electricity suppliers.

Mitigation of transient current peaks can be achieved by temporarily connecting an additional stator resistance R_1 in series with the generator stator winding. This approach represents a technically simple and economically more

favorable alternative to conventional methods based on the insertion of inductive elements.

An example of the modeled influence of an additional stator resistance $R_1=11\Omega$ applied for a duration of $t=100$ milliseconds during generator connection to the electrical grid at $t=50$ seconds, under the condition $\omega_m=\omega_e$, is presented in Fig. 16.

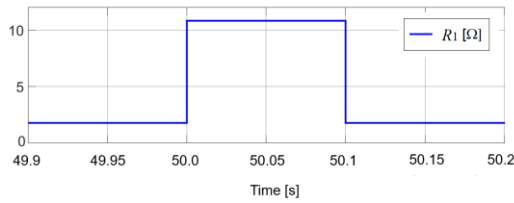


Figure 16. Variation of stator resistance during generator grid connection

Figure 17 illustrates the waveform of the shaft (turbine) angular speed ω_m and its short-term decrease at the moment when the additional stator resistance is inserted into the generator circuit.

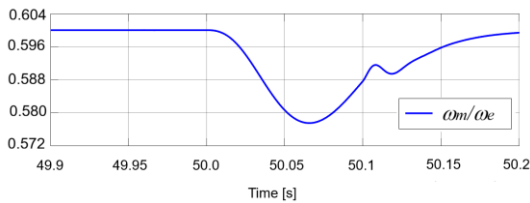


Figure 17. Waveform of the shaft mechanical angular speed ω_m after generator connection to the electrical grid using an additional resistance R_1

The waveforms of the individual stator current components are shown in Fig.18. Their maximum amplitude reaches approximately 18 A, corresponding to a reduction of the current peaks to about one half compared to the waveforms presented in Fig.14.

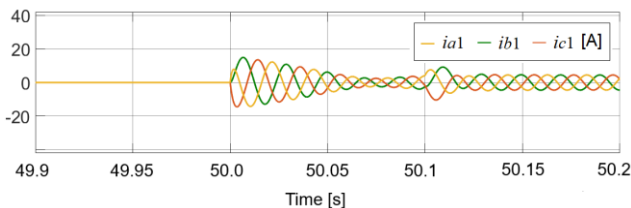


Figure 18. Waveforms of the individual components of the stator current i_1 after generator connection to the electrical grid using an additional stator resistance R_1

The simulation results demonstrate that this controlled connection strategy significantly attenuates transient stator current peaks and reduces the maximum torsional torque acting on the shaft to approximately one half of the values observed in the uncompensated case.

4.3 Sensitivity analysis of the SHPP model to parameter variations

The sensitivity of the proposed SHPP model to parameter variations was investigated by modifying the water time constant T_w , which represents one of the dominant dynamic parameters of the hydromechanical subsystem. The parameter T_w , often referred to as the water starting time, reflects the inertial properties of the water column in the penstock and is determined by its geometric and hydraulic characteristics.

For small hydropower plants, typical values of T_w range approximately from 5 s to 9 s, depending on the penstock length, cross-sectional area, and available water head [Kishor

2017, Munoz-Hernandez 2013]. In the case of the analyzed SHPP Krompachy, the nominal value is $T_w=7.15$ seconds.

To evaluate the robustness of the model, the parameter was varied within a realistic range corresponding to small hydropower plant configurations, specifically $T_w \in <5, 9>$.

The resulting responses of the normalized shaft angular speed over the complete SHPP start-up sequence are shown in Fig. 19.

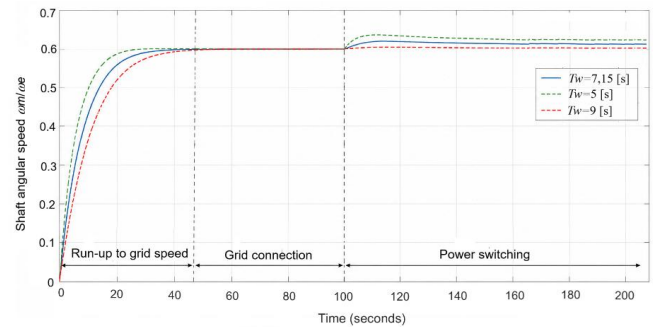


Figure 19. Sensitivity of the SHPP model to variations of the water time constant T_w during the complete start-up sequence.

The results indicate that variations of T_w significantly influence the transient response of the hydromechanical subsystem. Lower values of T_w produce faster turbine acceleration during the run-up phase, whereas higher values lead to slower dynamic response due to increased hydraulic inertia.

During the grid connection phase, the influence of T_w becomes substantially less pronounced, since the turbine angular speed remains approximately equal to the electrical angular speed of the grid. In contrast, during the transition to power control mode, variations of T_w affect the damping and settling characteristics of the transient response. Smaller values of T_w result in a faster but less damped response with higher overshoot, whereas larger values produce slower and more damped dynamics.

Despite these transient differences, the steady-state behavior of the system remains unchanged, indicating that the model preserves its static accuracy under parameter variation. These results demonstrate that the proposed simulation model exhibits robust dynamic behavior with respect to variations in key hydromechanical parameters.

The considered variation range reflects typical uncertainty in penstock properties, such as length and cross-sectional area, which may differ between installations or may not be precisely known. Therefore, sensitivity analysis confirms that the developed model can be reliably applied to a broader class of small hydropower plants with similar configurations.

5 CONCLUSION

This paper presented a comprehensive simulation framework for modeling and analysis of a small hydropower plant (SHPP), integrating hydraulic, mechanical, and electrical subsystems into a unified and physically consistent model. Emphasis was placed on the accurate representation of the electromechanical subsystem, especially the induction generator, using both simplified and complete dynamic models.

The developed model was validated using real operational data from the SHPP Krompachy, confirming its ability to accurately reproduce the dynamic behavior of the hydromechanical subsystem during the start-up phase. The comparison between simulated and measured turbine angular speed demonstrated a high level of agreement, with only minor deviations attributable to measurement uncertainties and unmodeled nonlinear effects.

A detailed comparative analysis of simplified and complete induction generator models revealed significant differences in their ability to capture transient electromagnetic phenomena. While the simplified torque-slip representation proved sufficient for steady-state analysis and slow dynamic processes, it failed to accurately describe short-term effects occurring during grid connection. In contrast, the complete dynamic model successfully captured transient current peaks, torque oscillations, and their interaction with the mechanical system. The results showed that these fast electromagnetic transients can reach critical levels, potentially affecting both electrical and mechanical components of the SHPP. Current peaks and torsional torque oscillations represent important factors in the design and dimensioning of electrical infrastructure, such as cables, circuit breakers, and protection devices, as well as in ensuring the mechanical integrity of the turbine-generator shaft system.

Furthermore, the study demonstrated that the insertion of additional stator resistance during generator connection represents an effective and technically simple method for mitigating transient current peaks and reducing mechanical stress. This approach provides a practical solution for improving the operational reliability of SHPP systems.

The performed sensitivity analysis further confirms that the proposed model is robust with respect to variations in key hydromechanical parameters, supporting its applicability to a wider range of SHPP installations with similar configurations. In summary, the proposed simulation model offers a robust and versatile tool for analyzing both steady-state and transient behavior of small hydropower plants. Its ability to capture the interaction between slow hydromechanical and fast electromagnetic phenomena makes it particularly suitable for design optimization, control system development, and evaluation of operating strategies in renewable energy systems. Future work will focus on extending the model to include fault conditions, advanced control strategies, and real-time implementation, further enhancing its applicability in practical engineering and research applications.

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APPENDIX

Parameters of the induction generator:

$P_R=315$ kW, $J=7.3$ kgm², $K_4=5.6106$ s⁻¹, $U_{1R}=400$ V, $R_1=0.01796$ Ω, $K_3=364.23$ s⁻¹, $I_{1R}=510$ A, $R_2=0.03656$ Ω, $K_1=1711.4$ H⁻¹, $T_{mR}=3126$ Nm, $L_{mV}=0.00933$ H, $K_2=1632.9$ H⁻¹, $n_R=1011$ revmin⁻¹, $M=0.00622$ H, $L_1=L_2=0.00045$ H, $n_p=6$

Hydraulic Turbine:

$P_m=330$ kW, $T_w=7.39$ s, $A_t=1.1123$, $D=1.4$ m, $q_{base}=4.5$ m³/s, $h_{base}=51.7$ m, $L=1$ 255 m, $h_r=0.95$, $q_{nl}=0.0434$ m³/s

Servo Drive:

$K_a=3$, $T_a=0.05$ s, speed limit: <- 0.2; 0.2>, position limit: <0.01; 0.975>

Governor:

$T_f=4$ s, Speed controller: $K_P=6.5$, $K_I=0.068$, Power controller: $K_P=0.15$, $K_I=0.1$

Mechanical link

$J_c=38$ kgm², $T_r=0.02$ s, $T_f=0.005$ Nm

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