Daniela Perduková, Pavol Fedor

Development of the complete model of the SHP with an asynchronous generator

Abstrakt Výskum malých vodných elektrární (MVE) ako významných zdrojov obnoviteľnej energie s negatívnym dopadom na životné prostredie patrí medzi aktuálne úlohy energetiky. Návrh parametrov MVE, určený analýzou dynamických javov pomocou špecifického simulačného modelu, ovplyvňuje výrobu elektrickej energie. Práca je venovaná oblasti modelovania systémov malých vodných elektrární so asynchrónnym generátorom s cieľom vytvoriť nástroj pre jednoduchý a presný návrh malých vodných elektrární a ich riadiacich štruktúr. Vyvinutý simulačný model MVE bol overený na dátach z reálnej MVE Dobšiná III a následne použitý na skúmanie dynamiky rýchlych elektromechanických javov počas jednotlivých režimov spúšťania MVE. Skúmanie týchto javov má význam pre dosiahnutie optimálnych rozmerov elektrickej siete (vrátane káblov a ističov), ako aj pre zabezpečenie efektívneho návrhu a prevádzky MVE. Získané výsledky potvrdili správnosť navrhnutého modelu MVE a jeho univerzálnu použiteľnosť pri riešení problémov optimálneho riadenia a dimenzovania MVE.

Kľúčové slová: malá vodná elektráreň (MVE); modelovanie; asynchrónny generátor; experimentálne overenie; elektrmechanické javy

Abstract The research of a small hydropower plants (SHP) as important sources of renewable energy with a negative impact on the environment belongs among the current tasks of power engineering. The design of the SHP parameters determined by analyzing dynamic phenomena using its specific simulation model affects the expected production of the electricity. The paper is dedicated to the field of modeling of small hydropower plant systems with an asynchronous generator, in order to create a tool for simple and accurate design of the small hydropower plants and their control structures. The developed simulation model of the SHP has been verified on data from real SHP Dobšina III and then used for investigation of the dynamics of fast electro-mechanical phenomena during individual start-up modes of the SHP. The investigation of these phenomena is important for achieving the optimal dimensions of the electrical grid (including cables and circuit breakers), as well as for ensuring the effective design and operation of the SHP. Obtained results confirmed correctness of the proposed SHP model and its universal applicability to solving the problems of the SHP optimal control and dimensioning.

Keywords: small hydropower plant (SHP); modeling; asynchronous generator; experimental verification; electro-mechanical phenomena

I. INTRODUCTION

In recent years, due to the growing consumption of electricity, the importance of small hydropower plants (SMEs) has been growing. This currently cover more than 2% of the total installed capacity of electricity in the world [1-2]. The production of electricity in hydroelectric power plants burdens the environment incomparably less than production based on traditional fossil fuels [3-4]. There does not exist no uniform definition of the SHP, but according to the IEEE Standard 1020-1988 [5] the SHP is defined as plant that unit power lies within the range between 100 and 5000 kW, its rated voltage is from 480 V to 13.8 kV and is equipped with an induction generator of a synchronous or asynchronous type.

Currently, multiple methods exist for simulating hydropower plants made up of individual subsystems [6-9]. These models are less complex than those for larger hydropower plants. This is because systems of smaller power capacities allow us to neglect certain factors, like the influence of water wave time constants, water hammer effects, and the role of surge chambers, due to their design and lower power capacities, [10-11]. At the same time, according to the scientific literature and papers [12-17], it is quite clear that the most frequently differing submodel of the overall hydropower plant simulation model is the submodel representing the hydraulic turbine and the processes associated with it. The difference lies in the authors' decision to proceed or not to with a linear, on otherwise strongly non-linear system, which has a not insignificant impact on the accuracy of the simulation model as well as on its scale [18].

The SHP models presented in [11-12], [17] allow to investigate the properties from the dynamic point of view of the slow hydro-mechanical part of the SHP (its time constants are in the order of seconds to tens of seconds), which are important for the design of its control. For the analysis of much faster dynamic processes of the power generator, the model of the SHP must be completed by a detailed description of its electromechanical part together with the model of the mechanical coupling between the turbine and the generator.

In large hydropower plants, a synchronous machine is commonly used as the generator [8-9], but small hydropower plants prefer asynchronous generators as:

1. Asynchronous generators do not require additional excitation sources. This is crucial, especially when the plant operates in island mode, where it is not connected to the wider grid. Asynchronous generators can start producing electricity without an external excitation source.
2. Simple construction and operation: Asynchronous generators have less complex construction and are easier to maintain. This simplicity is advantageous for small plants where ease of maintenance and reliability are key.
3. Grid connection: Asynchronous generators can be easily connected to the electrical grid. Their operation is robust and adaptable.

The article contains a description and models of individual MVE subsystems, from which its complete model was compiled using the MATLAB/SIMULINK program. The emphasis here is on the modeling of the electromechanical part of the SHP, where the current-flow model IM was used for the generator model instead of its simplified model based on the Kloss relation, which is most often used in the SHP models with an asynchronous generator [6], [9]. The proposed model (especially its hydro-mechanical part) was verified on data from the real SHP Dobšiná III.

This model has been utilized to explore the dynamic behavior of the electro-mechanical subsystem during the initial modes of Small Hydropower (SHP) operation. The investigation focused on three key modes: starting up the turbine to match the electrical grid speed, connecting the generator to the grid, and switching the SHP to power control mode. Throughout these modes, certain unwanted effects, such as current overshoots, may occur. It is critical when these phenomena do not meet the limits set by the grid's regulations. Exceeding these thresholds can cause operational disruptions within the SHP or its grid substations, and result in financial penalties if contracted energy quotas are breached.

The verification and simulation results proved that proposed model is universal and can be used for diagnosis, and analysis practically all problems related to the optimal control and dimensioning of the SHP.

II. THE SHP SIMULATIOM MODEL DEVELOPMENT

The basic topology of a small hydropower plant simulation model composition could be divided into several parts or smaller subsystems, respectively:

- Subsystem of Hydraulic Turbine Control (Governor)
- Subsystem of Servodrive controlling the water supply to the hydraulic turbine (Servo)
- Subsystem of Hydraulic Turbine
- Subsystem of other Eletromechanical parts of the system (Electrical Subsystem)

The complete model of the SHP is obtained by modeling its individual subsystems and their interconnection according to Fig. 1. Description of the used quantities in Fig. 1 are shown in Tab. 1.

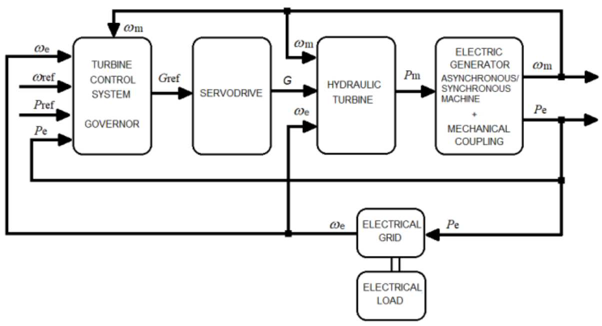

Fig. 1 Block diagram of a small hydropower plant

A. *Model of Hydraulic Turbine Control (Governor)*

For the purpose of developing our simulation model of a small hydropower plant, we have relied on the knowledge obtained from the description of different methods and procedures for the design of control structures for hydropower plants [6-9].

TABLE I
Description of the SHP Quantities

Variable	Unit
ω_{ref} – the reference value of the shaft angular speed which is the same as the electrical angular frequency of the grid	[rads^{-1}]
P_{ref} – turbine reference power	[W]
P_e – electrical power of the generator	[W]
ω_e – electric grid angular speed	[rads^{-1}]
G – servo drive position	[%]
G_{ref} – servo position reference value	[%]
P_m – mechanical power on the turbine shaft	[W]
ω_m – mechanical angular speed of the shaft	[rads^{-1}]

The turbine control fulfils two tasks:

1) turbine speed control in the generating area of the generator
2) control of the supplied power to the electrical grid (if required).

According to the above information, and taking into account the results published so far in this field [6-9], [11-12], [17] follows that the simplest model of such control is the control structure in Fig.2, which contains two controllers [9]. The angular speed controller R_ω is PID type and the power controller R_P of PI type. The switching to power control is provided by the logic signal d_{ref}.

In order to prevent the unwanted influence of rapid changes in the desired angular speed, a first-order filter with a time constant T_f is used in the control structure. At the turbine start-up, ω_{ref} may be different from ω_e, because the grid is not yet connected. When the angular speed of the turbine is synchronized with the electrical angular speed of the grid, the value of ω_{ref} is identical to ω_e.

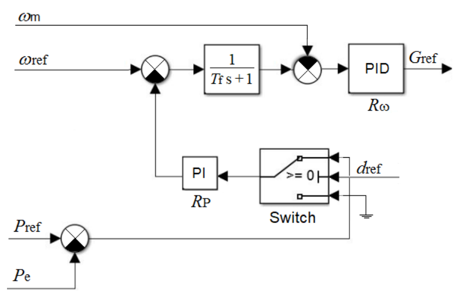

Fig. 2 Turbine control subsystem – Governor

B. *Servo Drive Model*

Our proposed simulation model of a small hydropower plant considers the use of a servo-drive in the position of the actuator providing the change of position, or opening and closing of the water supply to the hydraulic turbine. The model is represented as a second-order dynamic system in a block diagram (Fig.3), with the guide vane opening speed G_s and position G, as its state variables. In case where hydroelectric plants experience high water column levels, rapid changes in the servo-drive position can lead to phenomena like water hammer and cavitation. To enhance operational safety, the model includes a restriction on the speed at which the main valve can open. Additionally, there is a limit on the servo-drive output position to define the effective operational range where the turbine response to opening adjustments is significant. The servo-drive gain is denoted by K_a, and its time constant by T_a.

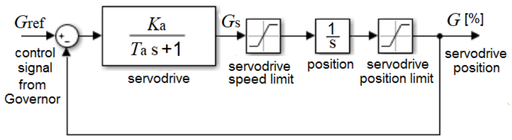

Fig. 3 Servo drive model

C. Hydraulic Turbine Model

The hydraulic turbine is considered the core component of a hydroelectric power plant, playing a crucial role in generating electricity. It is modeled as a complex nonlinear dynamic system. Ensuring the precision of this model is important for proper control methods and for the hydropower plant dynamic behavior to external load and factors [12].

Different turbine models vary in their approach how to include the turbine efficiency and its impact on the output mechanical power P_m [12, 16-17]. The paper utilizes a hydraulic turbine model that considers the flow efficiency at no load (denoted as q_{noload}) designed on the mathematical description presented in [12]. The hydraulic turbine block diagram is depicted in Fig. 4.

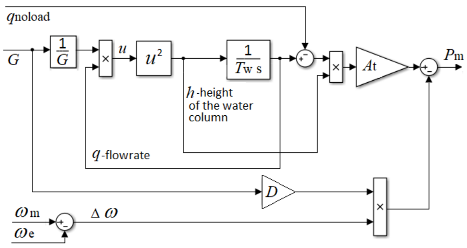

Fig. 4 Hydraulic Turbine model

The term q_{noload} denotes the turbine constant power losses, which are deducted from the current flow rate passing through the turbine. The adjusted flow is then multiplied by the water column height h. The variable $\Delta\omega$ indicates the difference between the mechanical angular speed of the shaft and the grid angular speed. The constant D represents the turbine load damping factor, related to the Penstock diameter, while G is the percentage of guide vane opening [%]. The water flow time constant T_w, also known as the water time constant or water starting time, along with the hydraulic turbine gain A_t were determined according [7].

D. Electro-mechanical subsystem model

The electro-mechanical subsystem consists of a model of the electric generator and a model of the mechanical coupling of the shaft connecting the turbine and the generator. The electro-mechanical model block diagram, shown in Fig. 5, includes U_1 as the grid voltage amplitude, f_1 as the grid frequency, which corresponds to the electrical angular velocity ω_e, and T_e is the generator electrical torque.

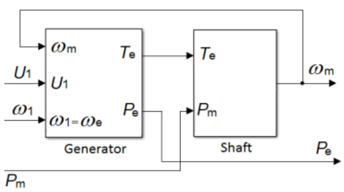

Fig. 5 Block diagram of generator

Model of the Mechanical Coupling

The generator-shaft subsystem coupling is depicted in Fig.6.

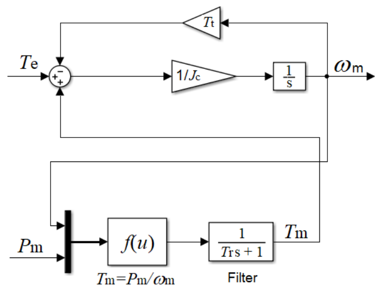

Fig. 6 Generator-shaft subsystem model

The model was proposed according the model referenced in [12]. Here, T_t denotes the friction torque (frictional losses), T_m represents the turbine mechanical torque, T_r is the time constant of the rotor in an asynchronous generator, which is associated with the rotor resistance and J_c is the total moment of inertia on the shaft.

Model of the generator

An IM was used as a generator in our model of the SHP. This type of generator is modeled in the SHP models in a simplified way based on the Kloss relation for its moment [12-14], [17]:

$$T_e = \frac{2U_1 s s_{max}}{s^2 + s_{max}^2} \qquad (1)$$

The block diagram of such a model is in Fig. 7, where U_1 is IM stator voltage, s and s_{max} are IM slip and its maximum slip, n_p represents number of poles, P_e is the generated electrical power on the shaft, which in case of an asynchronous machine is proportional to product of its torque T_e and the rotor angular speed ω_m.

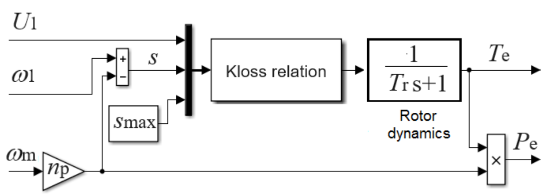

Fig. 7 Simplified block diagram of IM as a generator

Because our goal is to create the best possible SHP model with an asynchronous generator, suitable for accurate modeling and investigation of its fast electromagnetic phenomena, we replaced this simplified IM model with its complete model.

Several dynamic models of an IM are known in the literature, depending on the choice of state variables and the rotating coordinate system [19-20]. If the stator current and the rotor flux is chosen as the state variables, then the IM is described by a system of 5 nonlinear differential equations in the reference frame rotating by the synchronous speed, having the form:

$$\begin{bmatrix} \frac{\mathrm{d}i_{1x}}{\mathrm{d}t} \\ \frac{\mathrm{d}i_{1y}}{\mathrm{d}t} \\ \frac{\mathrm{d}\psi_{2x}}{\mathrm{d}t} \\ \frac{\mathrm{d}\psi_{2y}}{\mathrm{d}t} \end{bmatrix} = \begin{bmatrix} -\omega_0 & \omega_1 & -K_{12}\omega_\mathrm{g} & -K_{12}\omega_\mathrm{m}n_\mathrm{p} \\ -\omega_1 & \omega_0 & K_{12}\omega_\mathrm{m}n_\mathrm{p} & -K_{12}\omega_\mathrm{g} \\ M\omega_\mathrm{g} & 0 & -\omega_\mathrm{g} & \omega_2 \\ 0 & M\omega_\mathrm{g} & -\omega_2 & \omega_\mathrm{g} \end{bmatrix} \begin{bmatrix} i_{1x} \\ i_{1y} \\ \psi_{2x} \\ \psi_{2y} \end{bmatrix} + \begin{bmatrix} K_{11} & 0 \\ 0 & K_{12} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} u_{1x} \\ u_{1y} \end{bmatrix} \quad (2)$$

$$n_\mathrm{p}\frac{M}{L_2}\left(\psi_{2x}i_{1y} - \psi_{2y}i_{1x}\right) - T_\mathrm{load} = J\frac{d\omega_\mathrm{m}}{dt} \quad (3)$$

It is a current-flow model of a three-phase squirrel-cage IM [21-22], where the motor quantities (the stator current vector i_1 and the rotor flux vector ψ_2) are expressed using their components in the reference coordinate system $\{x, y\}$ rotating by the angular speed of the stator field ω_1. The parameters in (2), (3) can be determined from the motor parameters by the recalculation according to the following equations:

$$K_{11} = \frac{3}{2}\left(L_{s1} + \frac{L_{s2}L_\mathrm{h}}{L_{s2}+L_\mathrm{h}}\right)^{-1} \quad (4)$$

$$K_{12} = -\frac{3}{2}\left(L_{s1} + L_{s2} + \frac{L_{s1}L_{s2}}{L_\mathrm{h}}\right)^{-1} \quad (5)$$

$$\omega_0 = K_{11}\left[R_1 + \left(\frac{M}{L_2}\right)^2 R_2\right] \quad (6)$$

$$M = \frac{2}{3}L_\mathrm{h} \quad (7)$$

$$\omega_\mathrm{g} = \frac{R_2}{L_2} \quad (8)$$

$$L_2 = \frac{2}{3}(L_{s2} + L_\mathrm{h}) \quad (9)$$

The block diagram of the IM corresponding to (2), (3) is shown in Fig. 8, where u_{1x}, u_{2x} are the components of the stator voltage vector U_1.

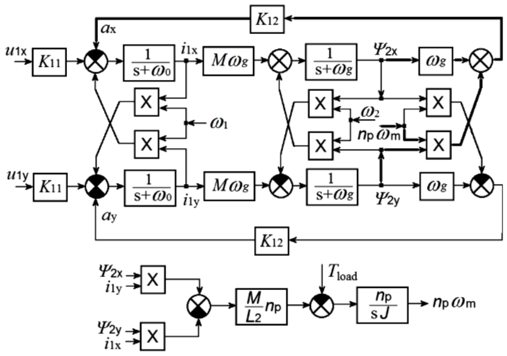

Fig. 8Block diagram of an induction machine (generator)

The description of the individual parameters of the IM are shown in Tab. 2.

TABLE II.
Induction Machine Parameters Description

Symbol	Quantity
P_R	rated power
U_{1R}	rated stator voltage
I_{1R}	rated stator current
T_{eR}	rated torque
n_R	rated revolution
n_p	number of poles
J	moment of inertia
ω_0	parameter defined by eq. (6)
L_2	parameter defined by eq. (9)
R_1	stator phase resistance
R_2	rotor phase resistance
L_m	main inductance
M	parameter defined by eq. (7)
$L_{s1} = L_{s2}$	leakage inductance
K_{11}	parameter defined by eq. (4)
K_{12}	parameter defined by eq. (5)
ω_g	rotor winding time constant – eq. (8)
ω_m	rotor mechanical angular speed
ω_1	angular speed of the stator voltage U_1
ω_2	slip angular speed $\omega_2 = \omega_1 - \omega_m$

III. VERIFICATION OF THE SHP MODEL ON PARAMETERS FROM THE REAL SHP DOBŠINÁ III.ŽITOČNÉ RADY

Based on the models of basic SHP subsystems presented in Chap. II., the overall SHP model according to Fig. 1 was created.

Naturally, the necessary part of designing such a simulation model of a small hydropower plant is also its verification based on the data of the existing system. For these purpose the small hydropower plant Dobšiná III, which consists of one Kaplan turbine of 275 kW directly coupled to an asynchronous squirrel cage generator of 315kW has been chosen.

Parameters of asynchronous generator of the SHP Dobsina III. are given in Tab.III. and parameters for its hydro-mechanical subsystem including parameters of speed power controllers of Governor are in Tab.IV.

TABLE III.
Parameters of asynchronou sgenerator

Symbol	Value	Symbol	Value
P_R	315 kW	R_1	0.01796 Ω
U_{1R}	400 V	R_2	0.03656 Ω
I_{1R}	510 A	L_m	0.00933 H
T_R	3126 Nm	M	0.00622 H
n_R	1011 rev.min^{-1}	$L_{s1} = L_{s2}$	0.00045 H
n_p	6	K_{11}	1711.4 H^{-1}
J	7.3 kgm^2	K_{12}	-1632.9 H^{-1}
ω_0	364.23 s^{-1}	ω_g	5.6106 s^{-1}
L_2	0.00652 H		

TABLE IV.
Parameters of hydro-mechanical subsystem

Symbol	Value	Symbol	Value
Hydraulic Turbine		Servo Drive	
P_m	275 kw	K_a	3.33
T_w	1.00594 s	T_a	0.07 s
D	0.0001 m	Speed limit	<– 0.2; 0.2> p.u.
A_t	1.1992	Position limit	<0.01; 0.975> p.u.
Governor			
T_f	4 s		
Speed controller R□ (PID)		Power controller R_P (PI)	
K_P	6.5	K_P	0.15
K_I	0.068	K_I	0.1
K_D	0		
Mechanical link			
J_c	40 kgm^2	T_r	0.02 s
T_t	0.005 Nm		

The correctness of the simulation model was verified by comparing the course of the mechanical angular speed ω_m of the turbine during its start-up to the grid speed before phasing the generator to the electrical grid. Figure 9 shows the start-up process of MVE Dobšiná III from the control system of real operation. From the graph it can be seen that the turbine will start up to the speed corresponding to the grid frequency in 25 seconds, i.e. the course of the transition of its mechanical angular speed ω_m stabilizes in the given time.

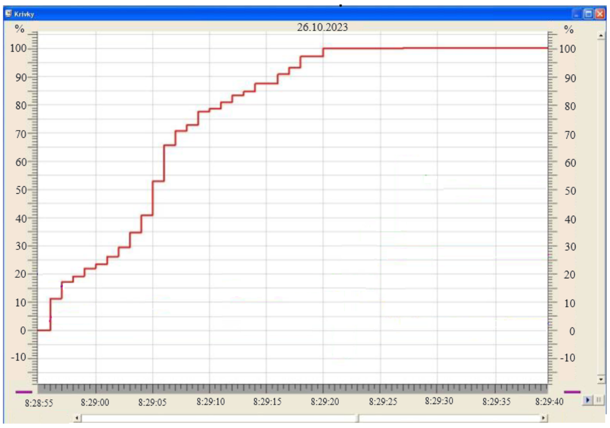

Fig. 9 Run-up of the small hydropower plant Dobšiná III. to the speed corresponding to the grid frequency - 100% (f_1=50 Hz), obtained from control system

The course of the mechanical angular speed ω_m of the turbine during its start-up to the grid speed obtained from the simulation model in the MATLAB/Simulink program is shown in Fig. 10., where due to the different normalization of the quantity ω_m, its value of 60% corresponds to the value of 100% in Fig. 9.

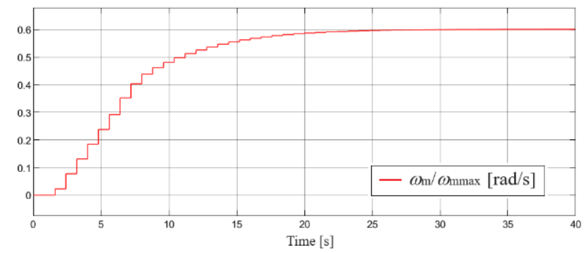

Fig. 10 Run-up of the small hydropower plant Dobšiná III. to the speed corresponding to the grid frequency - 60% (f_1=50 Hz) obtained from proposed simulation model of the SHP

From Fig. 9 and Fig. 10, we see that the dynamics of the transition of the mechanical angular speed ω_m of the turbine during its start-up to the grid speed is the same. It means that the turbine runs up to the grid speed and is ready to connect the generator to the electrical grid in time t=25 seconds. In this way, we verified the accuracy of the hydromechanical part of the simulation model, which includes all the properties of its subsystems, especially the turbine model itself, its nonlinearities, as well as the Governor control subsystem (speed control). The resulting differences during the transition of the mechanical angular speed ω_m can be caused, for example, by the output from the speed sensor installed in the Dobšiná III power plant, as well as by possible differences in the topology of its speed control, which were not known to us in detail.

IV. SIMULATION OF THE SMALL HYDROPOWER PLANT START-UP

With the help of such verified simulation model of the SHP, the start-up of a small hydropower plant with an induction generator was carried out. The research aims to perform a detailed examination of the electrical phenomena within the generator and its effects on the power grid, particularly concerning the emergence of unwanted effects such as stator current overshoots. These overshoots should remain within the limits set by the grid when the generator is connected to the grid and the SHP is switched to power control mode.

The SHP start-up has three basic modes:

1. the turbine start-up to the grid speed,
2. the generator connection to the electric grid,
3. the SHP switching to power control.

The SHP performance during the all start-up modes is depicted in Fig. 11a. In the first mode (t = 0÷50 s) the mechanical power on the shaft (P_m) is delivered by the turbine, which starts to run up to the grid electrical angular speed ω_e.

At time t = 50 seconds, the generator is connected to the power grid. Upon this connection, the generator behaves like an unexcited electrical machine, presenting minimal stator resistance to the grid. This leads to significant short-term overshoots in stator currents, that are stabilized at time t = 100 seconds. The generator is then in an excited mode and the turbine can be switched to the power control mode.

Figure 11a illustrates that during this mode of the SHP start-up, the generated power by the turbine (P_m) is transferred via the shaft to the generator and then delivered to the grid (P_e).

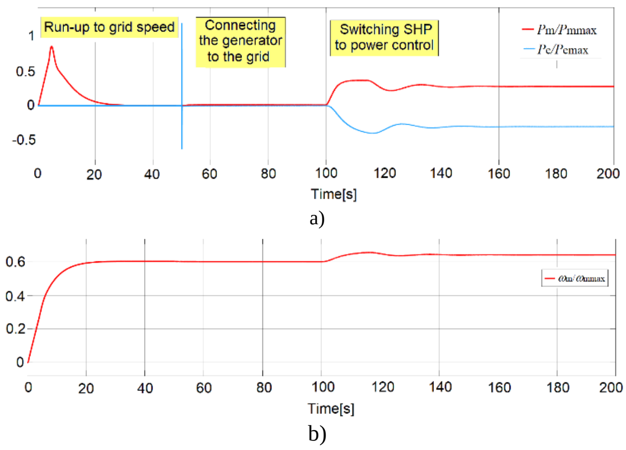

Fig. 11Simulation of the SHPP start-up
a) in terms of performances;
b) mechanical angular speed of the shaft.

Following the stabilization of dynamic phenomena at time t = 100 seconds, the turbine reaches an oversynchronous angular speed (represented by the mechanical angular speed of the shaft ω_e), which correlates to the required turbine power (P_{ref}) (see Fig. 11b).

Upon direct connection of the generator to the grid at time t = 50 seconds, the stator currents show four times higher overshoots than the rated currents, as depicted in Fig. 12.

Excessive current peaks are unwelcome in the electrical grid as they may lead to operational disruptions, including the activation of safety mechanisms like circuit breakers, or escalate financial expenditures due to the need for larger grid infrastructure or higher charges from energy providers. Consequently, accurately simulating these phenomenon is crucial for the conceptualization and sizing of SHP, particularly when they operate under non-standard conditions.

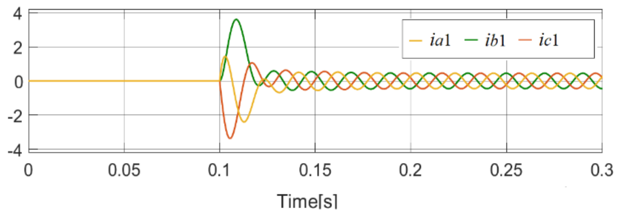

Fig. 12 Course of the stator current I_1/I_{1R} components of the generator when connected to the electrical grid

V. CONCLUSION

Energy power systems computer models simplify and accelerate their design process, while also reducing implementation costs. The complete SHP simulation model presented in the paper employs a current-flow model of an induction machine as a generator. This approach differs from earlier SHP models that used a simplified induction machine model based on the Kloss relation. It facilitates the modeling of all critical SHP subsystems, both hydro-mechanical and electrical, along with their interconnections.

The properties, mainly, of the hydro-mechanical part of this model have been verified on data obtained from real existing SHP Dobšiná III. The result proved that the model was set up and designed properly and corresponds to the real measured outputs from the simulated system. Utilizing proposed simulation model, the dynamic properties of fast electromagnetic phenomena have been analyzed throughout the SHP start-up modes. It is important to model these phenomena because transitions between operational modes may cause adverse effects on the SHP functionality, leading to economic consequences. Additionally, it is significant for meeting the electrical grid standards, which include the proper dimensioning of cables, circuit breakers, and other components.

The verification and simulation outcomes indicate that the proposed SHP simulation model is an effective tool for precisely analyzing its operational modes. It proves to be practical for addressing nearly all issues associated with the designing and control of the SHP.

ACKNOWLEDGMENT

This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-19-0210 and project VEGA 1/0363/23. Funded by the EU NextGenerationEU through the Recovery and Resilience Plan for Slovakia under the project No. 09I05-03-V02-00018.

REFERENCES

[1] H.S. Sachdev, A.K. Akella and N. Kumar, „Analysis and evaluation of small hydropower plants: A bibliographical survey,“ in: Renewable and Sustainable Energy Reviews, vol. 51, 2015, pp. 1013-1022, doi.10.1016/j.rser.2015.06.065.

[2] O. Doso and S. Gao, „An overview of small hydro-power development in India,“ in: AIMS Energy, vol.8, no. 5, 2020, pp.896-917, doi 10.3934/energy.2020.5.896

[3] S. Overshoote, Renewable energy: Power for sustainable future, Oxford University Press, 2018 , p. 656. ISBN 9780198759751.

[4] K. Mahesh, „Social, Economic, and Environmental Impacts of Renewable Energy Resources,“ Chapter in: K. Eloghene Okedu, A. Tahour, and A. Ghani Aissaou, Eds., “Wind Solar Hybrid Renewable Energy System,” Feb. 2020, doi: 10.5772/intechopen.77440.

[5] IEEE Guide for Control of Small Hydroelectric Power Plants. IEEE Std. 1020-1988; 1988, pp. 1-36.

[6] A. Acakpovi, E.B. Hagan, and F.X. Fifatin, “Review of Hydropower Plant Models,” in: International Journal of Computer Applications, vol.108, no.18, 2014, pp. 33-38, doi.10.5120/19014-0541

[7] N. Kishor and J. Fraile-Ardanuy, Modeling and Dynamic Behaviour of Hydropower Plants, London: The Institution of Engineering and Technology, 2017. p. 279. ISBN: 978-1-78561-195-7.

[8] H.J. Wagner and J. Mathur, Introduction to Hydro Energy Systems: Basics, Technology and Operation. Hedidelberg: Springer, 2011. ISBN 978-3-642-20708-2.

[9] G. Munoz-Hernandez, S. Mansoor, D. Jones, Modelling and Controlling Hydropower Plants. London: Springer, 2013. ISBN 978-1-4471-6221-6.

[10] R. Olexa, D. Perduková and P. Fedor, „Fuzzy Approach of Modeling a Hydraulic Turbine Efficiency,“ in: MM Science Journal, vol. 2020, 2020, pp. 4086-4092. ISSN 1803-1269. doi.10.17973/MMSJ.2020_11_2020033.

[11] D. Tsuanyo, B. Amougou, A. Aziz, B.N. Nnomo, D. Fioriti and J. Kenfach, „Design models for small run-of-river hydropower plants: a review,“ in: Sustainable Energy res, vol.10, no.3, 2023. doi.10.1186/s40807-023-00072-1.

[12] M. Sattouf, “Simulation Model of Hydro Power Plant Using Matlab/Simulink,” in: International Journal of Engineering Research and Applications, vol. 4, no.1, 2014, pp 295-301. ISSN 2248-9622.

[13] H. Fang and Z. Shen, „Modeling and Simulation of hydraulic transients for hydropower plants,“ in: Proceedings of IEEE/PES transmission and distribution conference and exhibition: Asia and Pacific, August 2005, pp. 1–4. doi.10.1109/TDC.2005.1546782.

[14] C.L.T. Borges and R.J. Pinto, „Small hydro-power plants energy availability modeling for generation reliability evaluation,“ in: IEEE Trans Power Syst, vol.23, no.3, 2008, pp. 1125-1135. doi.10.1109/TPWRS.2008.926713.

[15] Zhu, Jianguo, Li, Xianshan. Modularization modeling of the full-scope dynamic simulation for power system. In: Proceedings of Power and Energy Engineering Conference (APPEEC). Asia–Pacific; March 2010. pp. 1–4. doi 10.1109/APPEEC.2010.5448634

[16] D. Perduková,, M. Fedor, P. Fedor, „Various Approaches for a Design of the Hydraulic Turbine Model,“ in: 11th International Scientific Symposium on Electrical Power Engineering, Elektroenergetika 2022, 12.-14.9.2022, Stara Lesna, Slovakia. ISBN 978-805534104-0.

[17] J. Tiwari, A. Yadav, R.K. Jha and A.K. Singh, “Modelling and Simulation of Hydro Power Plant using MATLAB & WatPro 3.0,” in: Intelligent Systems and Applications, vol.7, no.8, 2015, pp. 1-8. doi.10.5815/ijisa.2015.08.01.

[18] E. Özbay and M. T. Gençoğlu, "Modeling of small hydro power plants," in: Proc. of National Conference on Electrical, Electronics and Computer Engineering, Bursa, Turkey, 2010, pp. 32-36.

[19] P. Palacký, M. Sobek, P. Hudeček, D. Slivka and V. Sládeček, “Asynchronous motor working as generator with VSI using flux field oriented control,” in: Proc. of 11th International Scientific Conference Electric Power Engineering (EPE), 2010, pp. 817 – 822

[20] M. Kuchař, P. Palacký, P. Šimonik, P. and J. Strossa, “Self-Tuning Observer for Sensor Fault-Tolerant Control of Induction Motor Drive,” in: Energies, vol. 14, no. 9, 2021, article no. 2564. doi.10.3390/en14092564.

[21] C.D. Tran, M. Kuchař, M. Sobek, V. Sotola and B.H. Dinh, “Sensor Fault Diagnosis Method Based on Rotor Slip Applied to Induction Motor Drive,” Sensors, vol.22, no.22, 2022, art. no. 8636. doi.10.3390/s22228636.

[22] D. Perduková, P. Palacký, P. Fedor, P. Bober and V. Fedák, „Dynamic Identification of Rotor Magnetic Flux, Torque and Rotor Resistance of Induction Motor,” in: IEEE Access, vol.8, 2020, pp. 142003-142015. ISSN 21693536. doi.10.1109/ACCESS.2020.3013944.

ADRESY AUTOROV

Daniela Perduková, Technical University of Košice, Department of Electrical Engineering and Mechatronics, Letná 9, Košice, SK 040 01, Slovak Republic, daniela.perdukova@tuke.sk

Pavol Fedor, Technical University of Košice, Department of Electrical Engineering and Mechatronics, Letná 9, Košice, SK 040 01, Slovak Republic, pavol.fedor@tuke.sk