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Development and Validation of Dynamic RMS Models for Power System Analysis

Petar Vinković, Renata Rubeša, Goran Levačić

Summary **— The increasing integration of converter-based renewable energy sources is reducing the inertia of power systems and amplifying transient oscillations following disturbances. As a result, the accuracy of dynamic simulation models of generating units has become essential for reliable assessment of system transient stability. This paper presents a validation procedure for a root-mean-square dynamic model of Unit D of the Zakucacˇ hydropower plant, based on measurements obtained from a phasor measurement unit during and after a real system disturbance. The validation process includes preparation of measurement data, alignment of the static model with steady-state measurements, and detailed tuning of dynamic model parameters. The achieved results demonstrate a high level of agreement between simulated and measured responses. In addition, the paper highlights the importance of standardizing requirements for the submission of simulation models, as accurate modeling of individual generating facilities directly enhances the credibility of system-level analyses and supports secure and stable power system operation under increasing system complexity.**

Keywords **— dynamic model, RMS model, validation, PMU**

I. Introduction

In April 2025, a massive power outage occurred on the Iberian Peninsula, representing the largest energy-related incident in Europe over the past decade. Although the causes of such events are often multiple, public criticism has increasingly been directed toward renewable energy sources (RES) and the ongoing energy transition. These concerns are not entirely unfounded, as the integration of RES, while essential for decarbonization, often displaces conventional generating units, resulting in a reduction of the overall inertia of the power system.

System inertia plays a crucial role in maintaining frequency stability by providing an immediate and inherent response of synchronous generators to active power imbalances. As system inertia decreases, the power system becomes more vulnerable to disturbances. In particular, following a major generation outage, the rate of change of frequency increases, the frequency nadir occurs earlier, and the depth of the frequency deviation becomes more pronounced, significantlyreducing the system's resilience to disturbance and increasing the risk of cascading outages triggered by protection systems.

In order to prevent such incidents, it is essential to identify potential stability issues in advance. This is only possible if the mathematical models used in system studies accurately represent the actual system behavior. In this context, model validation is of utmost importance, as it confirms the reliability and applicability of models used in stability analyses.

The first part of this paper presents a dynamic model validation procedure based on a single generating unit of the Zakucac hydropower plant. The second part emphasizesˇ the need to establish clear guidelines for the submission of dynamic models by generating units connecting to the power system.

II. Dynamic Model Validation

A. Role of Dynamic Models in Power System Studies

Mathematical models are used for the design, operation, and planning of power systems to describe the behavior of generating units, network components, and the system as a whole. Of particular importance are dynamic models, which enable the analysis of time-varying phenomena such as system response to disturbances, oscillations, voltage stability, and rotor angle stability.

In accordance with Commission Regulation (EU) 2017/1485 establishing guidelines on electricity system operation, commonly referred to as the System Operation Guidelines (SO GL), transmission system operators (TSOs) are explicitly required to assess the dynamic stability of the power system as part of continuous system operation and security planning. Dynamic stability refers to the ability of the power system to remain in a balanced and synchronized state following major disturbances, such as short circuits, sudden loss of generation, large load variations, or the operation of protection systems.

In practice, two main types of dynamic models are used. RMS models simplify simulations by considering only the root-mean-square values of voltages, currents, and powers, assuming quasi-stationary behavior. EMT (Electromagnetic Transient) models, on the other hand, enable detailed analysis of fast electromagnetic phenomena in the time domain, including high-frequency components with time resolutions on the order of microseconds.

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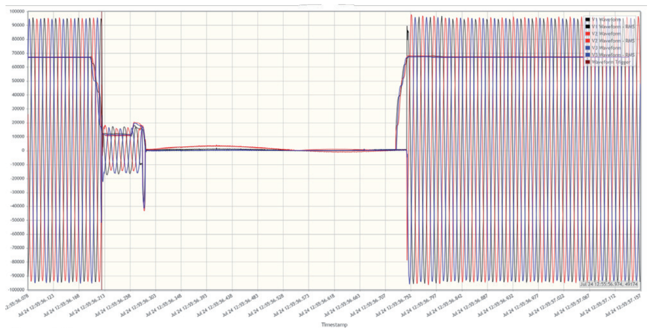

Fig. 1. Three-Phase Short Circuit on TL Jelinak - Gluncaˇ

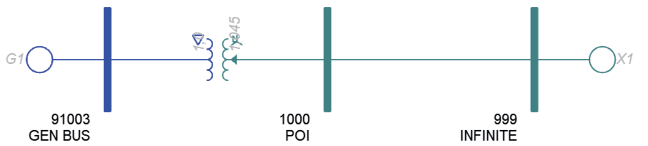

Fig. 2. Simulation Model Diagram

Although EMT models provide higher accuracy, especially in converter-dominated networks, their computational complexity and long simulation times limit their applicability in operational and planning studies of large-scale systems. Consequently, RMS models are widely used in operational planning, stability analysis, and grid connection studies, as they offer an acceptable trade-off between accuracy and computational efficiency.

This paper focuses on the development and validation of an RMS dynamic model of a generating unit based on real measurements obtained from a phasor measurement unit (PMU). Such validated RMS models form the foundation for reliable analysis of system behavior during and after disturbances and support informed operational and planning decisions.

B. Recorded Disturbance in the Croatian Power System

In July 2024, a three-phase short circuit was recorded on a 110 kV transmission line (TL) between the Jelinak and Glunca substations. Figure 1 shows the voltage waveformsˇ before, during and after the fault from the COMTRADE file. The estimated fault duration until protection operation was approximately 80 ms, after which the line was disconnected. Approximately 460 ms after disconnection, a successful automatic reclosing occurred. This event resulted in deviations of system frequency and voltage, which were particularly pronounced at electrically closer substations.

One of the substations where the disturbance was clearly observed was the Zakucac hydropower plant. During the inci-ˇ dent, only one of the four generators was in operation, namely Unit D, which is connected to the 110 kV busbar via a block transformer. This configuration enabled isolated observation of the response of a single generating unit, representing an ideal case for precise dynamic model validation. The diagram of the simulation model is illustrated in Figure 2.

Accordingly, the validation presented in this paper is carried out using the example of Unit D of the Zakucac hydropowerˇ plant, demonstrating the model's ability to accurately reproduce the system response during and after the disturbance.

C. Dynamic Model Validation Procedure

A prerequisite for dynamic model validation is the availability of PMU measurements, which serve as the primary data source for validation. PMUs enable synchronized recording of generator responses, providing a reliable basis for comparing simulated and measured responses. In other words, validation is only possible if the generating unit response during and after a disturbance has been captured by PMU measurements. The measurement resolution used in this study was 20 ms, corresponding to a reporting rate of 50 frames per second in a 50 Hz system, which represents a standard configuration in accordance with IEEE C37.118.1 [1]. It should be emphasized that this value represents the reporting interval of synchrophasor estimates rather than the internal signal sampling frequency of the PMU. For RMS dynamic validation focused on electromechanical phenomena, a 20 ms reporting interval provides sufficient temporal resolution. PMU phasor estimation algorithms typically employ window-based signal processing, and a small measurement delay may be present. Therefore, the measurement and simulation signals were timealigned prior to comparison.

The dynamic model validation process can be divided into three main steps:

1. **Preparation of measurement data:** The first step involves processing PMU data. The quantities of interest include RMS values of the active and reactive power of the generating unit, as well as frequency and voltage magnitude at the high-voltage busbar.
2. **Static model alignment:** Prior to dynamic model validation, the steady-state power flow must be properly aligned with the measured operating point. Accordingly, the simulated pre-disturbance active and reactive power outputs should closely match the measured values.
3. **Dynamic model validation:** The key validation step involves comparing the simulated dynamic response with the measured response during the disturbance. Model parameters are tuned to achieve the best possible agreement with measurements.

The steady-state parameters of the generator and the associated block transformer used in the simulation model are summarized in Tables I and II. Simulations were performed using the PSS®E software tool (Siemens PTI). The parameter notation follows the conventions used in the PSS®E environment. Figures 3 and 4 show the implementation of these parameters in the PSS®E environment. These parameters define the steady-state operating point used as the initial condition for the dynamic simulations.

The dynamic model of the generating unit includes the generator model, excitation system, turbine governor, power system stabilizer, and voltage measurement compensation model.

Although leading technical organizations such as IEEE, NERC, ENTSO-E, and CIGRE do not prescribe strict numeri-´ cal acceptance criteria for validated models [2]–[5], a set of engineering principles has been established in practice to assess model adequacy. Model quality is typically evaluated through both quantitative and qualitative comparison of simulated and measured responses under real disturbance conditions. model adequacy. Model quality is typically evaluated through both quantitative and qualitative comparison of simulated and measured responses under real disturbance conditions.

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TABLE I
GENERATOR STEADY-STATE PARAMETERS

Parameter	PSS®E	Value	Unit
Rated apparent power S_n	MBASE	160	MVA
Rated voltage (generator bus)	BASKV	16	kV
Maximum active power P_{max}	PMAX	144	MW
Minimum active power P_{min}	PMIN	63	MW
Maximum reactive power at P_{max}	QMAX	69.7	MVAr
Minimum reactive power at P_{max}	QMIN	-19.4	MVAr
Source impedance (real part)	RSOURCE	0	p.u.
Source impedance (imaginary part)	XSOURCE	0.2068	p.u.
Scheduled voltage	VSCHED	1.01	p.u.

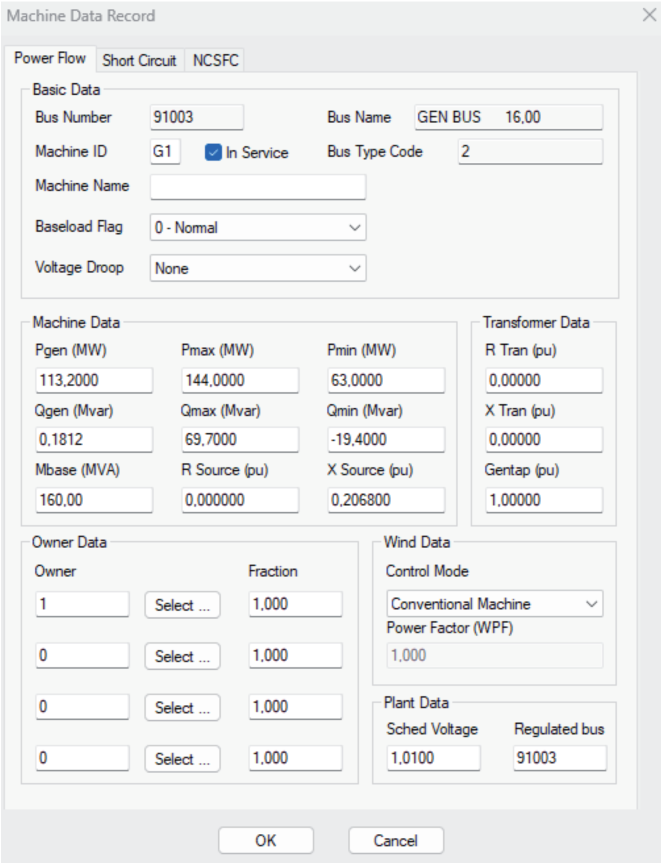

Fig. 3. Machine Data for Power Flow Analysis

TABLE II
BLOCK TRANSFORMER PARAMETERS

Parameter	PSS®E	Value	Unit
Rated apparent power S_n	Winding MVA	160	MVA
Rated voltage (HV side)	Winding 1 Nominal	121	kV
Rated voltage (LV side)	Winding 2 Nominal	16	kV
Tap setting voltage	Winding 1 Voltage	114.95	kV
Vector group	Vector Group	YNd5	–
Number of tap positions	Tap positions	7	–
Upper tap limit	R1max	1.155	p.u.
Lower tap limit	R1min	0.99	p.u.
Short-circuit (SC) losses	Load loss	510000	W
SC impedance magnitude	Z	0.131	p.u.
No-load losses	No load loss	60000	W
Magnetizing current	I0	0.00111	p.u.

Fig. 4. Transformer Data for Power Flow Analysis

In this context, an acceptable model should satisfy the following criteria: good agreement in key variables such asactive and reactive power, frequency, and bus voltage; acceptable deviations in amplitude and timing; consistency across different disturbance scenarios; numerical stability; and final acceptance based on engineering judgment considering the intended application of the model.

D. VALIDATION RESULTS

After all validation steps were completed, the response of the generating unit was simulated to the recorded frequency deviation and voltage dip. For this purpose, a playback model available in the PSS®E software package was used. The playback model allows measured time series signals, in this case the RMS voltage and frequency recorded by the PMU on the 110 kV busbar of the Zakucac hydropower plant, to beˇ injected directly into the dynamic simulation.

These signals are reproduced as time-varying inputs, enabling the simulated model to respond to the same excitation as the actual generating unit experienced during the disturbance. This approach eliminates the need to model the remainder of the network or the conditions that caused the disturbance and allows the analysis to focus exclusively on the response of the generating unit.

Figure 5 shows the RMS voltage value from the PMU at the point of interconnection (POI), while Figure 6 shows the frequency from the PMU at the same point. Figure 7 compares the voltage from PMU measurements with the voltage used as input to the simulation. Figure 8 compares the frequency from PMU measurements with the frequency used as input to the simulation. Figures 7 and 8 show how the playback model faithfully reflects the recorded measurement data in the simulation environment.

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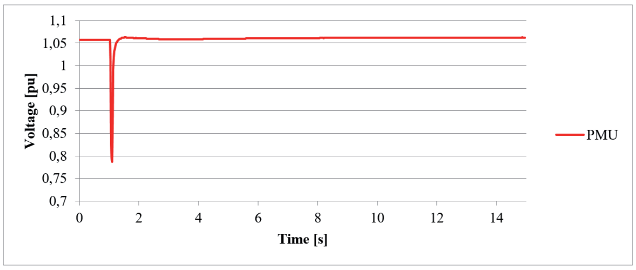

Fig. 5. RMS Voltage Value from PMU

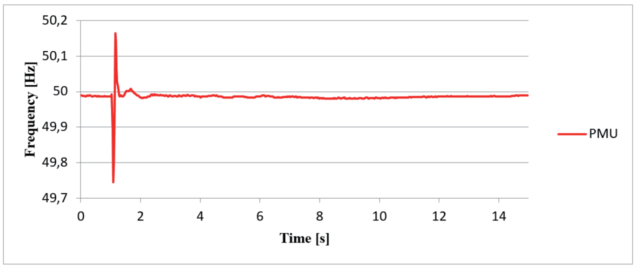

Fig. 6. Frequency Value from PMU

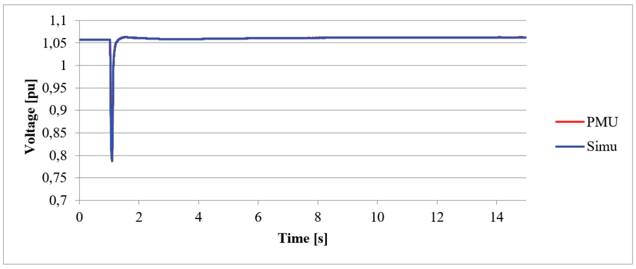

Fig. 7. Comparison of Voltage PMU Measurement and Simulation Input

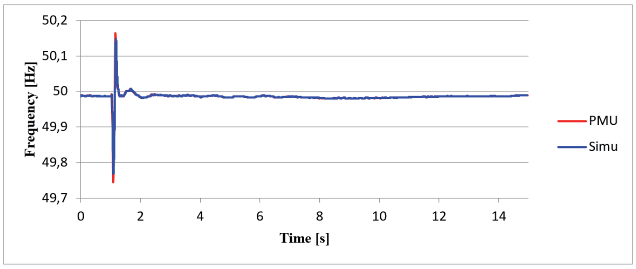

Fig. 8. Comparison of Frequency PMU Measurement and Simulation Input

Initial simulations revealed discrepancies in active and reactive power responses, indicating that the initial dynamic model did not sufficiently represent the actual unit behavior, as can be seen in Figure 9 and Figure 10. Therefore, parameter tuning was performed, including adjustments for inertia, time constants, reactances, excitation system parameters, and voltage measurement compensation.

Following tuning, very good agreement between the measured and simulated responses was achieved (Figure 11 and Figure 12), particularly during the first few seconds after the disturbance, which is critical for transient stability assessment. Remaining discrepancies in reactive power during the settling into a new steady-state indicated the need to include a reactive power regulator (Q-regulator) in the model.

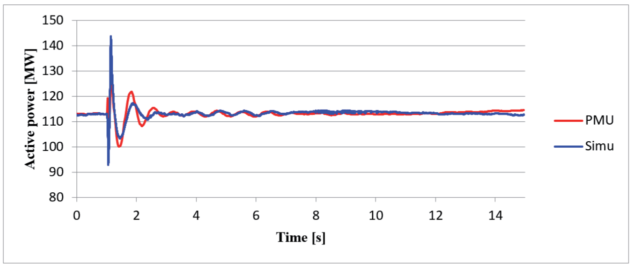

Fig. 9. Comparison of Measured and Simulated Active Power Response

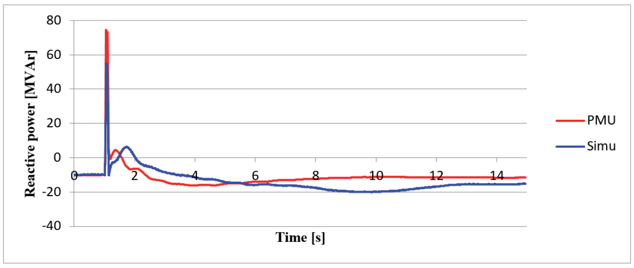

Fig. 10. Comparison of Measured and Simulated Reactive Power Response

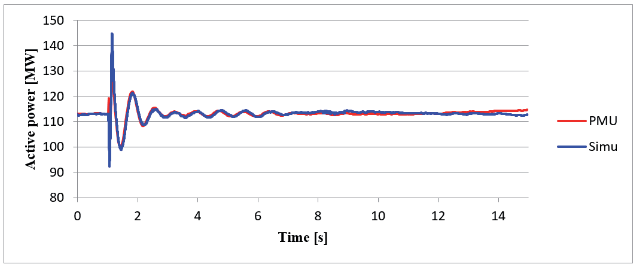

Fig. 11. Comparison of Measured and Simulated Active Power Response

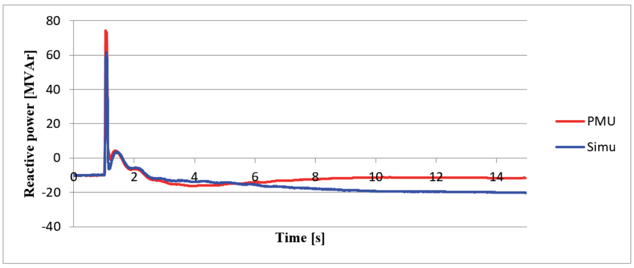

Fig. 12. Comparison of Measured and Simulated Reactive Power Response

The Q-regulator acts as a supervisory control over the excitation system, restoring reactive power output to its predisturbance reference value. As can be seen in Figure 13 and Figure 14, after incorporating and properly tuning the Qregulator, the reactive power response showed good agreement with measured data, resulting in an overall acceptable model validation.

E. Further Steps

The validation of the dynamic model of Unit D of the Zakucac hydropower plant represents only the first step inˇ a broader process of establishing systematically validated generating unit models within the Croatian power system. Following the successful validation of this unit, the logical next step is to extend validation activities to other generating facilities. It is important to emphasize that the validated model should also be examined under different types

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of disturbances, as validation against a wider range of operating conditions and events contributes to increased model robustness and confidence in its dynamic performance.

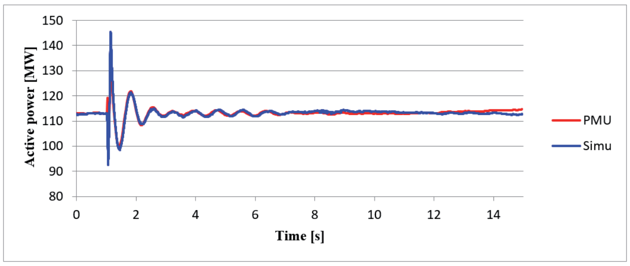

Fig. 13. Comparison of Measured and Simulated Active Power Response

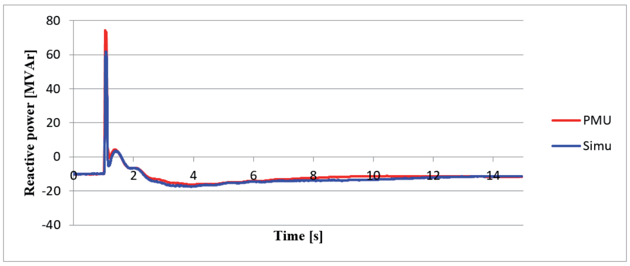

Fig. 14. Comparison of Measured and Simulated Reactive Power Response

A key prerequisite for successful validation is the availability of high-quality, time-synchronized measurement data. In this regard, the PMU coverage of the Croatian transmission system is at a high level and continues to improve. Expanding validation efforts, together with the development of standardized model submission requirements, will significantly enhance the reliability of dynamic studies and support secure power system operation under increasing shares of RES.

III. Submission of RMS Simulation Models of Generating Plants

The validation of simulation models of currently connected generating plants represents the basis for the final verification of the overall power system model. However, due to the continuous inflow of new connection requests for generating facilities, and in order to avoid retroactive model validation, the Croatian Transmission System Operator (HOPS) has initiated the development of a document defining the requirements for the submission of static and dynamic RMS models of generating plants.

The static and dynamic models together form a simulation model. The document will define guidelines for the submission and validation of simulation models of power park modules connecting to the transmission network of the Republic of Croatia. The defined guidelines will apply to conventional power plants, wind power plants (type III and type IV), solar photovoltaic power plants, and battery energy storage systems.

According to Article 81 of the Transmission System Network Code, the transmission system operator (TSO) must have accurate knowledge of the dynamic behavior of connected plants, as well as those intended to be connected to the transmission network. Upon request by the TSO, the transmission network user is obliged to provide the required data and technical documentation related to its facility [6]. Considering the increasing penetration of RES-based generating units and the associated reduction of overall system inertia, dynamic analysis of the behavior of multiple generating facilities has become essential for a reliable assessment of power system stability. Understanding the mutual interaction of these units is crucial for preventing disturbances and maintaining frequency stability under conditions of system transition.

The guidelines will be aligned with the recommendations of the Western Electricity Coordinating Council (WECC) regarding the submission of second-generation generic models [7]. Generic models enable manufacturers to represent their equipment without disclosing proprietary information to other users.

In the first phase, the simulation model would be submitted a specified number of days prior to the planned connection of the facility to the network. This initial model must include all key components: the generator model, excitation system, turbine governor, power system stabilizer (if applicable), and, where necessary, compensation and supervisory control loops. Along with the model itself, technical documentation must be provided, including a list of the generic models used, numerical values of all parameters, and a description of their origin. After connection to the network, an updated simulation model must be resubmitted, including possible corrections of parameters of the previously submitted static or dynamic model. Corrections may arise from the final selection of control equipment, observed differences in system responses, or the execution of commissioning tests. In this phase, the simulation model is submitted together with the final verification test report.

The submitted simulation model will be validated against field measurements obtained through the Operational Test Plan and Program of the generating facility. The validation procedure would follow the same methodology as presented earlier in this paper. Specifically, voltage and angle (frequency) measurements at the POI would be recorded and reproduced in the simulation, after which the active and reactive power responses obtained from the simulation model would be compared with field measurements.

The document would define requirements regarding the accuracy of simulated and measured responses, based on which the submitted simulation model would be deemed acceptable or unacceptable.

This consideration is currently limited to RMS models; however, trends indicate that transmission system operators are increasingly requiring the submission of EMT models as well, particularly for converter-based grid users. EMT models extend the conventional classification of power system stability (angle, frequency, and voltage stability) to include resonance stability and converter-driven stability. A prerequisite for diagnosing “hidden issues” such as resonance is the accuracy and quality of the available data. Operators in Australia (AEMO) and the United Kingdom (NGESO) are examples where users are required to submit EMT models [8], [9]. In the forthcoming period, the need to require EMT models will be considered in order to perform more detailed analyses of interactions and the impact of new users on the network.

IV. Conclusion

With the increasing integration of converter-based RES, the inertia of the power system is decreasing, while oscillations of transient phenomena following disturbances are becoming larger and more pronounced. In this context, the accuracy of simulation models of generating units becomes crucial for the assessment of system transient stability. This paper presents a validation procedure for the RMS model of Unit D of the Zakucac hydropower plant using data collected by a PMU˘ device during and after a recorded disturbance. The process includes the preparation of measurement data, alignment of the static model with measurements, and precise tuning of dynamic model parameters. The result is a

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high level of agreement between simulated and measured responses. Furthermore, the need for standardization of requirements for the submission of simulation models is emphasized. Reliable modeling of individual generating facilities directly contributes to the credibility of system-wide simulations and represents a key tool for preserving the stability and security of power system operation in an increasingly dynamic and complex energy environment.

Acknowledgments

Generative AI tools (ChatGPT, OpenAI, GPT-4) were used solely to improve language clarity and readability.

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