



Parameter Estimation of User-Defined Control System Models for Itaipú Power Plant using Modelica and OpenIPSL

Meaghan Podlaski, Luigi Vanfretti, Marcelo de Castro Fernandes, Jonas Pesente E-mail: <u>meaghan.podlaski@gmail.com</u> & Web: <u>http://ALSETLab.com</u>

Outline



- Background
 - Itaipú power system introduction
 - User-defined power system controls
- Software tools:
 - OpenIPSL
 - RaPId and FMI Toolbox
- Automated calibration process methods:
 - Power system models using Modelica
 - Estimation methodology
- Case study
 - Results of parameter calibration
 - Future works

Background - Itaipú Binacional

- Hydro plant with 20 generators located on the Panará River between Brazil and Paraguay
 - 10 generators rated at 737 MVA/60Hz, and 10 generators rated at 823.6 MVA/50 Hz
 - Each generator can produce 700 MW, enough to supply power to a city of 1.5 million people
 - Entire **plant** can generate **14 GW**, which would be enough for about half of New York State's peak load for a given day

AL

- In this work:
 - 737 MVA salient pole generator with phasor measurement unit (PMU) attached at the terminal bus of the machine
 - **CPS development** requires well designed models, especially where it is difficult to develop prototypes
 - How do we take a modeling approach suitable for CPS development?
 - How do we know the models developed are accurate using statistical measurements?



Software Introduction: OpenIPSL



Modelica Tools for Power Systems

- Modelica is a promising language for modeling complex systems, such as the emerging electric power grids;
- Many libraries have been developed in Modelica to exploit its benefits;
- Among the power system libraries, there is OpenIPSL:
 - Robust library: software-to-software validated models;
 - Friendly to users familiar with power system analysis tools;
 - Latest version comes with the hybrid three-phase/positive-sequence interface.
 - 💓 OpenIPSL
 - C Copyright
 - Examples
 - Electrical
 - NonElectrical
 - Interfaces
 - Types

Get it online on Github at: <u>http://openipsl.org</u>



Software Introduction: FMI (Functional Mock-up Interface) Standard ALSE

- Motivation: Need to solve large scale integrated modeling and simulation engineering problems
- FMI Functional Mock-up Interface
 - Open interface standard for model exchange between different modeling and simulation environments.
- Two main approaches:
 - 1. Export models from some tools, import into other tools for simulation
 - 2. Co-simulation of models in different tools





Software Introduction: RaPId - Rapid Parameter Identification ALSET

- RaPId is a MATLAB toolbox providing a general framework to solve system identification problems.
- The SW is modular and extensible, with a plug-in SW architecture allowing to use different optimization, simulation and signal processing techniques.
- A common application of RaPId is to attempt to tune the parameters of the model so as to satisfy the user-defined fitness function
- A major part of this research is to develop and implement new methods using system identification theory for different power system applications.
- 1. Measurements
- 2. Define calibration parameters in RaPId
- 3. Simulate FMU in Simulink
- 4. Compare model output to measurements
- 5. Use residual to determine new parameters







- A. Tables containing the PMU data for the active and reactive power data
- B. System data contains frequency and base power for the system.
 - The machineData block contains parameter data stored in a record, which is propagated to the system components.
- C. User-defined turbine governor
- D. Salient pole generator with exponential saturation from OpenIPSL library
- E. User-defined automatic voltage regulator (AVR)
- F. User-defined power system stabilizer (PSS)
- G. Output active and reactive power real connections for FMU analysis
- H. Controlled voltage source component
- I. Tables containing real and imaginary voltage components from the PMUs





model Pulso Re-Implementing the User-Defined Itaipu Controllers parameter Real p1 = 0; parameter Real p2 = 1; parameter Real p3 = 1e10; Previously, we studied the IEEE standard models using these parameter Real p4 = 1; • Modelica.Blocks.Interfaces.RealInput u; PMU measurements. Modelica.Blocks.Interfaces.RealOutput y; These models are already included in the OpenIPSL equation 0 if u<p1 then y = 0;</pre> Library. elseif (u>p1 and u<p3) then y = p2; All of the user-defined models have been developed by Itaipu's else y=p4; end if; engineers using CduEdit to answer the question: how do standard end Pulso; models impact model performance compared to user-defined models? Arithmetic The engineers at Itaipu use an industry-specific software to ī.⊕+ implement their models. Additional functions were created for the Modelica equivalent ĭ×→ user-defined models like the Pulso model In the AVR, we had to re-implement the various limiters and Ĩ÷+ main AVR control system → P1 → Dynamic & Limit Input & Output main AVR loop Comparison Modelica Logic Operators Trigonometric ower and Logarithm implementation Nonlinear Hz Limite Signal & Integers elect. Delay and Samle For Help, press F1 erexcitati ANATEM model nderexcitatio Rensselaer

Re-Implementing the User-Defined Itaipu Controllers: Validation

ALSET

- Previously, we studied the IEEE standard models using these PMU measurements.
 - These models are already included in the OpenIPSL Library.
- To prove that we can trust the simulations for the parameter calibration study, we also validated the models.









Preparing models for Calibration: FMI Toolbox/RaPId

- A. Input voltage measurements split into a real and imaginary component. Measurements are from PMUs.
- B. FMU containing the Modelica model
- C. Output of FMU: simulated P and Q
- D. Measurements of P and Q for graphical comparison
- E. Output P and Q results to the work space. This is updated every iteration.
- F. Scopes to monitor the simulated response against the measurements during each simulation run.
- Parameters of components optimized using fmincon and particle swarm optimization function, initial guess updated and tracked using RaPId





- 1. Develop system in Modelica using OpenIPSL library and re-implement models from ANATEM and CduEdit.
- 2. Export completed model as an FMU using model exchange.
- 3. Use FMU in Simulink and RaPId to set up system to compare PMU measurements to the model.
- 4. Use RaPId toolbox in MATLAB to calibrate parameters of machine, AVR, PSS, and TG sequentially for two sets of measurements.





Sequential Parameter Estimation Process for User-Defined models



- Each parameter is calibrated sequentially for each component in the system
- The results from the previous calibration are used as the initial guess for the next calibration step
- When new components are added, the parameters from the previous components are simultaneously updated

Algorithm 1 Sequential parameter calibration using heuristic solver, then gradient solver

Use PSO algorithm:

x = vector for all parameters to be calibrated x_{min} = vector of lower limit of all parameters calibrated x_{max} = vector of upper limit of all parameters calibrated $x = \min f(x)$ such that $x_{\min} \le x \le x_{\max}$ Use fmincon solver: p = empty vector $p_{min} = \text{empty vector}$ $p_{max} = \text{empty vector}$ For parameter in x: p = p.append(x) % Use results of PSO as starting guess x $p_{min} = p_{min}$.append (x_{min}) $p_{max} = p_{max}$.append(x_{max})

 $\min f(x)$ such that $p_{\min} \le p \le p_{\max}$





- 1. Optimize objective function to determine the next parameter guess $\min f(x)$ such that $\{ p_{min} \le x \le p_{max} \}$
- 2. Simulate the response of the system using parameter values found in optimization
- 3. Determine fitness of solution where:

$$\epsilon_{1} = \begin{bmatrix} P_{out}^{simulated} - P_{out}^{reference} \\ Q_{out}^{simulated} - Q_{out}^{reference} \end{bmatrix}^{T}$$
$$f(x) = \sum_{i=1}^{m} \sum_{j=1}^{n} (\epsilon_{ij} * \epsilon_{ij})$$

4. Continue until maximum number of iterations or error tolerance is achieved
a. In this test, max iterations was 5000 and error tolerance was 1e-5



Overview of results



- Used measurements from two different faults events to calibrate parameters for both generic IEEE models and Itaipu user-defined models
 - September 22, 2015
 - November 2, 2016
- Match transient response of the model to the post-fault response of the physical system
- Determine intervals of confidence on each parameters based on each experiments' results
- Models are simulated in Dymola with a variable time step solver (Dassl) and an error tolerance of 10⁻³.





Case 1: September 22, 2015 Results

- Calibrated parameters to fit PMU measurements for a fault
- Possible modeling error of the generator and control models pushes the active power generation higher during the fault at the one second mark
 - Same results were seen using a different calibration method developed by Itaipu's engineers
- Generic IEEE models perform significantly better than Itaipu UD models.
 - Some error in the modeling of the AVR and PSS cause there to be too much reactive power during the calibration simulations.
 - Generic models have a lower Euclidean norm error (1.107) compared to UD (1.2)





ALSET

Case 2: November 2, 2016 Results

- Generic IEEE models perform significantly better than Itaipu UD models.
- Improved fit with the active power measurements for both models.
- Adding user-defined TG model creates a large dip in reactive power during fault recovery.
 - Need to improve user-defined model or switch to using a more detailed IEEE standard model instead.





Errors with User-Defined TG model

- The user-defined TG causes a high error, so we also tested the models with a standard IEEE hydroelectric turbine-governor model (IEEE HYGOV TG).
- The IEEE model is more accurate than the user-defined model, showing the Itaipu TG model has some control component that causes it to absorb significant amounts of reactive power
 - Possible error in the transfer function that causes the consumption of reactive power under certain conditions instead of returning to steady state





Discussion and Conclusion



This study raises importance of model validation and maintenance.

- Thanks to the availability of PMU measurements, increased and expanded model maintenance and validation is becoming more possible.
 - Previously engineers would have to take measurements during commissioning tests or wait until the plant was taken offline for maintenance.
- Prior to performing the parameter calibration, we expected that the user-defined models would produce better results.
 - Itaipu plant control models were likely defined in the early 1990s, prior to any IEEE standard control models.
 - There may have been changes in the model and physical system since its creation, but they have not been reflected in the models.

Importance of reusable, replaceable models

- IEEE models might be more "simple", but they have a broader application scope that can capture system dynamics with better accuracy.
- Although we had a more detailed model from Itaipu, it has not been maintained over the years.
 - Calibration results show that the standard models are an adequate replacement that *will be maintained and can be reused among many models.*



References



Stefan Andersson and Jonatan Strömner. Model calibration of a vertical wind power plant using Dymola/Modelica. 2013.

Cepel. ANAREDE - Network Analysis Program, a.

Cepel. ANATEM - Analysis of Electromechanical Transients, b.

Cepel. CDUEdit - User-Defined Controller Editor, c.

Dassault. Dymola user manual vol 2. 6.10. Technical report, Dassault Systemes AB, March 2018.

IEEE. IEEE Recommended Practice for Excitation System Models for Power System Stability Studies. Technical report, IEEE Power and Energy Society, 2016. URL https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=7553421.

Itaipu Binacional. Generating units.

J. Chen, P. Shrestha, S. Huang, N. D. R. Sarma, J. Adams, D. Obadina, and J. Ballance. Use of synchronized phasor measurements for dynamic stability monitoring and model validation in ERCOT. In 2012 IEEE Power and Energy Society General Meeting, pages 1–7, July 2012. doi:10.1109/PESGM.2012.6345152.

P. Kundur. Power System Stability and Control. McGraw-Hill.

L. Vanfretti, M. Baudette, A. Amazouz, T. Bogodorova, T. Rabuzin, J. Lavenius, F. Jose Gomez-Lopez. RaPld: A modular and extensible toolbox for parameter estimation of Modelica and FMI compliant models.2016. doi:10.1016/j.softx.2016.07.004.

L. Vanfretti, W. Li, T. Bogodorova and P. Panciatici. Unambiguous power system dynamic modeling and simulation using modelica tools. IEEE Power Energy Society General Meeting, pages 1–5, 2013. doi:10.1109/PESMG.2013.6672476.



References



M. Baudette, L. Vanfretti, J. Rabuzin, M. Murad. iTesla Power Systems Library (iPSL): A Modelica Library for Phasor Time-Domain Simulations. doi:10.1016/j.softx.2016.05.001.

M. Podlaski, L. Vanfretti, J. Pesente and P. H. Galassi. Automated parameter identification and calibration for the Itaipu power generation system using modelica, fmi, and rapid. 7th Workshop on Modeling and Simulation of Cyber-Physical Energy Systems (MSCPES), pages 1–6, 2019. doi:10.1109/MSCPES.2019.8738793.

Mathworks. fmincon Interior-Point Algorithm with Analytic Hessian. Technical report.

Modelon. FMI Toolbox User's Guide 2.6.4. Technical report, Modelon AB, July 23 2018.

NEPLAN AG. EXCITER MODELS: Standard Dynamic Excitation Systems in NEPLAN Power System

Analysis Tool. Technical report, NEPLAN AG, a. URL https://www.neplan.ch/wp-content/uploads/2015/08/Nep EXCITERS1.pdf

NEPLAN AG. TURBINE-GOVERNOR MODELS: Standard Dynamic Turbine-Governor Systems in NEPLAN Power

System Analysis Tool. Technical report, NEPLAN AG, b. URL https://www.neplan.ch/wp-content/uploads/2015/08/Nep TURBINES GOV.pdf

NEPLAN AG. POWER SYSTEM STABILIZER MODELS: Standard Dynamic Power System Stabilizers in NE-

PLAN Power System Analysis Tool. Technical report, NEPLAN AG, c. URL https://www.neplan.ch/wp-content/uploads/2015/08/Nep PSSs.pdf

P. Pourbeik, G. Chown, James Feltes, F. Modau, S. Sterpu, R. Boyer, K. Chan, L. Hannett, D. Leonard, L.T.G. Lima, W. Hofbauer, L. Gerin-Lajoie, S. Patterson, J. Undrill, and F. Langenbacher. Technical report, IEEE, 01 2013.

Z. Huang, P. Du, D. Kosterev, and S. Yang. Generator dynamic model validation and parameter calibration using phasor measurements at the point of connection. IEEE transactions on power systems, 28(2):1939–1949, 2013.

