

# Automated Parameter Identification and Calibration for the Itaipu Power Generation System using Modelica, FMI, and RaPIId

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**Abstract**—Power system modeling and simulation are essential tools in the power industry. System models allow for the understanding system operations, perform system planning studies, and help identifying and correcting problems within the system. The error between models and physical system response must be minimized to ensure that that simulations used in studies provide an accurate representation of the power system. Phasor measurement data can be used to calibrate models and reduce modeling errors. In this paper this process is automated for the Itaipu system using RaPIId, a software tool that integrates measurements, models in Modelica/FMI standards, and optimization routines. This is achieved by using a classical gradient optimization method to calibrate parameters to the phasor measurements. Two calibration methods are presented here, where parameters of a synchronous generator, automatic voltage regulator, and power system stabilizer are estimated.

**Index Terms**—Modelica, FMI, synchronous generator parameter estimation

## I. INTRODUCTION

### A. Motivation

New advancements in renewable generation and control systems can help create a resilient power grid that limits our negative impact on the environment. In order to determine which technologies have the highest benefit, simulation-based studies are indispensable; as a result, high accuracy dynamic power system models are necessary. Low confidence in the parameters of individual components in a system leads to more conservative or even erroneous assessments. In addition, there is inherent uncertainty due to changes in the system parameters due to wear and aging of system components. Testing opportunities on the physical power system is limited because the existing system cannot be compromised for experimentation and it would be costly to build another system for such purposes [?]. The results of this paper provide alternate ways to model the power system and derive model parameters with high accuracy.

Measurements obtained from phasor measurement units (PMU) help improve the power system modeling while creating and developing accurate models through real-world measurement data [2]. Combining this idea with new modeling and simulation tools [3] allows for the development of

new methods and tools to calibrate parameters of various power system components. Using a set of measurements from PMUs attached at the terminal bus of Itaipu Binacional, the world's second-largest renewable hydro-electric dam, the parameters of different components of the power generation can be calibrated. This generator produces 700 megawatts [4], an amount of power capable of supplying a city of 1.5 million people.

### B. Related Works

This paper leverages previous works related to turbine and generator calibration, as well as power system model validation using the Modelica and functional mock-up interface (FMI) standard. Previous studies focus on automated calibration of models using PMU measurements; the parameter identification methods explored in these studies include extended Kalman filter techniques [2] and other methods. The FMI standard and Modelica have been used to simulate and validate models for other physical systems [5], including power systems [1].

### C. Paper Contribution

This paper contributes a study focused on calibrating a generator model and its control systems using a classical gradient optimization method. The models in this study were calibrated using the FMI Toolbox [6] and RaPIId [7] in MATLAB. Two calibration methods are introduced and compared to determine the most effective method.

### D. Paper Organization

This paper is organized as follows. Section II discusses the setup of the models using Modelica/FMI and the optimization problem using the RaPIId toolbox in MATLAB. Section III introduces the optimization problem formulation and Section IV presents case studies for Itaipu's system. Conclusions are drawn in Section V.

## II. POWER SYSTEM MODELING FOR ESTIMATION

The Itaipu system was modeled using a synchronous machine with excitation control systems, and coupled with PMU measurements corresponding to the voltage magnitude, angle, active power, and reactive power consumption at its terminal bus, utilizing the Modelica modeling and programming language. The voltage measurements from the PMU

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were injected into the terminal bus to obtain the generation output.

### A. Modelica model

1) *Modelica model overview*: The model was implemented in Dymola using in the Modelica language using the OpenIPSL [11] library. The Itaipu generators are salient pole generators with exponential saturation. The generator was modeled using the GENSAE model. The simple excitation model (SEXS) was used for the AVR and the STAB3 model was used for the PSS. The voltage measurements from the PMU are injected into the system at the terminal bus to calibrate the generator, AVR, and PSS parameters. These models for the PSS and AVR are the simplest models that can be used from the OpenIPSL and PSS/E models. This choice was made because the exact models used in the system were not available for the present study.

The model was exported from Dymola as a Functional Mock-up Unit (FMU) [8] to calibrate the models' parameters using MATLAB's optimization solver, `fmincon` [9], and Simulink. The optimization runs were executed for up to 5000 iterations using an error tolerance of  $1 \times 10^{-5}$ . The parameter values were changed at each iteration with the goal of providing the best optimization fit to the reference measurements using RaPIId [7], a MATLAB toolbox for rapid parameter identification.

The power system model was developed using the Modelica language and Dassault's Dymola software as shown in Figure 1. The components are labeled as follows:

- A. Tables containing the PMU data for the active and reactive power measurements
- 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 all system components.
- C. GENSAE generator model<sup>1</sup>, a salient pole generator with exponential saturation GENSAE, where the parameters to be estimated are:

$$\bar{p} = [X_d, H, R_a, X'_d, D, X_q, X''_d, X''_q, T'_{d0}, T'_{q0}, T''_{d0}, X_l]^T$$

- D. SEXS automatic voltage regulator (AVR)
- E. STAB3 power system stabilizer (PSS)
- F. Controllable voltage source component
- G. Tables containing real and imaginary voltage components from the PMU measurements

The definition for each of the parameter abbreviations are located in the appendix.

The model for the SEXS AVR [12] is shown in Figure 2. The time constants in the 'leadLag' ( $T_1$  and  $T_2$ ) and 'simpleLagLim' ( $K$  and  $T$ ) block will be calibrated using RaPIId after the generator parameters are calibrated.

The model for the STAB3 PSS is shown in Figure 3. The gain  $K$  and time constants for all of the simple lag blocks

<sup>1</sup>In previous work, the Itaipú plant has been modeled with a simpler generator model with parameters  $X_d$ ,  $H$ ,  $R_a$ , and  $X'_d$ . The order of parameter selection is derived from [13]

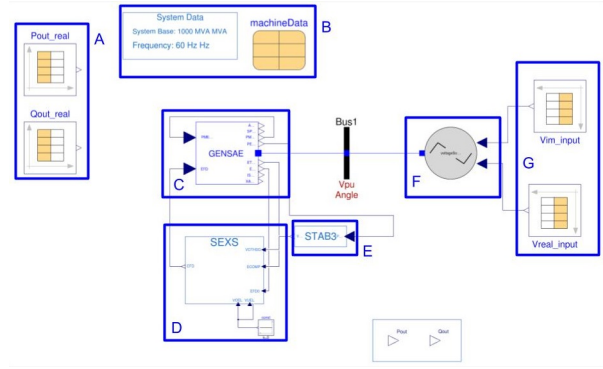


Fig. 1 Modelica model of the generator AVR and PSS

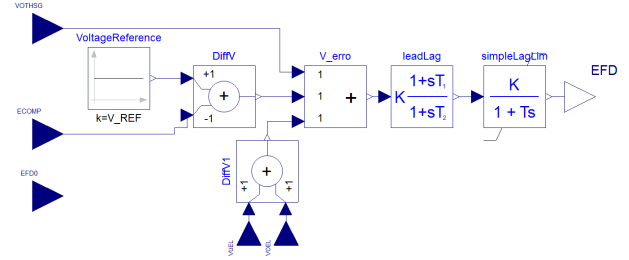


Fig. 2. SEXS model from OpenIPSL

will be calibrated using RaPIId after the AVR and generator are calibrated.

2) *Software Validation with PSS/E*: Modelica is not currently used by most power system analysts. To ensure that the model above gives the same results as the mainstream power system modeling software PSS/E, the results from software-to-software verification are shown in Figure 4 below using a single machine infinite bus power system model identical to the one in PSS/E<sup>2</sup>. The system has a fault at the infinite bus at 2 seconds and is cleared at 2.1589 seconds.

3) *Coupling PMU measurements to the Modelica model*: The voltage measurements obtained from the PMU are imported into the tables shown in block G in Figure 1. These measurements are fed into the voltage source block F in Figure 1. In the model, flow variables represent a conserved quantity in a model, usually the result of a difference across variables of a component model. An example of a flow variable would be current across a resistor. Potential variables represent values within a component which would cause it to react; an example would be voltage. Hence, the voltage

<sup>2</sup>Note that the PSS/E model is only used to verify expected behavior of the implemented model against traditional power system tools to increase confidence in the Modelica model (see [15]). Meanwhile the Modelica model is used for the remainder of the studies.

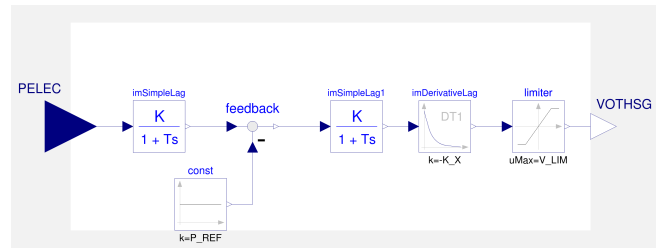


Fig. 3. STAB3 model from OpenIPSL

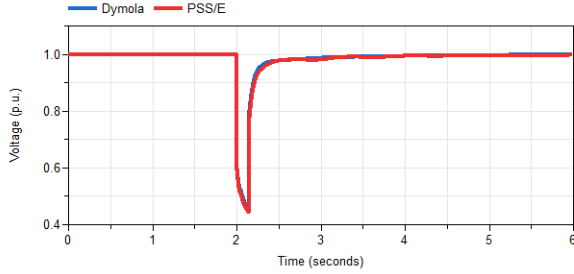


Fig. 4. PSS/E and Modelica result comparison for generator terminal voltage

Machine parameters		
Tpd0	machineData.Gen1.Tpd0	d-axis transient open-circuit time constant (s)
Tppd0	machineData.Gen1.Tppd0	d-axis sub-transient open-circuit time constant (s)
Tppq0	machineData.Gen1.Tppq0	q-axis transient open-circuit time constant (s)
H	machineData.Gen1.H	Inertia constant (s)
D	machineData.Gen1.D	Speed damping
Xd	machineData.Gen1.Xd	d-axis reactance
Xq	machineData.Gen1.Xq	q-axis reactance
Xpd	machineData.Gen1.Xpd	d-axis transient reactance
Xppd	machineData.Gen1.Xppd	d-axis sub-transient reactance
Xppq	machineData.Gen1.Xppq	q-axis sub-transient reactance
Xl	machineData.Gen1.Xl	leakage reactance
S10	machineData.Gen1.S10	Saturation factor at 1.0 pu
S12	machineData.Gen1.S12	Saturation factor at 1.2 pu
R_a	machineData.Gen1.R_a	armature resistance

Fig. 5. Record usage for parameterization of the generator model

source changes the "potential" variables according to the values in the tables using  $u1$  and  $u2$  are the output from the tables in block G; modeling in the real and imaginary components of the voltage in block F as follows:

$$\begin{aligned} p.vr &= u1; \\ p.vi &= u2; \end{aligned}$$

The real and imaginary voltage components are then used to compute the voltage magnitude and angle, as well as the power injections as follows:

$$\begin{aligned} V &= \sqrt{p.vr^2 + p.vi^2}; \\ \theta &= \arctan((p.vi)/(p.vr)) (180/\pi); \\ P &= -(p.vr*p.ir + p.vi*p.ii)*S_b; \\ Q &= -(p.vr*p.ii - p.vi*p.ir)*S_b; \end{aligned}$$

4) *Model architecture and parameterization:* All of the parameters for the system are stored in the 'machineData' record in block B of Figure 1. As shown in Figure 5, the parameters in each of the components are declared such that they can be altered by changing the record stored in the machineData block. There is a record for each experiment so that the results of the calibration of each parameter can be easily tracked.

### B. Preparing models for RaPID

The models were optimized using RaPID [7], a MATLAB toolbox used for parameter calibration and optimization that uses models exported using FMI standard for Model Exchange, called Functional Mock-up Units (FMUs). Models developed using Modelica tools, including Dymola, support this standard, as well as many non-Modelica tools.

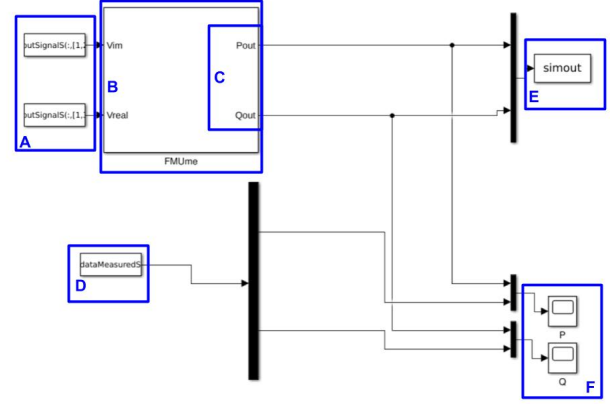


Fig. 6. Itaipu system in Simulink using the FMI Toolbox for use in RaPID

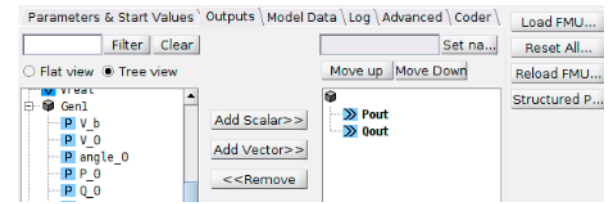


Fig. 7. Outputs tab of block C for FMI toolbox in Fig. 5

RaPID uses both Simulink blocks and MATLAB functions from the FMI Toolbox for MATLAB [6] to simulate and perform the computations of the model. The models need to be configured in a Simulink block, and a MATLAB script is used to specify measurements, define an optimization problem, and to provide an initial guess of the parameters. For the experiments herein, the complete system configured in Simulink is shown in Figure 6, labeled as follows:

- Input voltage measurements.
- Output of the FMU; simulated P and Q.
- FMU containing the Modelica model.
- Measurements of P and Q for graphical comparison.
- Output to the workspace.
- Scopes to monitor the simulated response against the measurements during each simulation run.

Figure 7 shows the output tab of the 'FMUme' block of the FMI Toolbox. Different outputs can be declared in this tab, which are shown as P and Q in Figure 6.

After each optimization, the change in parameters can be observed in Figure 8. In this case, every parameter which was calibrated is located under the tab 'machineData', if a parameter undergoes a change, it is automatically highlighted with an asterisk. These parameter values are changed according to the solution of the optimization problem using RaPID.

## III. PARAMETER ESTIMATION METHODS

The `fmincon` [9] solver is a nonlinear programming solver which finds the minimum of a problem defined by Equation (1). This method was chosen over other solvers as it was computationally less expensive than other solvers

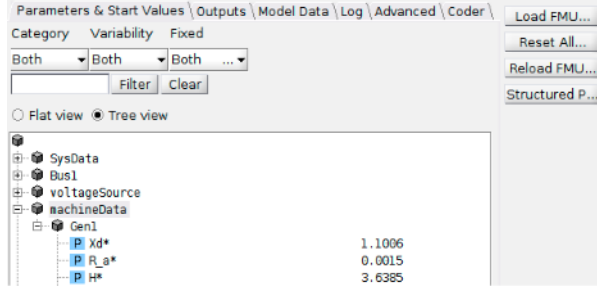


Fig. 8. Parameters tab at the 'FMUme' block from the FMI Toolbox, a \* indicates that the parameter has been modified from its original value

available, such as particle swarm optimization (PSO) algorithms.

In Equation (1), the lower and upper limits to the optimization problem are defined as  $p_{min}$  and  $p_{max}$ .

$$\min f(x) \text{ such that } \{ p_{min} \leq x \leq p_{max} \}. \quad (1)$$

During each optimization run using `fmincon`, the estimated parameter vector  $\bar{p}$  is used to simulate the response of the system. The absolute difference between the simulation and measurements is calculated at each time step, as follows:

$$\epsilon_1 = \begin{bmatrix} P_{out}^{simulated} - P_{out}^{reference} \\ Q_{out}^{simulated} - Q_{out}^{reference} \end{bmatrix}^T \quad (2)$$

where  $P_{out}^{simulated}$  is the output from the simulation for the active power,  $P_{out}^{reference}$  is the active power measurement, and similarly for  $Q_{out}$ . From here, the objective function is determined by computing the Frobenius norm from the mismatch  $\epsilon_1$  between measurements and the simulations for both the active and reactive power. For each of the norms of a measurement and simulation pair, the sum of mismatches is calculated again, which returns the fitness of the simulation to the measurements. Both the active and reactive fitness are weighted equally when solving for the parameters solution by minimizing:

$$f(x) = \sum_{i=1}^m \sum_{j=1}^n (\epsilon_{ij} * \epsilon_{ij}) \quad (3)$$

To improve the calibration of voltage control device parameters, the minimization problem is reduced and thus the new objective function is reduced to:

$$f(x) = \|\epsilon_2\| \text{ where } \epsilon_2 = [Q_{out}^{simulated} - Q_{out}^{reference}]^T \quad (4)$$

1) *Sequential Estimation Methodology*: The optimization process adopted in this paper is outlined in the flowchart in Figure 9. It consists of three sequential phases. In Phase A, the generator parameters were calibrated first. The order in which the parameters were selected starts with the parameters used in the simplest possible representation of a synchronous machine. Parameters are added by constraining simplifications until parameters of the subtransient model are added. In Step 1 in Figure 9, the stages for calibrating the parameters is shown in Figure 10, where the superscript  $|^{(i-1)}$  indicates the initial guess used for each parameter at iteration  $i$  for  $i = 1, \dots, n-1$  where  $n = 13$  is the number of parameters in the GENSAE model. In Stage 15, all of the parameters are

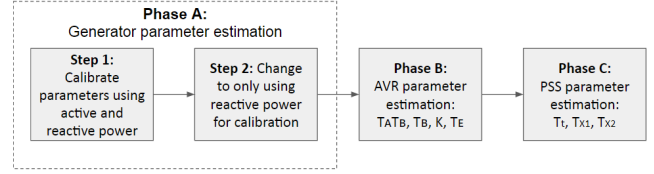


Fig. 9. Flowchart for sequential parameter calibration

Stage	
1	$X_d  ^{(0)}$
2	$X_d  ^{(1)} R_a  ^{(0)}$
3	$X_d  ^{(2)} R_a  ^{(2)} H  ^{(0)}$
$\vdots$	$\vdots \quad \vdots \quad \vdots \quad \ddots$
12	$X_d  ^{(11)} R_a  ^{(11)} H  ^{(11)} \dots X_l  ^{(0)}$

Fig. 10. Illustration of estimation algorithm for GENSAE parameters.

calibrated, while in Stage 1 only  $X_d$  is calibrated. During the calibration of the generator parameters, the field voltage was kept constant using the initial values computed within the Modelica model. In Figure 1, this is located on the right side of the generator as an output pin labelled EFD0. Note that the initial guess at each stage is updated using the estimation results from the previous stage.

The AVR parameters (see Appendix) are calibrated holding the generator parameters constant using the final estimate values from stage 1. The AVR is connected to the EFD0 output from the generator, then the AVR output is connected to the EFD input of the generator; all of the other reference voltages (VOEL, VUEL, and VOTHSG) are set to zero. After all of the AVR parameters are optimized, this process is repeated to calibrate all of the PSS parameters in Phase C (see Appendix). Again, the reference voltages VOEL and VUEL are set to zero, but VOTHSG uses the PSS output as its input.

In Phase A, both the active and reactive power mismatches  $\epsilon_1$  and  $\epsilon_2$  will be used to calibrate the generator parameters by minimizing Equation 3. In Phases B and C, the control system components were calibrated using only the reactive power mismatch,  $\epsilon_2$  in (4), as the AVR and PSS affect the reactive power output of the generator more than the active power output. During this phase, the fitness will be calculated according to Equation (4).

2) *Simultaneous-first Estimation Methodology*: Another method used for calibration was to optimize the generator, AVR, and PSS parameters all at once. After all parameters were calibrated simultaneously, the estimates obtained are use as a starting guess with the sequential method above with the goal of providing the best possible initial guess.

Finally for both proposed methods, the measurements were filtered using the signal analyzer toolbox in MATLAB, using a 15Hz low pass filter.

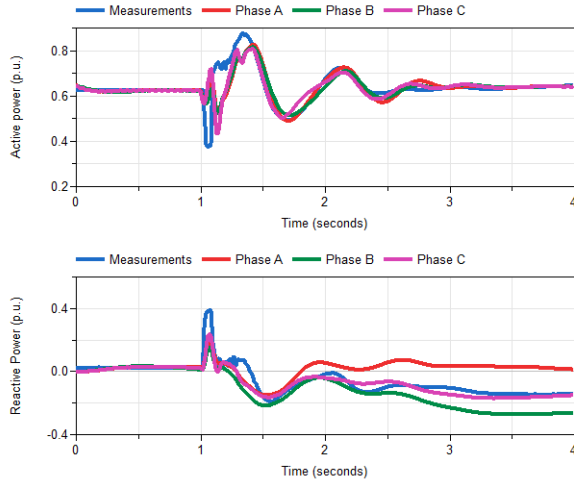


Fig. 11. Case 1: September 22, 2015 calibration results by phase

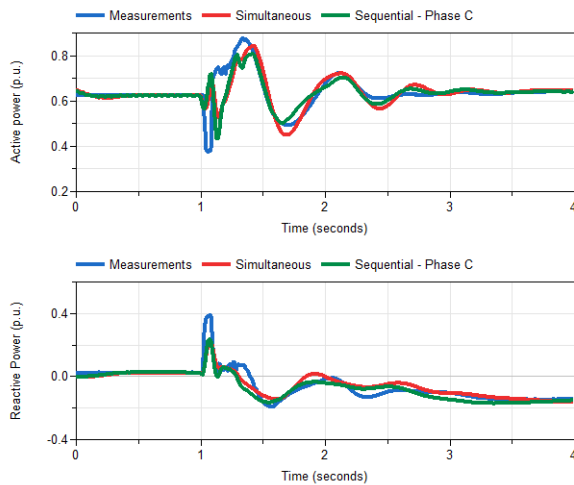


Fig. 12. Case 1: September 22, 2015 calibration results

#### IV. CASE STUDIES

The Itaipu model had its component parameters calibrated for two separate sets of measurements corresponding to events where a fault or disturbance occurred at the terminal bus of the generator, as described in [14].

##### A. Results - Case 1: September 22, 2015

The results for the Itaipu system calibration by phase is shown in Figure 11. A large error still exists at the onset of the fault, at  $t \approx [11.25]$ , due to the voltages at the fault sway the model to calculate a peak in active power, when in actuality, the active power drops to 0.4 pu. This is likely due to unmodeled dynamics related to the fault and protective actions and not the generator.

The results of the sequential calibration method at Phase C are compared to the results of the simultaneous calibration method in Figure 12. The sequential method creates a better fit for the parameters.

The results from the system calibration using the filtered measurements are shown in Table IV-A. During the initialization of the system, most of the parameter values converged to solutions at higher per unit values. As more parameters were

TABLE I  
CASE 1: PARAMETER ESTIMATES

GENSAE					SEXS				
	Sequential		Simultaneous			Sequential		Simultaneous	
	Initial	Final	Initial	Final		Initial	Final	Initial	Final
$X_d$	1.9643	1.4102	1.9827	1.1006	$T_A T_B$	48.3004	45.647	27.8264	29.635
$R_a$	0.0385	0.05	0.0002	0.0015	$T_B$	0.0937	1.0276	0.0369	0.0267
H	4.6682	3.5597	2.236	3.639	K	62.093	463.152	183.21	118.47
$X'_d$	1.9471	1.7845	1.501	1.2775	$T_E$	7.48	3.746	3.614	4.036
D	0.756	0.4445	0.9999	0.9771	STB3				
$X_q$	1.5083	1.5058	1.8531	1.3653	Sequential		Simultaneous		
$X'_q$	0.1588	0.1073	0.194	0.1867	Initial	Final	Initial	Final	
$X''_q$	0.7793	0.9992	0.7751	1.0062	$T_t$	69.059	69.06	66.211	66.1894
$T'd0$	11.792	11.12	4.972	29.635	$T_{X1}$	84.6235	84.6236	83.454	83.454
$T''d0$	0.929	0.6922	1.066	10.332	$T_{X2}$	36.4596	36.46	20.013	20
$T''q0$	8.651	0.5653	0.9712	0.4611					
$X'_t$	0.3425	0.23	0.134	0.156					

TABLE II  
CASE 2: PARAMETER ESTIMATES

GENSAE					SEXS				
	Sequential		Simultaneous			Sequential		Simultaneous	
	Initial	Final	Initial	Final		Initial	Final	Initial	Final
$X_d$	1.9995	1.2561	1.8281	1.7317	$T_A T_B$	23.215	95.8283	8.3886	8.3268
$R_a$	0.00018	0.05	0.0147	0.009	$T_B$	1.029	1.1625	0.4556	0.4589
H	4.78	4.6785	4.0618	3.8262	K	464.76	462.97	119.69	118.01
$X'_d$	1.9995	1.785	1.9015	1.9906	$T_E$	1.1008	3.7906	0.2744	0.2688
D	0.9893	0.4445	0.7385	0.96	STB3				
$X_q$	1.9999	1.675	1.5137	1.5232	Sequential		Simultaneous		
$X'_q$	0.248	0.1073	0.2881	0.29	Initial	Final	Initial	Final	
$X''_q$	0.9993	0.995	1.9465	1.9893	$T_t$	68.936	69.1043	66.9319	66.4022
$T'd0$	6.5787	12.12	2.6711	12.5378	$T_{X1}$	82.87	84.5148	83.7863	83.49
$T''d0$	0.5077	0.5244	0.5751	0.6192	$T_{X2}$	38.631	36.1782	24.2504	19.995
$T''q0$	0.0065	3.5444	6.7844	4.7775					
$X'_t$	0.251	0.13	0.12	0.156					

calibrated, the parameter values decreased to more realistic values.

A histogram for the inertia (H) is shown in Figure 13. The value converges to about 3.6 seconds, as shown in Figure 13. These results indicate that the parameters converge to their final value over the entirety of the calibration process; the outlier points typically occurred during the initial steps of Phase A and when few parameters were being calibrated.

As more parameters are added to the calibration for each experiment, the value of each parameter generally decreases from the initial value for those of the generator. The time constants for the control components generally increase after each optimization run.

##### B. Results - Case 2 - November 2, 2016

Figure 15 shows the calibration results for the second measurement data set. The reactive power measurements and simulation match better than with the previous case. The largest error occurred directly after the fault where the reactive power simulation is 0.2 per unit lower than the actual measurements, which would have contributed to the

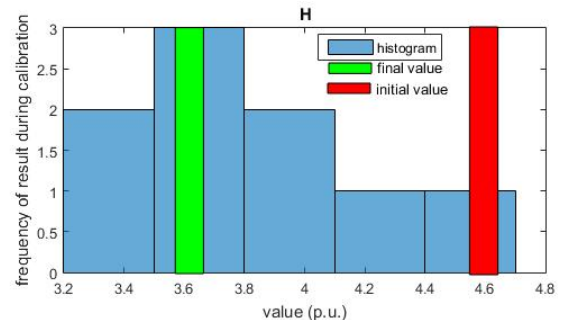


Fig. 13. Case 1: generator inertia histogram



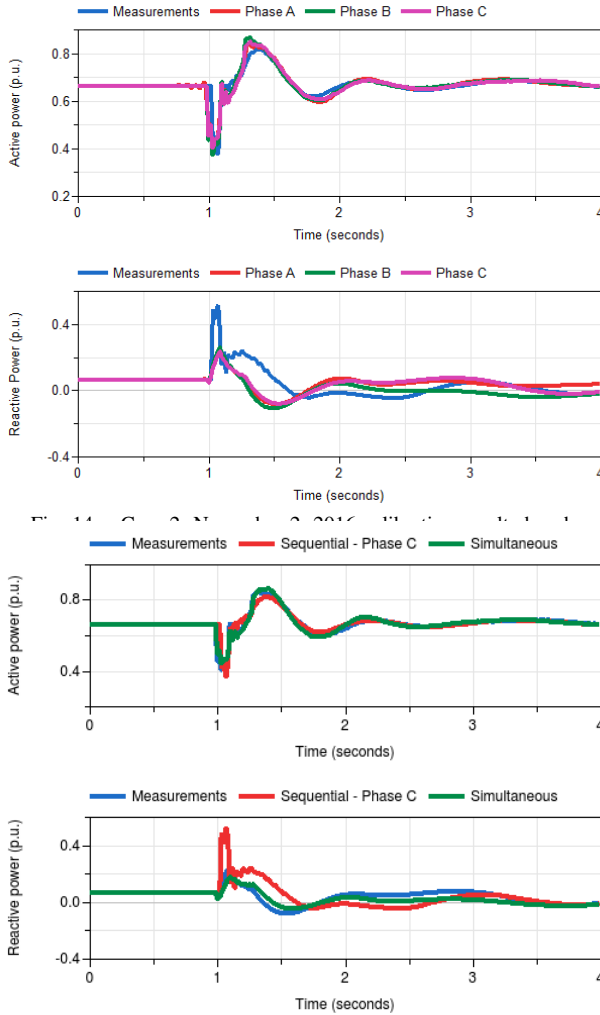


Fig. 15. Case 2: November 2, 2016 calibration results

errors seen in the system later in the simulation. This can be improved in the future by increasing the reactive power generated by the machine during the fault and it is possible that another optimization solver method must be used to calibrate the control system parameters to ensure lower error.

The initial and final parameters for the test set are shown in Table II; as the calibration process progressed, the parameter values converged to lower, more realistic parameter values for most of the machine parameters in Phase A.

## V. CONCLUSION AND FUTURE WORK

The case studies in this paper show that a sequential optimization of the plant parameters help improving the accuracy of the final parameter set. The proposed approach suggests that engineering know-how can help in developing the different stages of the optimization problem, and help understanding the influence of each of the model parameters in the governing dynamics in the measured data.

While the filtered data produces good results to calibrate the active power output from the two dates studied, further development is needed to determine model parameters which would fit the reactive power generation better. This could be

achieved by utilizing other optimization solver algorithms to determine the best parameters for the system, as they would offer more flexibility in determining a solution that would fit the measurements better. More importantly, more accurate model for the AVR and PSS at Itaipu can also be developed and calibrated.

## APPENDIX: VARIABLES AND PARAMETERS

Parameter name	Details
$T_{d0}^d$	d-axis transient open circuit time constant
$T_{d0}^s$	d-axis sub transient open circuit time constant
$T_{q0}^s$	q-axis sub transient open circuit time constant
H	Inertia constant
D	Speed damping
$X_d$	d-axis reactance
$X_d'$	d-axis transient reactance
$X_d''$	d-axis sub transient reactance
$X_q'$	q-axis sub transient reactance
$X_q$	q-axis reactance
$X_l$	leakage reactance
$T_A T_B$	AVR time constant
$T_B$	AVR time constant
K	AVR gain
$T_f$	PSS time constant
$T_{X1}$	PSS time constant
$T_{X2}$	PSS time constant
$K_X$	PSS gain

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