Proceedings of the National Power Systems Conference (NPSC) - 2018, December 14-16, NIT Tiruchirappalli, India

Improvements in Synchronous Generator Parameter Tuning Using PMU Data

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Abstract— **To maintain grid security and stability, simulations play an important role in several applications of power system planning and operation e.g. in dynamic security assessment, design of new Special Protection Schemes and implementation of online-Special Protection Schemes. However, the technical barrier in using simulation results is the lack of accurate dynamic model parameters for a generator. This paper presents a novel way to validate and tune the given synchronous machine parameters by using PMU data comprising generator responses during grid disturbances. The paper presents an improvement achieved in model accuracy after tuning the parameters based on their impact on disturbance timeline e.g. sub-transient phase, transient phase or throughout the disturbance**

Keywords—**Generator Model Validation, Phasor Measurement Unit, Root Mean Square Error, Special Protection Schemes.**

I. Introduction

Wide Area Measurement Systems (WAMS) provide real time information regarding the system's state to operators, which is essential with growing power grid's size and complexity. After unbundling of the electricity business, deregulation and open access, the importance of real-time information has further increased with the emergence of Dynamic Security Assessment (DSA) and Remedial Action Schemes (RAS)/System Protection Scheme (SPS) which may help in avoiding blackouts [1]. Using the current state of the system, different scenarios are simulated to predict the margins required to ensure stability. For these estimated margins to be accurate, the dynamic model of generator used for simulation should also be accurate [2]. The various benefits of the model validation along with the problems faced with inaccurate models are described in [3]. Difficulties in the current procedure for carrying out model validation and recommendations for the implementation of online validation of models are presented in [4].

The emergence of PMUs as synchronized and high time-resolution sensors in the grid has been beneficial for several real-time applications and has improved the post-mortem analysis of grid events. There are several initiatives undertaken in India to utilize this technology in the past decade [5-8]. Power System Operation Corporation Limited (POSOCO) has published a report on model validation in the Indian scenario and has carried out a case study using on-site testing [9]. The importance of Power System modelling for planning studies is highlighted in [10], along with typical values for generator model parameters based on their output power ratings. However, generators from certain manufacturers may have parameters deviating from the said typical values. In view of this, the research presented in this paper focuses on how to improve the model validation and tuning techniques by using PMU data.

The paper has been divided into three parts. Section 2 provides an overview of the existing methodology of model validation using PMU data along with its limitation as a case study using actual PMU measurements for a 500 MW class thermal generator data from Indian grid. An improved technique is suggested in Section 3 for parameter validation along with the results. In Section 4 the proposed method is further validated for an additional data using actual PMU measurements for an 800 MW class thermal generator data from Indian grid.

II. Generator Model Verification

After the North American blackout in 1996, in the WECC region, it was noticed that there was a mismatch between simulation results and the recorded waveforms which might have caused the lack of response from operators. To rectify these errors, the guidelines for periodic model validation were envisaged and enforced by the NERC [11,12]. However as described in [9], the on-site verification of all parameters requires heavy investment that included shut-down of generation units. As a result, it can only be carried out during scheduled maintenance. To overcome these difficulties, the use of disturbance data, sourced from real-time measurements such as PMUs, was investigated to validate generator models while they remain online without visiting the generation site [13].

PMU data-based model validation involves comparison of simulated results with the recorded disturbance data. After setting up the baseline model, which captures the initial conditions before the disturbance, the available model is simulated to obtain the response to the changes in the grid. The output of the generator model is recorded and evaluated by comparison with the recorded disturbance data [14]. Based on the difference between the two waveforms, the model is

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modified so that the response moves closer to that recorded value. Several techniques have been explored to achieve the reduction of error between the recorded and simulated values for model validation. Some of the techniques start with a baseline model while others assume a black-box model [15].

Most commercially available model validation tools start with a baseline model and estimate the sensitivity of the parameters towards the error [16-19]. Once the sensitivity is determined, the most sensitive parameters are tuned in descending order of sensitivity to attain the minimum error possible. However, as there are several parameters, the solution to reduce the mismatch may not be unique as noticed in the NASPI-NERC workshop conducted in October 2016 [20].

Power system simulation tools such as PSS/E have recently introduced features to reduce the power system to a point of PMU availability using an equivalent generator model at the PMU connected bus. The time-stamped PMU measurements of voltage and frequency are played back using the equivalent generator. The simulated output of real and reactive power from the generator under study are recorded as a consequence of this frequency and voltage. These values are compared with the recorded data to validate the model parameters [21]. In Figure 1, the equivalent generator (for playback, represented as P) is shown to the right side and generator under study or whose model is to be validated is shown on the left side.

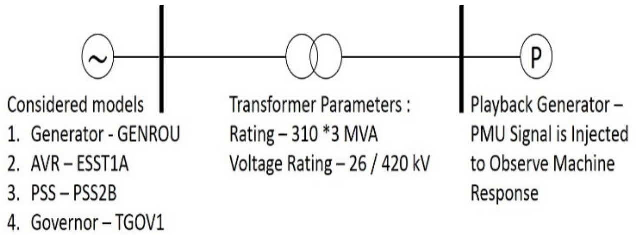


Figure 1. Single Line Diagram Representing Model Used for Tuning

The model using above playback tool can be validated using various method. The first method used for validation in this paper is Root mean square error (RMSE) method. An overview of the procedure followed for tuning synchronous generator parameters is shown in Figure 2. In this case, Root Mean Square Error (RMSE) is used to compute the error between the simulated (P_{Sim}) and measured (P_{Meas}) waveforms.

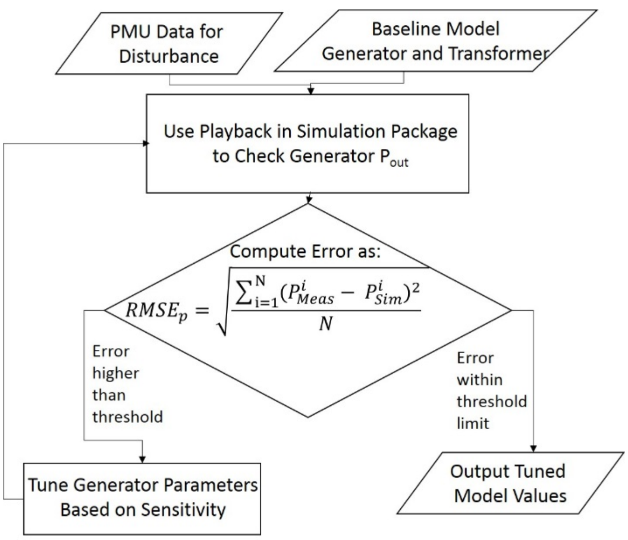


Figure 2. Tuning Process for Synchronous Generator Parameter Tuning

The above method was used for tuning of a 500 MW machine in Indian power system using playback tool. Table 1 shows the results of the tuning process using RMSE method. In this tuning, only the synchronous generator parameters were tuned assuming that the AVR, PSS and turbine-governor parameters has already been verified. The parameters which have higher sensitivity values and are therefore modified to match the measured response are *H*, *Xq* and *X'q*. The remaining other parameters of generator are unchanged. There were two important issues encountered with the above mentioned tuning methodology as listed below including the likely reasons behind these issues. These identified reasons were further used to propose improvements in the RMSE method.

Table 1: Results of Tuning Considering RMSE for 500 MW class generator

Parameter	Before Tuning	After Tuning with RMSE
T'do (> 0)	9.14	9.14
T"do (> 0)	0.04	0.04
T'qo (> 0)	2.5	2.5
T"qo (> 0)	0.2	0.2
H, Inertia	4.052	2.4
D	0	0
Xd	2.31	2.31
Xq	2.19	1.5
X'd	0.253	0.253
X'q	0.665	1.1
X"d = X"q	0.253	0.253

A. Issue of error in the first and second peak of disturbance

By using RMSE method, the model response of generator could be improved by decreasing the mismatch (Error) in real power output from 0.39 to 0.12. However, observing the first and second peak of the model response after tuning in Figure 3, a noticeable difference exists between the recorded and simulated responses. Theoretically, sub-transient and transient parameters such as reactances and time-constants impact the waveform just after the disturbance and could cause the deviation immediately after the disturbance which is visible in the first and second peak. The impact of parameters affecting the response just after disturbance may be relatively lower as compared with the parameters that affect the entire waveform if we use RMSE based error that compares full disturbance waveform. Hence, the sensitivity of these parameters is lower and could lead to tuning errors.

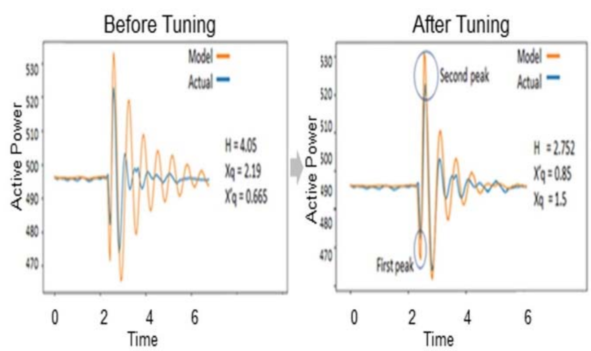
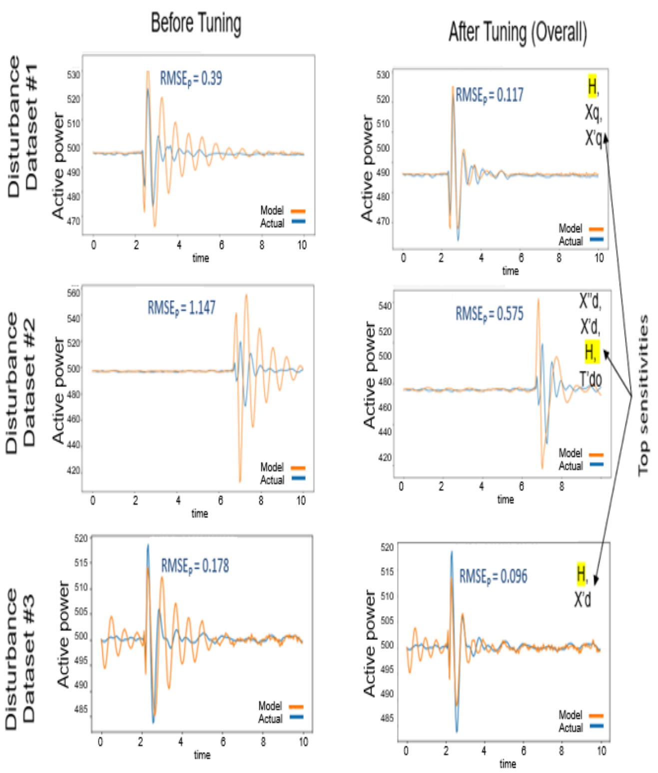


Figure 3. Tuning Parameters Using Conventional Method on disturbance dataset for 500 MW class generator

B. *Issue of changing parameter's sensitivity with disturbance data*

It was recorded that when the RMSE method was applied on different datasets, the result of sensitivity-based prioritization of parameters was not consistent as can be seen in Figure 4. Although, it can be observed that certain synchronous machine parameters such as Inertia (H) appear consistently among top three sensitive parameters while using different disturbance datasets, other parameters e.g. Xq, X'q are not consistent. This affects the parameter's contribution in the generator response. In this case also, the reasons explained in issue (1) could hold true. The disturbance data differs from each other e.g. the



first and second peaks may have relative more contribution in the overall waveform and therefore, the transient and sub-transient parameters may become more sensitive if tested using certain disturbance dataset as can been be seen in the case of Dataset 2 in Figure 4.

Figure 4. Change of Sensitivity with Disturbance Data for 500 MW class generator

The two challenges mentioned need to be overcome to improve the accuracy of parameter tuning using disturbance data. The two issues are linked to the priority of picking up different parameters for tuning. To ensure all the parameters are considered, the evaluation method needs to be enhanced by considering the impact of the generator parametrs during different stages of the disturbance. Section 4 elaborates on proposed method to tackle these issues.

III. RMSE+ Method

RMSE+ method refers to modification of the evaluation criteria for validation and tuning, which is developed to overcome the two issues of RMSE as mentioned in the previous section. Figure 5 captures the enhancements in evaluating the error using additional metrics.

As can be seen in Figure 5, modification is made to compare the model and response with RMSE error-based criteria for synchronous parameters that have sustained effect for the entire duration of disturbance and first ($P^{1st\ Peak}$) and second peak ($P^{2nd\ Peak}$) based criteria for sub-transient and transient parameters respectively.

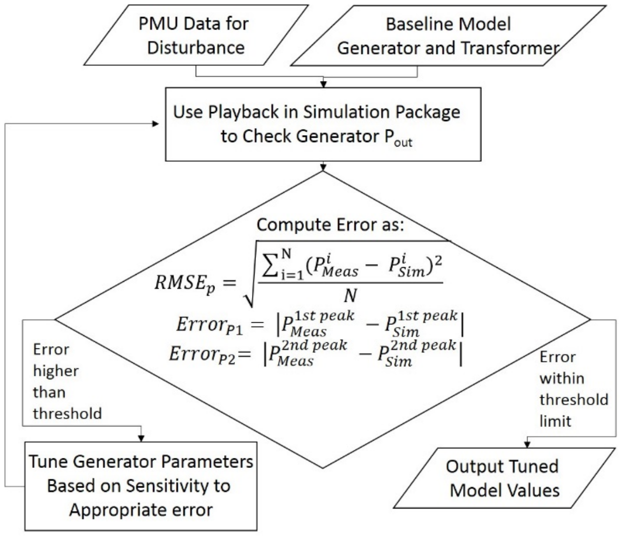


Figure 5. RMSE+ Technique for Parameter Tuning

The same criterion is used for tuning too.

Table 2: Tuning Results with RMSE+ Method for 500 MW class Generator

Parameters	Before Tuning	Proposed (RMSE+)
T'do (> 0)	9.14	3.5
T"do (> 0)	0.04	0.1
T'qo (> 0)	2.5	2.5
T"qo (> 0)	0.2	0.1
H, Inertia	4.052	2.4
D	0	0
Xd	2.31	2.31
Xq	2.19	1.5
X'd	0.253	0.3
X'q	0.665	1.1
X"d = X"q	0.253	0.15

Table 2 captures the results of the tuning with RMSE+ algorithm applied to the disturbance dataset shown in Figure 3 for the 500 MW class generator. Several transient and sub-transient parameters are modified to achieve a better match with the additional errors considered.

The result of tuning has improved as shown in Figure 6, when compared with the result shown in Figure 3. As seen, the errors in the first and second peak has drastically reduced. To further validate the proposed method, another generator of 800 MW was tuned following the same procedure. These results of the tuning are described in Section 4.

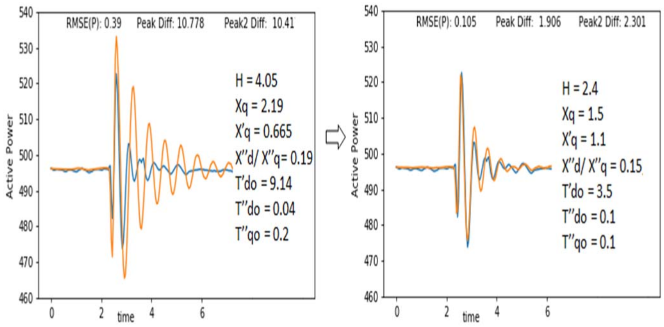


Figure 6. Tuning Improvement with RMSE+ Technique for 500 MW class generator

IV. VALIDATION OF THE RMSE + TUNING APPROACH

An 800 MW class thermal generator was tuned using three disturbance datasets recorded using PMU located at the point of coupling within the power plant. One of the disturbances was used for tuning while the other two were used for validation. The most severe disturbance was considered for tuning. Table.3 captures the results of parameter tuning.

Table 3: Tuning Results with RMSE+ Method for 800 MW class generator

Parameter	Before tuning	After tuning
H	4.5	3.6
Xd	2.07	2.4
Xq	2.04	2.4
X"d, X"q	0.265	0.1
T"do	0.033	0.25
T'do	8.6	6.0

As described in the flow-chart in Figure 5, for the synchronous parameters such as H, Xd and Xq, RMSEp is used, whereas for T"do, X"d and X"q, ErrorP1 is used and for X'd, ErrorP2 is used. Table.4 presents the result of the evaluation criteria RMSEp and ErrorP1 before and after tuning.

Table 4: RMSE+ Results for all Three Datasets for 800 MW class generator

Dataset	$RMSE_P$		$Error_{P1}$		$Error_{P2}$	
	Before tuning	After tuning	Before tuning	After tuning	Before tuning	After tuning
#1	0.483	0.353	19.15	0.911	28.083	14.944
#2	0.484	0.24	5.568	7.853	10.762	9.815
#3	3.164	1.789	122.86	83.65	61.352	54.488

In the validation cases #1 and #2, the RMSEp has been successfully reduced using the tuning results of case #3. However, in case of ErrorP1, it may be noted that for dataset#2, there is a marginal increase in the error after tuning. Although the 'before tuning' base value of ErrorP1 was on the lower side, the increase indicates need for further tuning sub-transient parameters. The outcome of the tuning is captured in the waveforms shown in Figure 7.

Comparing the results for RMSE and RMSE+ methods, it can be observed that by capturing the impact of the sub-transient and transient parameters are captured more comprehensively using RMSE+ approach. In the period immediately following the disturbance, the simulated and recorded waveforms match quite closely demonstrating the advantage of the proposed methodology compared to simple RMSE.

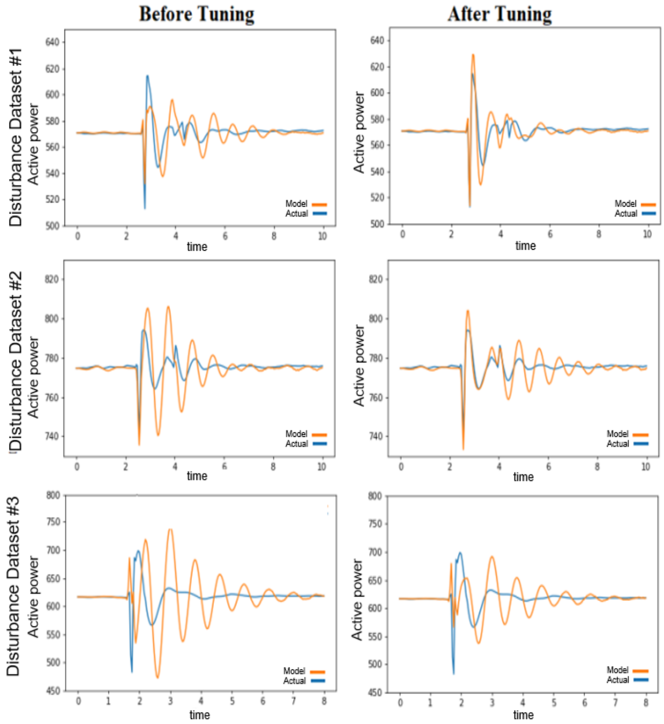


Figure 7. Improvement in model response for first and second peak by using RMSE+ method

It may further be noted by using multiple disturbance datasets for tuning and validation, the errors in PMU measurements, especially during transients could be minimized.

V. CONCLUSION

The conventional technique of model validation and tuning uses only one quantifier i.e. the RMSE error. While validating and tuning, this quantifier is used to judge the result of whether the model has reached a reasonable accuracy or not. However, in the proposed RMSE+ method for generator model validation, the concept of multiple quantifiers for error in model response is introduced. Each of these errors cater to a specific set of parameters based on well-founded principles of generator control system response e.g. sub-transient and transient parameters have an important effect on the first and second peak after disturbance and therefore ErrorP1 and ErrorP2 were included as quantifiers in addition to existing RMSEp. With the help of additional quantifiers, the mismatch between the simulated and captured disturbance waveforms was brought down, indicating a more accurate model. As the procedure described in the paper was aimed at validating and tuning synchronous machine parameters, in the future proposed PMU based model validation technique will be extended for the tuning of controllers such as AVR/PSS and turbine governors.

Acknowledgment

The authors acknowledge the support and encouragement given by Hitachi and POSOCO management. The authors are indebted to Hitachi and WRLDC personnel for their inputs for the content in the paper. The views expressed in this paper are that of the authors and may not represent the views of the organization to which they belong.

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