Application of Small Signal Analyses in Model Validation Studies

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SUMMARY

This paper describes a systematic five-step approach for model validation and parameter tuning studies of generating units using small-signal analysis method. The proposed approach uses frequency domain analysis of the model along with sensitivity analysis and root locus techniques to systematically identify and fine tune the parameters that have the most significant impact on the model's response. In step one, the dominant mode of the generating unit is identified from actual measured quantities obtained during field testing. For this purpose, Prony analysis is used to extract the frequency and damping ratio of the system modes from the recorded field measurements.

In step two, using the existing mathematical models of the generating unit, the modes are calculated in frequency domain based on the eigenvalue analysis of the linearized system model.

The objective of this study is to match the modes that are determined in step two with the modes that are natural characteristic of the system, identified in step one. To achieve this, in step three, sensitivity analysis is employed to pinpoint the parameters that have the most significant impact on the modes, i.e. having the highest sensitivity factors. By using sensitivity analysis, no prior knowledge is required on the parameters that have the most significant impact on the results.

Once the dominant parameters are identified, root locus approach is deployed in step four to trace the developed model modes with respect to changes in the parameters identified in step three. By changing parameters in different directions, the eigenvalues are changed until they match the modes obtained from field testing, which helps aligning characteristics of the developed model and the inherent modes of the system. Finally, the accuracy of the mathematical models is further examined through time-domain simulations in step five. This is the last step to ensure that the model produce desired results in both frequency and time domain. The paper demonstrates a step by a step procedure on how to apply the proposed approach for model validation study of solar farm using real-world recordings and data from an actual farm.

KEYWORDS

Frequency domain analysis, power system control, power system simulation, Prony analysis, sensitivity analysis, small-signal analysis, time-domain simulation.

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Introduction

The objective of a generator model validation study is to find proper mathematical models and tune parameters of those models so that they can accurately represent a generating unit. The accuracy of these models is of paramount importance to the electrical utilities as these models are used in system-wide planning and operation studies that are conducted regularly [1]. In fact, the cause of at least two large scale power outages in the Western Interconnection in 1996 was attributed to inaccurate representation of generating units in that region [2].

Conventionally, tuning parameters of a model is performed through either trial and error approach or using an optimization-based technique [3]. Both of these methods lack a systematic approach when fine tuning parameters and require some background knowledge or deep understanding of the models when selecting the parameters that have the most significant impact on the results.

This paper describes a five-step, systematic approach for model validation studies of generating units using small-signal analysis. The proposed approach is described in details in the next section. Then, a step-by-step procedure on how to apply the proposed approach on a solar farm using real world recordings and data is demonstrated in the following sections.

Proposed Approach

The proposed approach consists of five steps. The first step is to identify dominant mode of the system, which is the mode with largest contribution to the plant's response. For example, response of the plant to a system fault or during a staged test may be oscillatory primarily due to some complex modes, or the dominant mode.

Several methods are discussed in the literature to identify the dominant mode in a measured signal. These methods include Prony Analysis, Fast Fourier Transform, S-Transform, Wigner-Ville Distribution, Hilbert-Huang Transform, and Matrix Pencil Method, which can be used to estimate the low frequency modes in a given ring down signal [4]. In this paper, the Prony Analysis is used for the purpose of extracting the frequency spectrum of the given signal.

Once the dominant mode is determined in step one, the corresponding mode in the frequency domain needs to be determined in step two, which is accomplished by performing a complete eigenvalue analysis on the mathematical models of the system in frequency domain. From the list of all eigenvalues (modes), the dominant mode of the system will be determined. Note that the objective of a model tuning study is to match the dominant mode of mathematical models with the dominant mode found in the actual measurement as determined in step one.

To this end, parameters of the mathematical models with the most significant impact on the dominant mode need to be initially identified. To achieve this, sensitivity analysis is performed to find the sensitivity of a mode with respect to a parameter. In this approach, a pair of modes is calculated, one of them with the original parameter value and the other one with a "perturbed" parameter value. The advantage of the sensitivity analysis is that no prior knowledge of the parameters and their contribution to the overall model response is required.

Once the dominant parameters are identified, root locus approach is deployed, in step four, to trace the dominant mode with respect to changes in the parameters identified in step three. By changing parameters in different directions, the eigenvalues are changed until they match the modes obtained from field testing, which helps aligning characteristics of the developed model and the inherent modes of the system. Finally, the accuracy of the mathematical models is further examined through time-domain simulations in step five. This is the last step to ensure that the model is indeed accurate in both frequency and time domain.

Case Study

System and Models Description

The case study considered in this paper is a photovoltaic (PV) power plant that is connected to 230 kV transmission system through a 34.5/230 kV substation transformer. The plant comprises of 65 solar inverters manufactured by different vendors that are connected to the collector system through pad mount transformers. The plant has three feeders.

The industry standard is to represent such plants with a single machine equivalent system in power flow [5], as shown in Figure 1. Table 1 and Table 2 show the generator and branch model parameters in power flow model. All the per-unit values are based on 100 MVA.
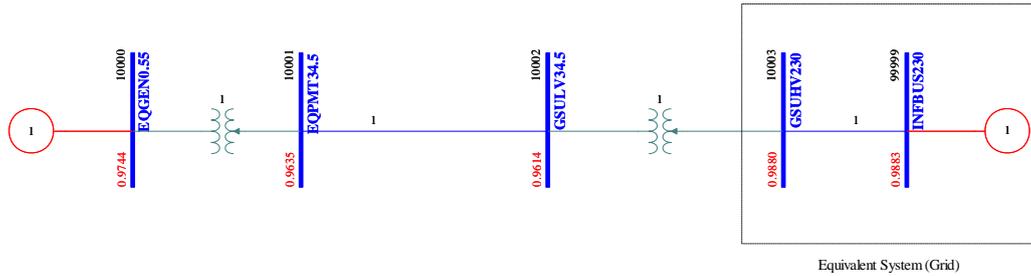

Equivalent System (Grid)

Figure 1: Single-Line Diagram of the Study System in Power Flow

Table 1: Generator Parameters in Power Flow Model

Bus number	Generator ID	# of inverters	Base MVA	Base kV	Pmax	Pmin	Qmax	Qmin
1000	1	65	122.95	0.55	116.416	0	36.96	-36.96

Table 2: Branch Parameters in Power Flow Model

Branch	MVA Base	R (pu)	X (pu)	B (pu)	Comments
Pad Mounted Transformer	100	0.0065	0.0519	0	Nameplate value, Typical X/R = 8
Collector Feeder	100	0.0023	0.0017	0.0097	Provided by the plant owner.
Station Transformer	100	0.0027	0.1073	0	Nameplate value, Typical X/R = 40

A solar farm can be dynamically represented by the 2nd generation of generic renewable generator models recommended by the PV power plant dynamic modelling guideline [6]. Table 3 describes the three dynamic models that are employed for representing solar plants in GE PSLF and PTI PSS/E programs.

Table 3: Dynamic Models for Solar Plants

PSLF Model	PSS/E Model	Description
regc_a	REGCA1	Renewable Energy Generator/Converter Module
reec_b	REECB1	Renewable Energy Electrical Control Module for Large Scale PV Farms
repc_a	REPCA1	Renewable Energy Plant Controller Module

The generator/converter model parameters are associated with the regc_a model as shown in Figure 2. Table 4 presents the model parameters for the renewable energy generator/converter module used in this model validation study. The regc_a model uses the real (Ipcmd) and reactive (Iqcmd) current commands generated by electrical controller (reec_a) as inputs and it produces the real (Ip) and reactive (Iq) injection currents as outputs.
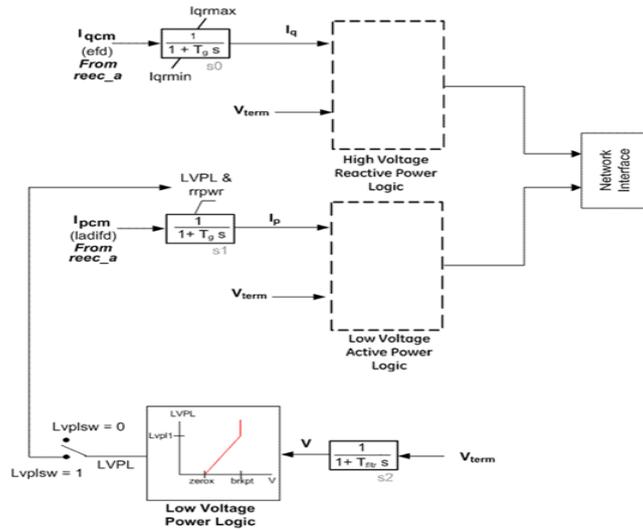
Figure 2: Block Diagram of Renewable Energy Generator/Converter Model (regc_a)

Table 4: Parameters of Renewable Energy Generator/Converter Model (regc_a)

Parameter	Value	Parameter	Value	Parameter	Value
MVA Base	122.95	vtmax	1.2	tfltr	0.02
lvplsw	1	lvpnt1	0.8	iqrmax	99
rrpwr	10	lvpnt0	0.4	iqrmin	-99
brkpt	0.9	qmin	-1.3	xe	0
zerox	0.4	accel	0.7		
lvpl1	1.22	tg	0.02		

The electrical control system of a PV solar farm can be represented by reec_b model. Figure 3 shows the block diagram for the reec_b model and Table 5 summarizes the parameter set for this model. The reec_b model has the real power reference (Pref) and reactive power reference (Qref) as its inputs that can be externally controlled by a plant controller model, or they may be initialized using powerflow solution and kept constant during dynamic simulation. The real (Ipcmd) and reactive (Iqcmd) current commands are the outputs of this model that are sent to the generator/converter model (regc_a).
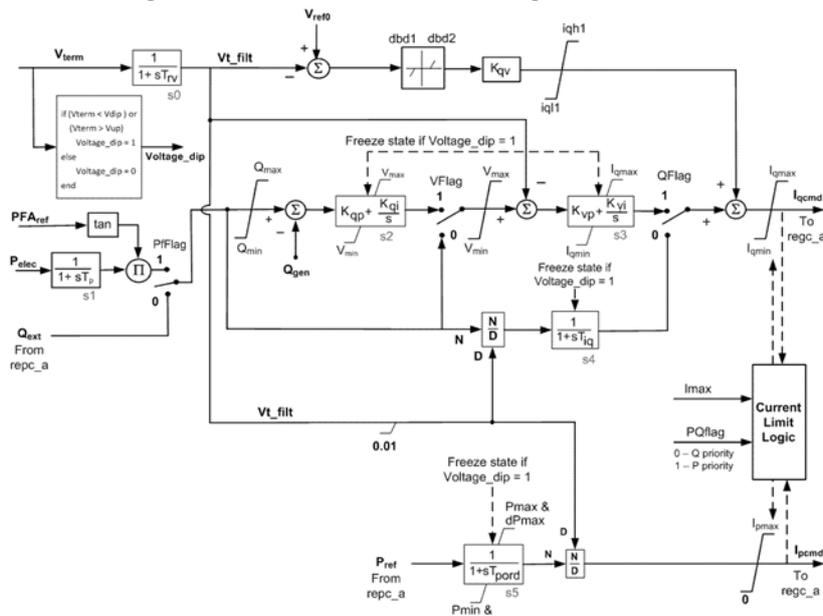

Figure 3: Block Diagram of Renewable Energy Electrical Control Model for PV Farms (reec_b)

Table 5: Parameters of Renewable Energy Electrical Control Model (reec_b)

Parameters	Value	Parameter	Value	Parameter	Value
mvab	0.0	tp	0.05	dpmax	99
vdip	-99	qmax	0.31	dpmin	-99
vup	99	qmin	-0.31	pmax	1
trv	0.02	vmax	1.1	pmin	0
dbd1	-0.05	vmin	0.9	imax	1.1
dbd2	0.05	kqp	0.1	tpord	0.02
kqv	0.0	kqi	1.0	pfflag	0
iqh1	1.25	kvp	1.0	vflag	0
iql1	-1.05	kvi	100	qflag	1
vref0	0	tiq	0.02	pqflag	0

The plant controller of a solar farm can be represented by repc_a model and Figure 4 shows the block diagram of this model. Note that this site was normally operating in reactive power control mode and the frequency control was disabled. To mimic this control logic, both RefFlg and FrqFlg are set to 0. Table 6 shows the initial repc_a model's parameters set as derived from the controller settings along with some typical values. However, some parameters need to be tuned to achieve better agreement between field measurements and simulation results.
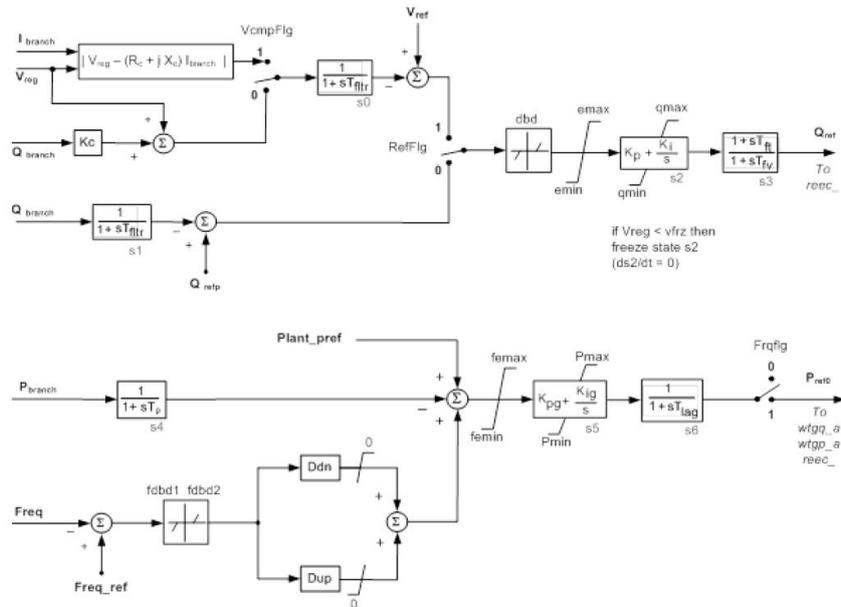

Figure 4: Block Diagram of Renewable Energy Power Plant Controller Model (repc_a)

Table 6: Parameters of Renewable Energy Power Plant Controller Model (repc_a)

Parameters	Value	Parameter	Value	Parameter	Value
mvab	0.0	rc	0.0	fdbd1	0
rbus	10003	xc	0.0	fdbd2	0
IbFrom	10003	kc	0.0	femax	0.5
IbTo	99999	vcmpflg	1	femin	-0.5
BrID	1	emax	0.1	pmax	1.0
tfltr	0.02	emin	-0.1	pmin	0.0
kp	0.1	dbd	0	tlag	0.1
ki	1.0	qmax	1.1	ddn	50
tft	0.0	qmin	0.9	dup	50
tfv	0.15	kpg	1.0	frqflg	0
refflg	0	kig	1.0	outflag	1
vfrz	0.8	tp	0.25	puflag	0

Step 1: Finding the Dominant Mode from Measurement

During staged tests, a 15 MVAr reference step change was introduced to the plant controller and the plant's response was recorded at the point of interconnection, i.e. high side of the substation transformer. Prony analysis was conducted on the measured reactive power waveform and results are shown in Figure 5. Based on this analysis, the dominant mode has the frequency of 0.051 Hz and damping of 29.4%.
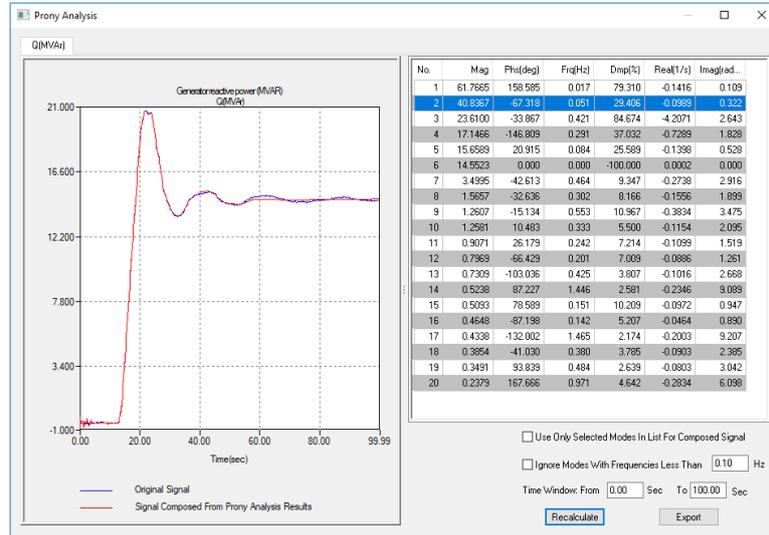

Figure 5: Prony Analysis on the Measured Waveform

Step 2: Finding the Dominant Mode in Frequency Domain

A complete eigenvalue analysis was conducted on the mathematical models described in the previous section using Small Signal Analysis Tool (SSAT) [7]. The SSAT study shows that the dominant mode has the frequency of 0.62 Hz and damping of 76% (i.e., -4.57±3.90j). By comparing this mode to the dominant mode from Step 1, it can be seen that the frequency and damping of these two modes are significantly different. The objective of a model tuning study is to match this mode with the mode obtained in the previous step and to this end, the parameters that have significant impact on the dominant mode first need to be determined.

Step 3: Identifying Parameters with Most Significant Impact on the Dominant Mode

The effect of a parameter change on modes can be studied through sensitivity analysis. Using SSAT, the sensitivity analysis was conducted on the dominant mode for several controller parameters in the electrical and plant controller models. Table 7 summarizes the result of this study and as shown, Kp, Ki, and Tfv parameters of the plant controller described in Figure 4 have the most significant impact on this mode. These parameters are located on the reactive power regulator path and they participate in low-frequency regulation of the reactive power response, indicating that sensitivity analysis results match the expected outcome.

Table 7: Sensitivity Analysis for the Dominant Mode (i.e., Freq. of 0.62 Hz and Damping of 76%)

Parameter	Model	Base Value	Frequency Sensitivity	Damping Sensitivity
Kqp	REEC	0.1	0.001	-0.001
Kqi	REEC	1.0	0.000	0.000
Kvp	REEC	1.0	0.006	-0.012
Kvi	REEC	100	-0.003	0.002
Kp	REPC	0.1	-3.414	4.081
Ki	REPC	1.0	0.991	-0.643
Tfv	REPC	0.15	0.723	-3.107

Step 4: Adjusting Parameters to Tune the Dominant Mode

By changing the parameters that were identified in Step 3, the dominant mode of the system will vary. Tracing the dominant mode with respect to these changes determines which set of parameters results in the closest match with the dominant mode identified in Step 1. Figure 6 illustrates the mode trace plot for this case study, where the direction of the arrows signifies increasing of the corresponding parameter. Based on the mode trace results, Kp = 0.03, Ki = 0.15, and Tfv = 5 lead to a dominant mode that has frequency of 0.055 Hz and damping of 29.9%, which is very close to the dominant mode obtained in Step 1.
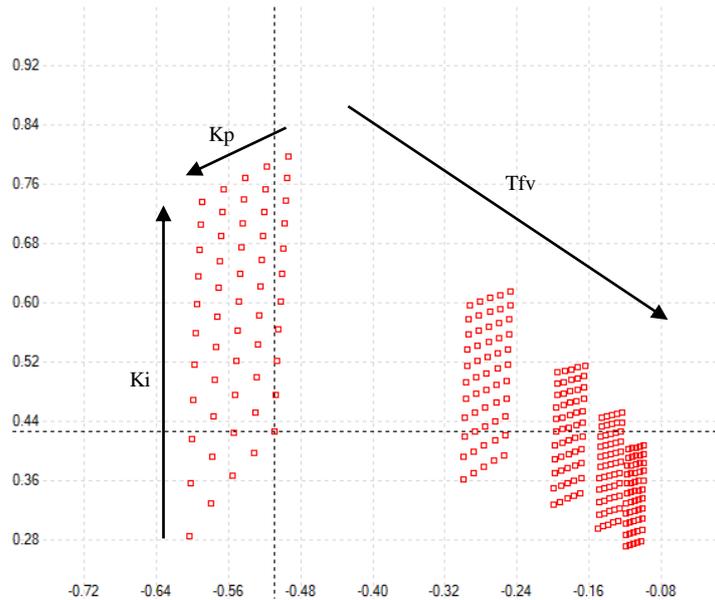
Figure 6: Mode Trace Plot for the Dominant Mode

Step 5: Checking the Results in the Time Domain

To ensure that the tuned parameters are also valid in time domain, a dynamic simulation study is performed and results are shown in Figure 7. This figure compares the response of the plant from the original models (dashed red line) and the tuned models (solid green line) with the actual recording during the staged test (dotted black line). As shown, the tuned models very closely mimic the actual plant's response.
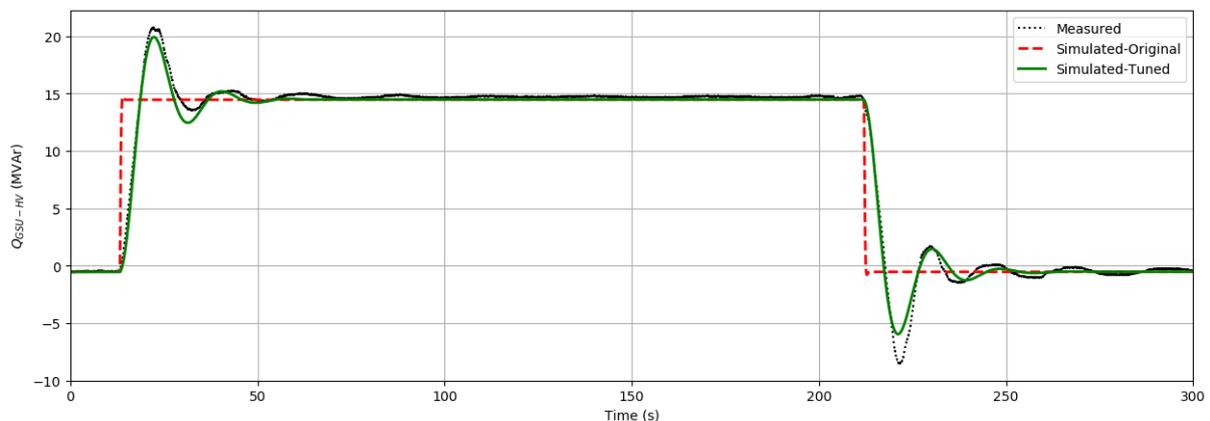
Figure 7: Comparing Time Domain Results

Conclusion

The paper proposed a systematic approach for model validation studies using small-signal analysis techniques. The proposed approach consists of five steps as follows: i) identifying the dominant mode of a system through Prony analysis of the actual plant response to an event or a staged test; ii) determining the equivalent dominant mode of the mathematical model of the system through eigenvalue analysis; iii) identifying parameters of the models that have the most significant impact on the dominant mode through sensitivity analysis; iv) adjusting parameters to tune the dominant mode using mode trace (root-locus) analysis; v) fine turning and verifying the accuracy of the results using time domain simulations. A real-world case study for model tuning and validation of a solar farm was used to evaluate effectiveness of the proposed approach and it was demonstrated that a more accurate mathematical model can be achieved in a systematic way by employing the proposed 5-step method. .

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