Root Locus Analysis of the Generic WECC Photovoltaic Power Plant Model

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***Abstract* – This paper documents the effect that the PI controller gains in the generic WECC photovoltaic power plant have on the system modes.**

Key Words – Generic photovoltaic model, photovoltaic power plant (PVPP), root locus.

I. INTRODUCTION

The Western Electricity Coordinating Council (WECC) WECC, through its Renewable Energy Modeling Task Force (REMTF), has been leading efforts aimed at developing models for photovoltaic power plants (PVPPs) suitable for use in bulk power system analyses. These efforts have resulted in the implementation of this type of models in several transient stability programs extensively used in North America for power system planning studies. The models allow for the representation of equipment built by different manufactures; for this reason, they have been denoted as "generic". The rationale behind their development, the description of their components, model naming conventions, as well as time-domain validation test results have been documented in several publications [1], [2], [3].

As a sequel to the efforts outlined above, the work described in this paper has the objective of providing additional insights into the dynamic characteristics of the generic photovoltaic power plant (g-PVPP) by studying its frequency domain characteristics. More specifically, the work is aimed at establishing the effect that the gains of the proportional-integral (PI) controller in the plant and electrical controller have on the eigenvalues of a g-PVPP for different levels of generation. Controller gains are typically adjusted to meet performance specifications, their effect and relation on the system modes allows for the assessment of potential control improvements and/or constraints. Furthermore, since numerical stability is also related to the system modes, an understanding of the modal characteristics of the g-PVPP also provides insights into the expected numerical performance of the model.

The study approach is straightforward and consists of a root locus analysis of the test system used in [2]. The test system represents an aggregate model of a g-PVPP, a GSU transformer, an equivalent collector system, and a substation transformer, connected to a large system; the one line diagram of the system is shown in Figure 1. The system captures the fundamental characteristics of this type of power plants and allows for their detailed analysis. The single g-PVPP shown in Figure 1 is the model recommended by WECC to represent PVPPs in WECC base cases and has been used extensively in the development of generic renewable dynamic models (PV, wind, and energy storage) [1-5].

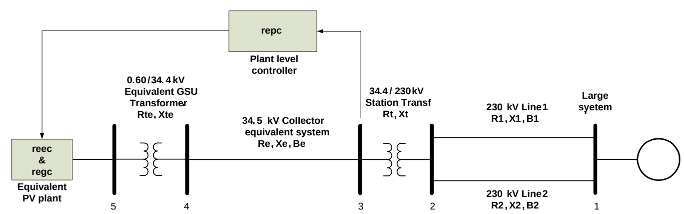

Figure 1. Test System

The rest of the paper is organized as follows: In Section II the interconnection between the components of a g-PVPP and their associated block diagrams are described. Section III covers the study results; Section IV presents the conclusions reached.

II. g-PVPP MODULES AND CONNECTIVITY

The g-PVPP model consists of three modules: generator/converter, electrical controller, and plant-level controller. The overall structure of a g-PVPP model is shown in Figure 2 (the labels regc, reec, and repc are the names specified for the respective modules [3], [6]); V_{meas} and P_{meas} represent remote measurements of voltage and power; I_q and I_p are current injections into the network.

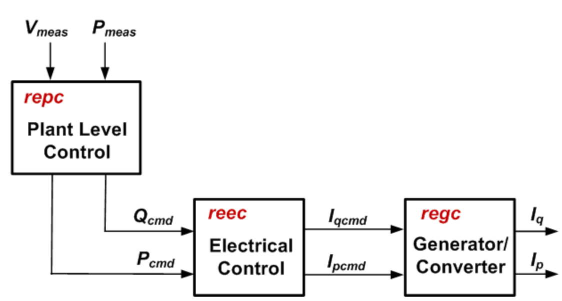

Figure 2. Structure of the generic PVPP model

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The generator/converter module represents a high bandwidth current regulator that injects real and reactive components of inverter current into the external network in response to real and reactive current commands. The electrical controller module emulates the active and reactive power controls. Two proportional-integral blocks represent the reactive control and local voltage response. The plant-level controller is a module used when plant-level control of active and/or reactive power is desired. This controller provides the ability to control one aggregated g-PVPP using remote measurements (Figure 1 shows the plant-level controller having as inputs measurements from the low side of the substation transformer). The linearized representations of these modules are shown in Figures 3, 4 and 5. The complete block diagrams which include nonlinearities can be found in [3].

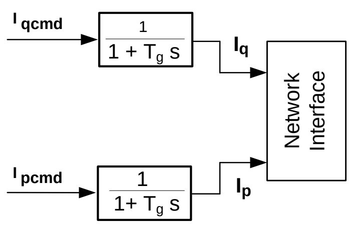

Figure 3. Generator/Converter Linear Model

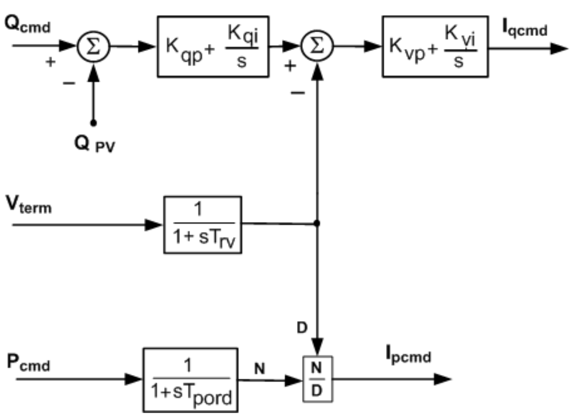

Figure 4. Electrical Controller Linear Model

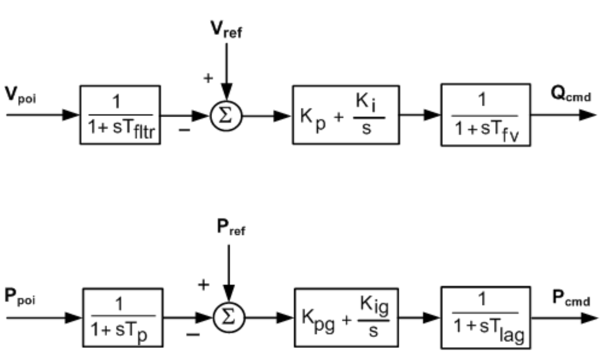

Figure 5. Plant-Level Controller Linear Model

III. EIGENVALUE ANALYSIS

There are eight PI controller gains in the g-PVPP model – four are part of the electrical controller model and four are part of the plant-level controller model. Table 2 lists these gains and their nominal values. The "nominal" parameter values are those used in Ref. [2]; the plant is rated at 110 MVA.

To ascertain which gains are related to specific system eigenvalues a root locus plot was computed for each PI gain. To this end, each gain was varied from zero to a value where it was possible to reach a conclusion regarding the system stability. The values over which each gain was varied are labeled "Range" in Table 2. The system linearization and time-domain simulations were carried out using GE's transient stability program, PSLF; the eigenvalue computations were performed with Matlab.

Model*	Gain	Nominal value	Range
EC	Kqp	0.0	0 to 30
EC	Kqi	0.1	0 to 4.5
EC	Kvp	0.0	0 to 30
EC	Kvi	40.0	0 to 460
PC	Kp	18.0	0 to 600
PC	Ki	5.0	0 to 200
PC	Kpg	0.1	0 to 9
PC	Kig	0.05	0 to 30

*: EC = Electrical Controller; PC = Plant-level Controller

Table 2. PI Controller Gains

Three PV generation levels were considered in the study:

Case	P_{pv} [MW]	Q_{pv} [MVAr]
1	100	0
2	50	50
3	0	100

Table 1. PV Plant Generation Levels

In the first case, the PV plant is only generating real power; in the second case, the generation is evenly divided between real and reactive power; and in the third case only reactive power is generated. The last case is an extreme case intended for analysis purposes.

The results obtained for Case 1 (P_{pv} = 100 MW, Q_{pv} = 0 MVAr) are summarized in Figures 6 and 7. Figure 6 shows the root locus for each of the PI gains in the Electrical Controller, Kqp, Kqi, Kvp, and; Figure 7 shows the root locus for each of the PI gains in the Plant-level Controller, Kp, Ki, Kpg, and Kig. With two exceptions, Kqp and Kvp, both figures only show those eigenvalues that migrate toward the unstable half of the complex plane. The root locus for Kqp and Kvp in Figure 6 do not exhibit unstable roots. The green points are the eigenvalues that correspond to the nominal parameter values. These eigenvalues are listed in Table 3. Evidently, the g-PVPP for the given conditions is very stable – this has been observed in time domain simulations.

Mode #	Real	Imag.
1	-16.41	10.32
2	-16.41	-10.32
3	-57.98	11.90
4	-57.98	-11.90
5	-68.20	0
6	-50.00	0
7	-30.90	0
8	-12.49	0
9	-8.69	0
10	-0.70	0
11	-0.19	0
12	-0.05	0

Table 3. System Eigenvalues (for nominal parameter values)

The root locus plots for the PI gains in the electrical controller (Figure 6) show that increasing the proportional gains, Kqp and Kvp, does not lead to system instability. The same cannot be said about the integral gains Kqi and Kvi: When Kqi is approximately 0.27, eigenvalues 9 and 10 split into a complex pair which becomes unstable with a frequency of 2.1 Hz (13.2 rad/sec) when Kqi has a magnitude of 2.8. This is confirmed via the time domain simulations of the original non-linear system as shown in Figure 8. This figure shows the system response to a small perturbation at time one second for three values of Kqi; the sustained oscillations in the middle plot corresponds to Kqi = 2.8. In all cases considered in this work, unstable modes were confirmed with time domain simulations (for reasons of space only one time domain simulation is included in the paper). The gain Kvi is mainly related to the complex pair -16.41 ± j 10.32 (eigenvalues 1 and 2). This pair migrates toward the right side of the complex plane as Kvi increases. The system is stable for 0 <= Kvi < 345. It could be argued that the value of Kvi that leads to system instability is too large for a practical case.

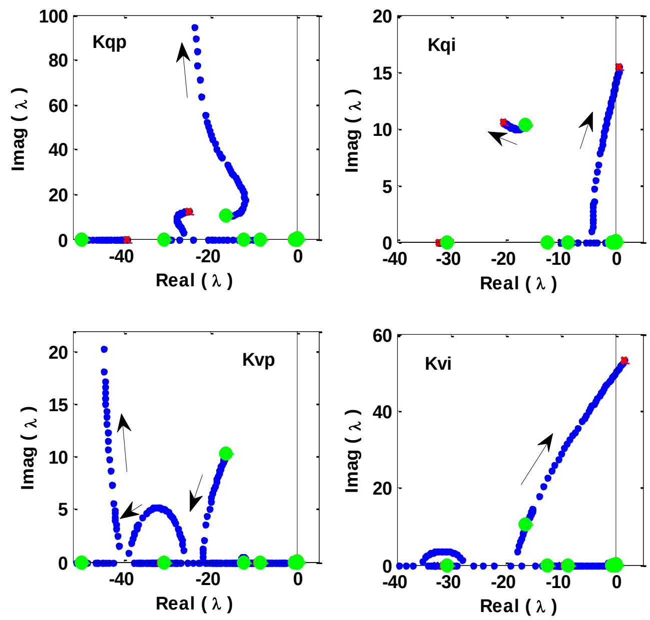

Figure 6. Root Locus for Electrical Controller PI Gains

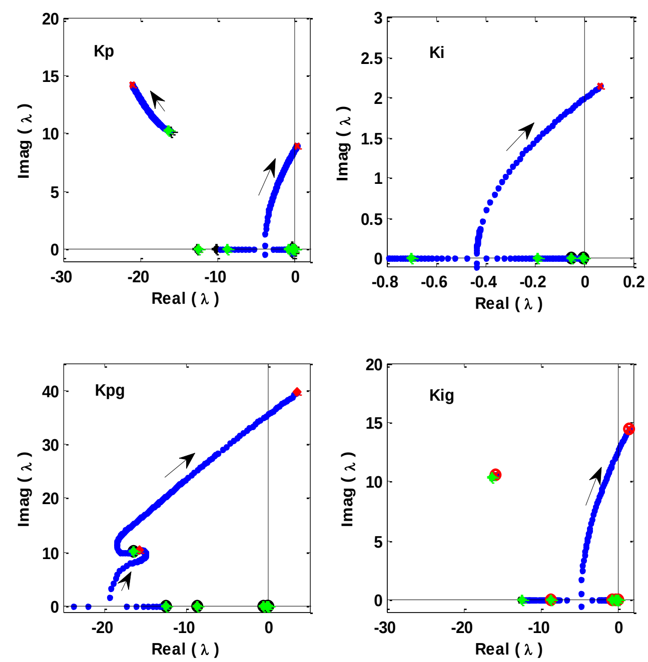

Figure 7. Root Locus for Plant-Level Controller PI Gains

Figure 7 shows the root locus plots for the PI gains in the plant-level controller. For this controller, increasing any of its gains leads to system instability. However, in all cases the magnitudes of the gains that causes the system to become unstable are at least one order of magnitude larger than the nominal values proposed in Ref. [2], this in turn implies a rather small likelihood of encountering stability problems in practical situations. The next paragraph summarizes the results related for the plant-level controller gains.

Kp is mainly associated with eigenvalues 1, 2, 9, and 10. Eigenvalues 9 and 10 split into a complex pair when Kp is approximately 59, this pair becomes unstable for Kp = 480. Ki is associated with eigenvalues 10 and 11. These modes split into a complex pair when Ki is approximately 7.3, the pair becomes unstable for Ki = 170. Kpg is associated with several eigenvalues, including eigenvalues 1, 2, 7, and 8. The complex eigenvalue 1, 2 pair migrates toward the right hand side of the complex plane and becomes unstable when Kpg is approximately 4.55. Kig is associated with eigenvalues 11 and 12. This pair of real eigenvalues splits into a complex pair when Kig = 2.1. The system becomes unstable when Kig = 17.

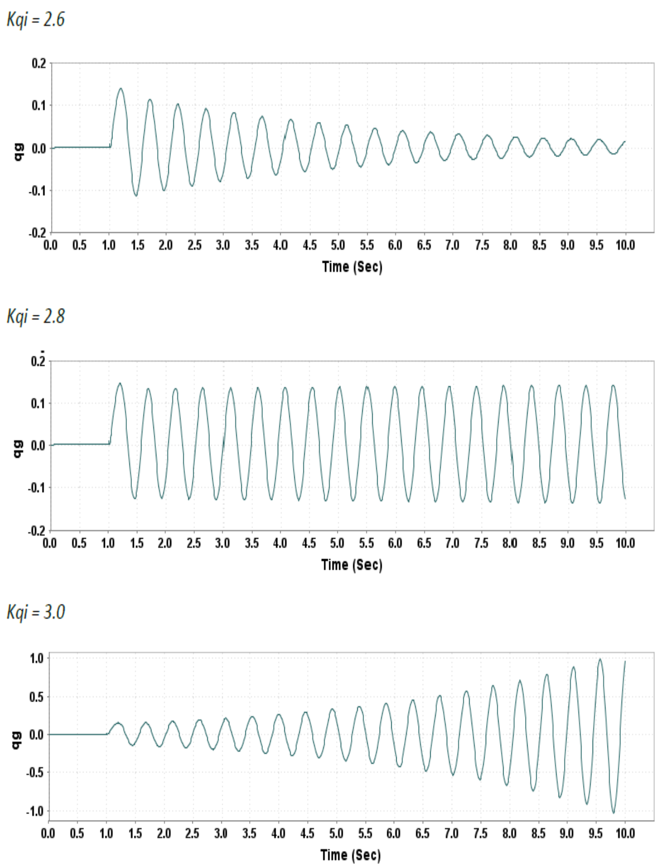

Figure 8. Time Domain Simulation for Gain Kqi

The results obtained for Case 2 (P_{pv} = 50 MW, Q_{pv} = 50 MVAr) and Case 3 (P_{pv} = 0 MW, Q_{pv} = 100 MVAr) are very similar to those obtained for Case 1. Figure 9 shows the eigenvalues for the three generation levels considered. Of particular interest is the fact that the system eigenvalues are quite similar for the three different cases. Furthermore, the root locus plots for the different gains exhibit very similar patterns, e.g., Figure 10 shows one branch of the root locus for the Kp gain – the root locus plot for the three cases considered are very similar. In general, it was observed that the main difference between the three cases studied is that larger gains are required to make the system unstable for Case 3. This is illustrated in Figure 11 which shows a section of a branch of the root locus for Kpg. The last eigenvalue plotted for all cases corresponds to Kpg = 9. Whereas this value of Kpg causes Cases 1 and 2 to be unstable, Case 3 remains stable.

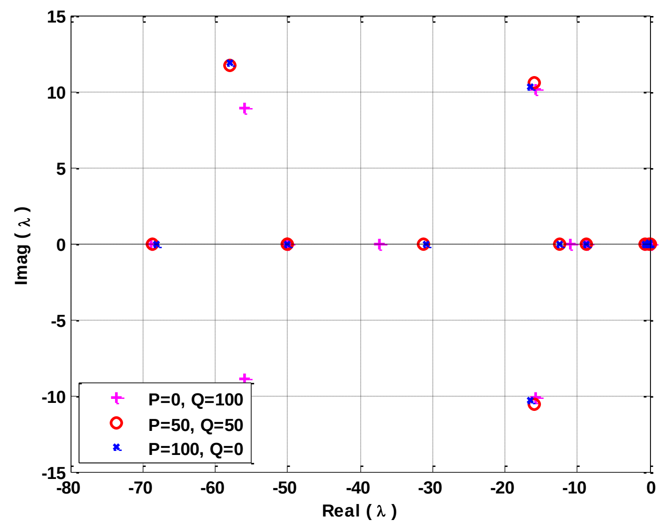

Figure 9. System Eigenvalues for Cases 1, 2, 3

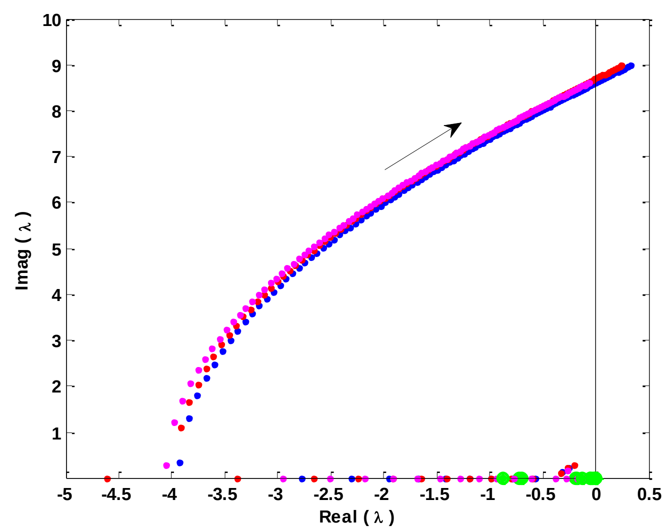

Figure 10. Root Locus Branch for Kp for Cases 1, 2, 3 (Case1: blue, Case 2: red, Case 3: magenta)

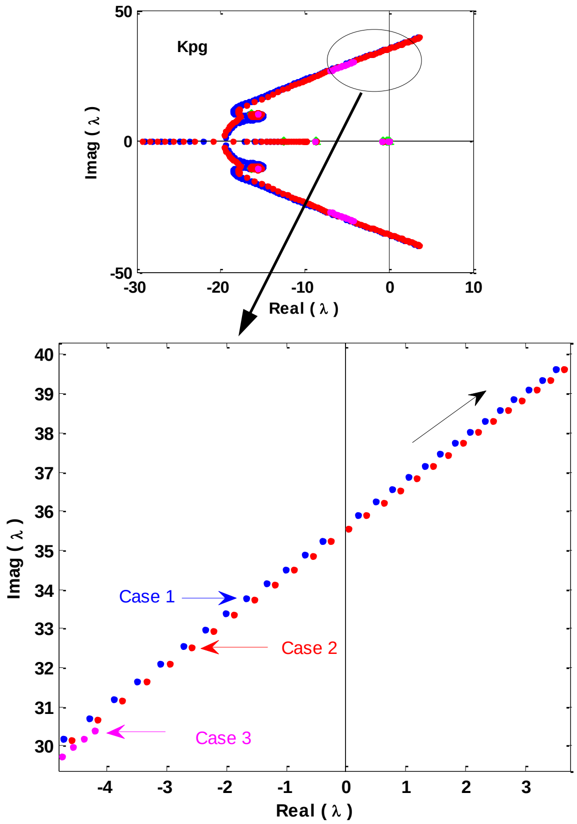

Figure 11. Root Locus Branch for Kgp for Cases 1, 2, 3 (Case1: blue, Case 2: red, Case 3: magenta)

IV. CONCLUSIONS

The results obtained in the course of this investigation documents the relation between specific PI controller gains in a photovoltaic power plant represented by the generic PV model and the system eigenvalues when the plant is connected to a large system.

The work presented also complements the multiple works related to the test system carried out in the time domain and provide additional insights into the dynamic characteristics of the generic PV model.

It has been shown that eigenvalue plots for the system conditions considered exhibit very similar characteristics and that the system is stable for a wide range of gains and operating conditions. These results and observations have practical implications as they underline potential flexibility in the design of plant controllers.

Future work would entail the analysis of the system equivalent impedance and collector on the system modes.

ACKNOWLEDGMENT

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