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PROJECT TITLE: ASSESSMENT OF THE UNIVERSAL FEASIBILITY OF USING POWER SYSTEM HARMONICS AS LOSS OF MAINS DETECTION FOR DISTRIBUTED ENERGY RESOURCES

CONTRACT NUMBER: RD3-21 **MILESTONE NUMBER: 3** **REPORT DATE: DECEMBER 21, 2009**
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MILESTONE REPORT

EXECUTIVE SUMMARY

The purpose of this project is to assess the universal applicability of harmonic signatures as a means for detecting unintentional islanding of distributed generation equipment such as photovoltaics. This report covers the time period October 01, 2009, and December 15, 2009, and describes our progress on Milestone 3. Milestone 3 has been completed, and substantial progress has been made on Milestones 4, 5 and 6. Substantial accomplishments include:

- Completion of a photovoltaic system model in the EMTP-RV power system simulation software.
- Completion of a three-phase wind turbine model in EMTP-RV.
- Completion of IEEE 13 and 34-bus distribution feeder models in EMTP-RV.
- Holding of our second face-to-face coordination meeting.

Project funding is provided by customers of Xcel Energy through a grant from the Renewable Development Fund.

TECHNICAL PROGRESS

Milestone #3 consisted of: completing an EMTP-RV model of a PV system; completing an EMTP-RV model of a wind turbine; and holding our second face-to-face coordination meeting.

PV model

We have completed a photovoltaic (PV) system model in the EMTP-RV simulation software. EMTP-RV (which stands for "ElectroMagnetic Transients Program—Restructured Version"; see www.emtp.com) was selected because of its suitability for the type of modeling we will be performing, low cost, and the team's familiarity with it. The PV model is shown in Figure 1 below. We have used the switch-averaged model of the power stage, which boils down to the multiplication block "Fm1" and the three controlled current sources. We model a three-phase output by appropriately time-delaying a single-phase output (that is, we have not implemented a vector or other direct three-phase current controller). We believe this approach to be sufficient for our purposes because the dynamics of the current controller are much faster than those we are studying here, and thus are not the drivers for the behavior we are looking for.

The maximum power point tracker (MPPT), shown in Figure 2, is a classical perturb-and-observe (P&O) type using a fixed step size and step interval. The PV array model, shown in Figure 3, is based on a lookup table using a scalable PV I-V curve that can model a PV array of arbitrary size. This approach is simple and simulates quickly, but it has the drawback of having a fixed array fill factor. This drawback primarily affects the operation of the MPPT, and the literature along with our past experience suggests that even then the effect is relatively minor. Thus, since the fixed fill factor is not a problem in the present application and the speed of simulation is extremely helpful, we have retained the lookup table-based simulation. The MPPT controls the voltage of the PV array via output current control from the inverter; that is, the output current is changed to cause the PV voltage to track a setpoint. The setpoint is then perturbed in the P&O scheme. This appears to be the method used by most inverter manufacturers, based on conversations with them and on measurements made on commercial units.

Figure 4 shows the PV output power under the control of the MPPT, for a 10 kW PV system starting from open circuit voltage under full sun. The MPPT response is clearly seen; it rises from zero to a steady-state 10 kW, then holds there. The response is a bit slow and is more typical of larger inverters, indicating that a bit of tuning might be required for smaller inverters, but the basic functionality is clearly verified.

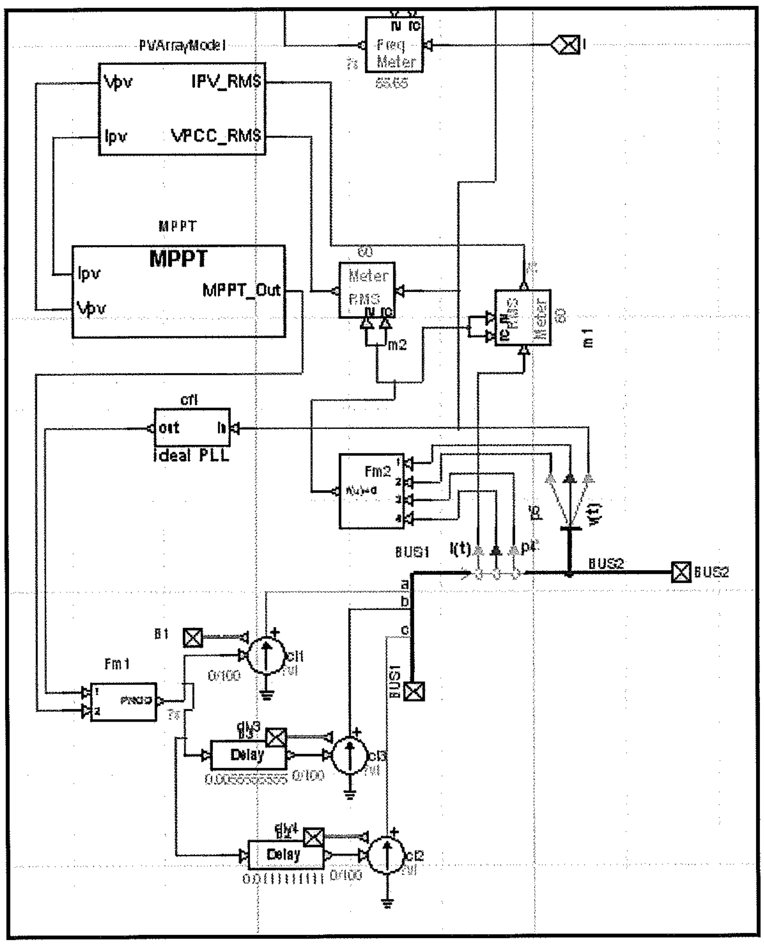

Figure 1. PV system model developed in EMTP-RV. The three-phase current sources are at the lower left.

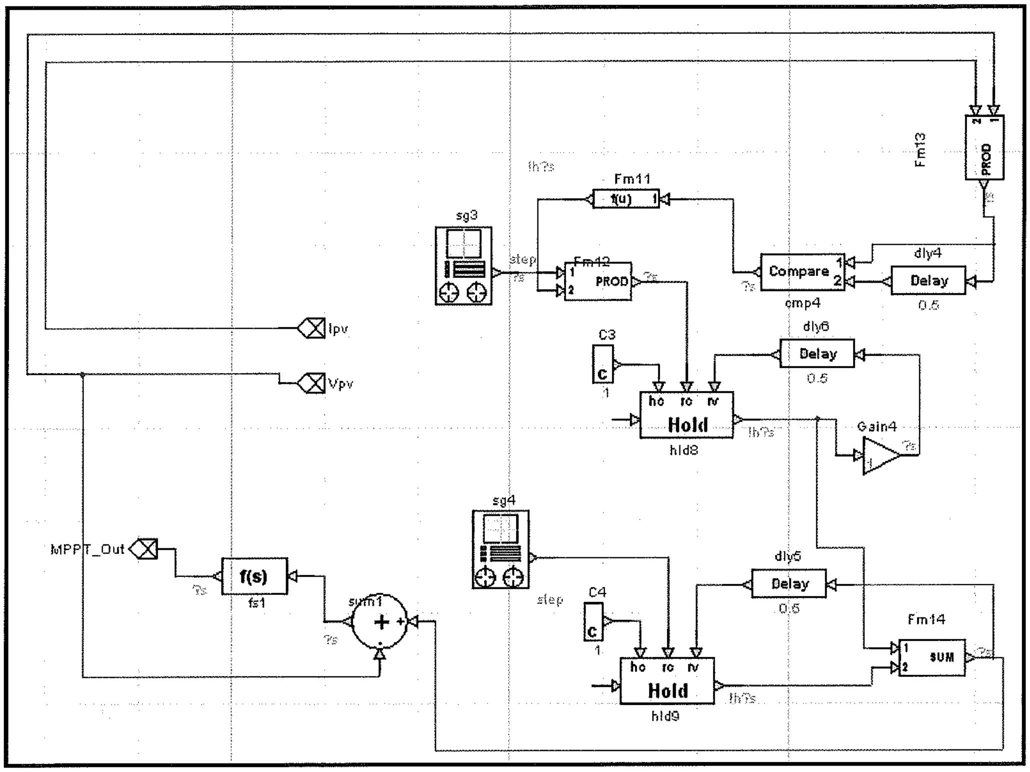

Figure 2. Perturb-and-observe (P&O) maximum power point tracking controller for the PV system. The product block "Fm13" at the upper right computes the PV power (Ipv and Vpv have been smoothed by windowed averaging before reaching this block). The delay block "dly4" and comparator "cmp4" compare the present power reading to the previous one (the heart of P&O). The rest of the blocks determine how to change the increment for the next cycle, compute the new PV voltage command, and issue it via the "MPPT_Out" tab.

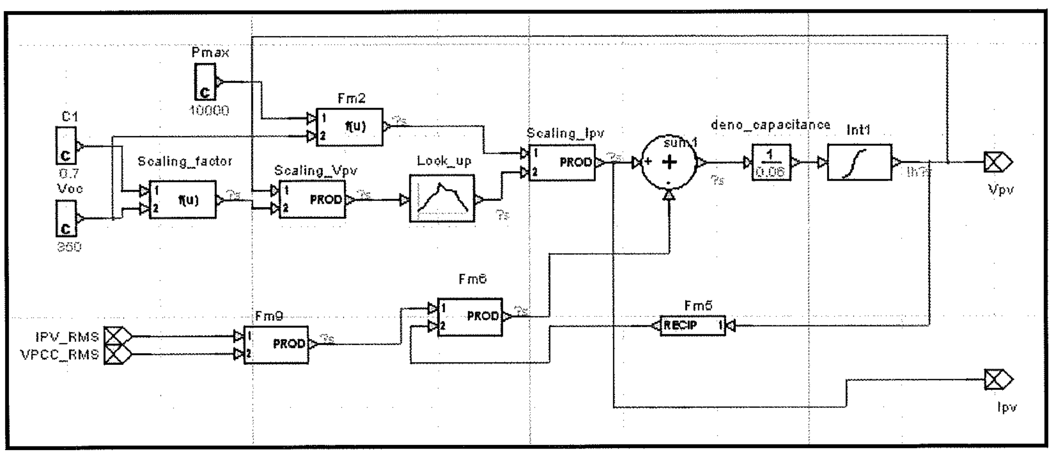

Figure 3. PV array model. The lookup table near the center of the figure stores the I-V curve. The summation block just to the right of center represents Kirchhoff's Current Law taken at the common node between the PV array, the large buffer capacitor, and the switch bridge, so that the output signal of that summation block is the current flowing into the buffer capacitor. Then, the gain and integrator take the buffer capacitor current and compute the buffer capacitor voltage.

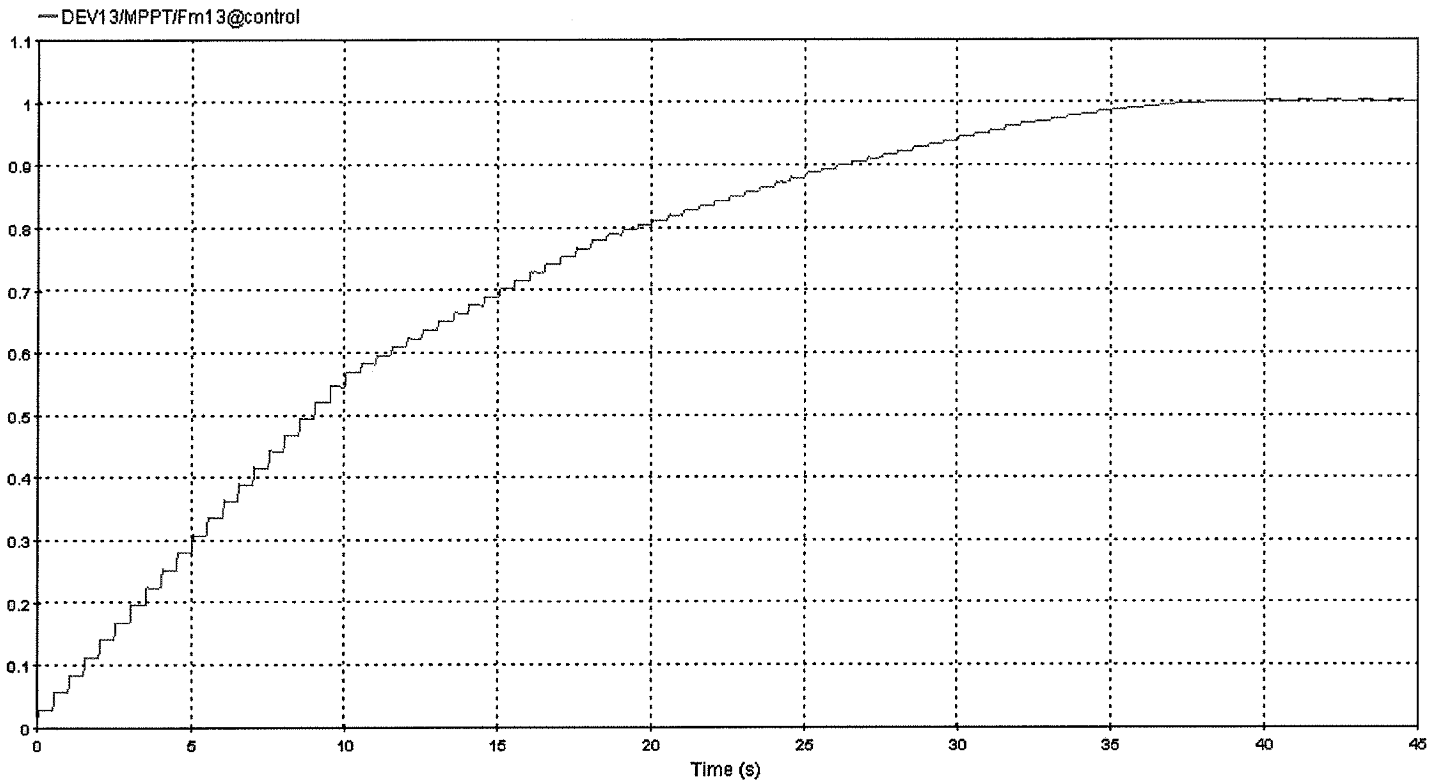

Figure 4. Plot showing PV system output power under the control of the MPPT when starting from open-circuit voltage under full sun, which is something of a worst case. The vertical scale is in units of tens of kW (this is a 10-kW system). The MPPT control action is apparent, although the MPPT is a bit slow and probably not yet properly optimized.

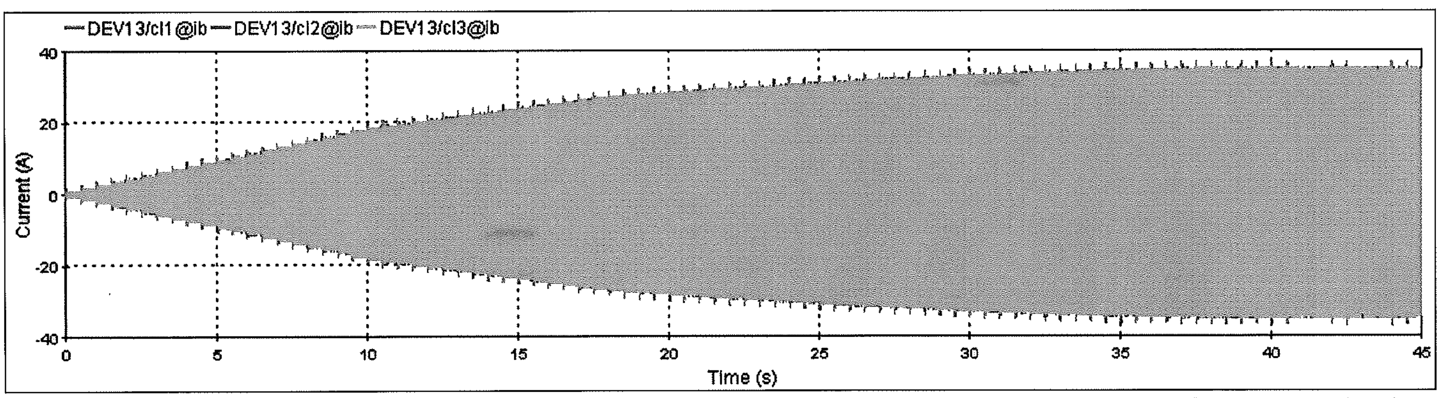

Figure 5. PV system output current waveforms from the same simulation as in Figure 3. Again, the MPPT action is apparent.

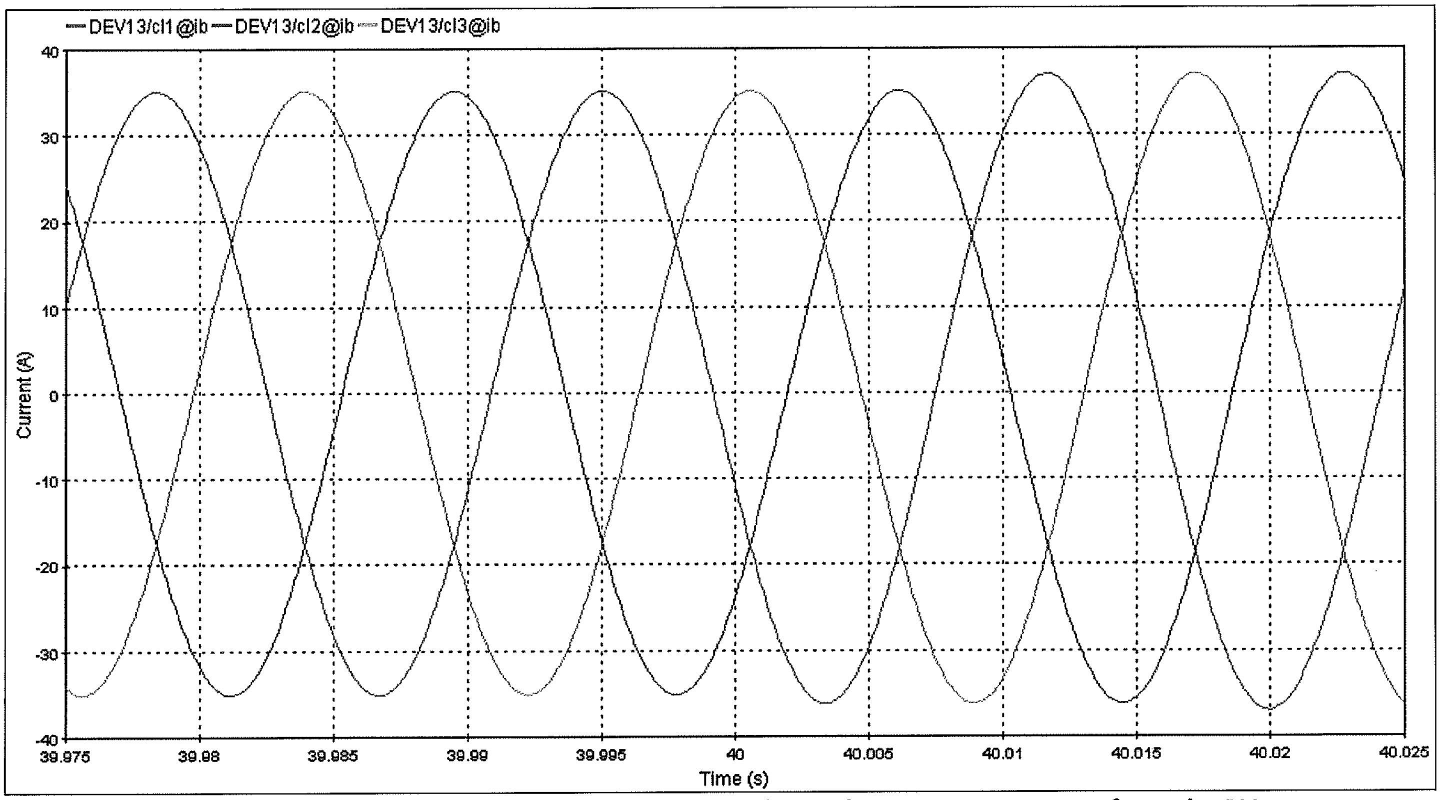

Figure 6. Zoomed-in view of Figure 4, showing the three-phase output currents from the PV array.

Wind turbine model

Because of its considerable experience base in this area, Enernex was tasked with development of the wind turbine model. Ultimately, Enernex will produce two models: one appropriate for small, residential-scale turbines, and the other suitable for utility-scale Type III turbines as might be seen in a CBED project. The model shown here is more appropriate for the CBED application; the residential-scale turbine model is similar, but has a single-phase version and does not use active blade pitch control. As will be seen in Figures 7-11, the basic wind turbine model functionality is verified.

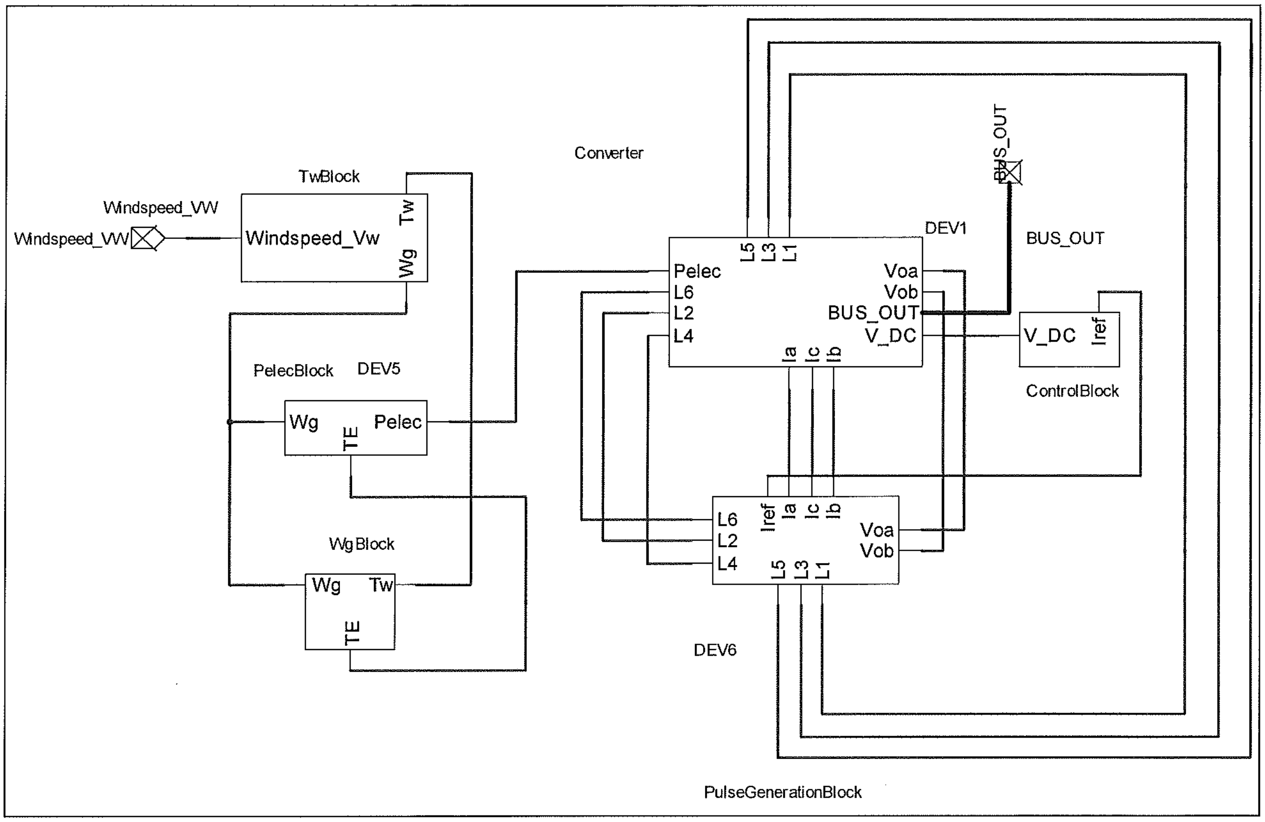

Figure 7. Wind turbine model. The upper-left block "TwBlock" converts wind speed (currently assumed constant) into mechanical torque. The "PelecBlock" computes the electrical power and electrical torque (TE) produced by the generator. The "WgBlock" block contains an electrical representation of the mechanical drivetrain of the wind turbine that reasonably captures the mechanical system dynamics. The "Converter" block contains the switch bridge (see Figure 8), and the "PulseGenerationBlock", also labeled "DEV6", generates the control pulses for the switch bridge using hysteresis control (see Figure 9).

Figure 8. Contents of the "Converter" block in Figure 7. The electrical power is converted to current by the blocks at the far left. The buffer capacitor is shown near the center, and the three-phase switch bridge with antiparallel diodes is shown at the far right. Output filter inductors for each phase, which are also the inductors used for the hysteresis current control, are also shown.

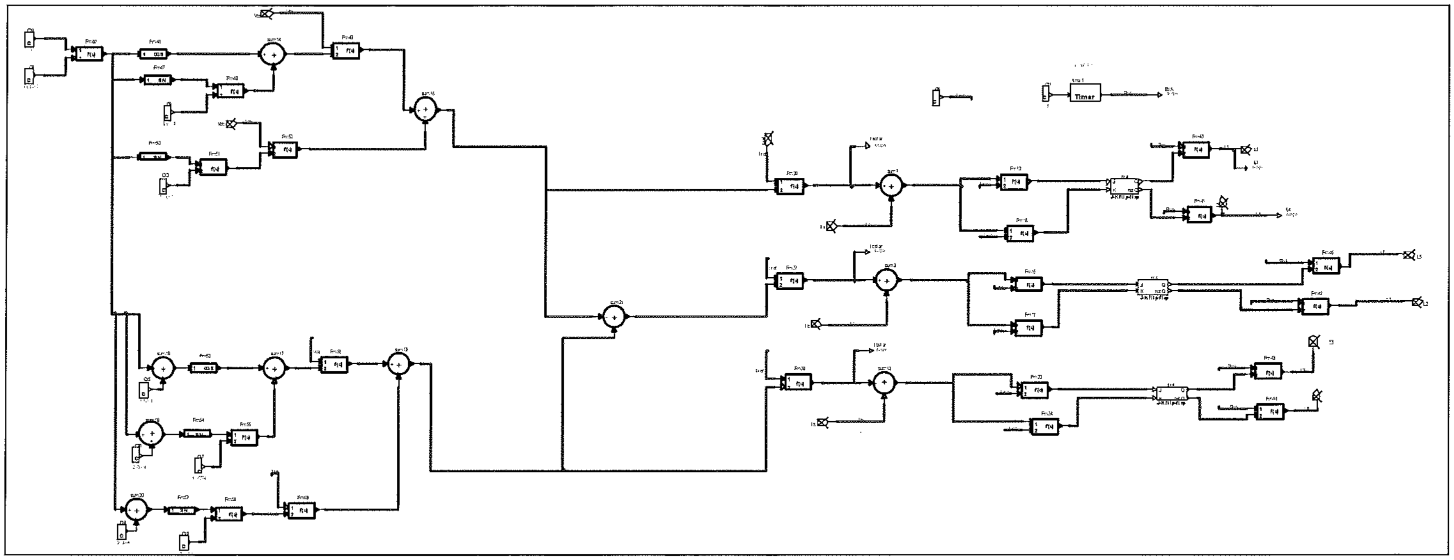

Figure 9. Contents of the "PulseGenerationBlock" block in Figure 7. This figure is unfortunately difficult to read in this format, but it does show the general layout; output current references are generated at the left, then compared to the actual measured output inductor currents in the blocks to the right, to determine whether the measured current is within one hysteresis tolerance band of the reference current. These comparisons are used to generate "up" or "down" switching commands for each phase leg.

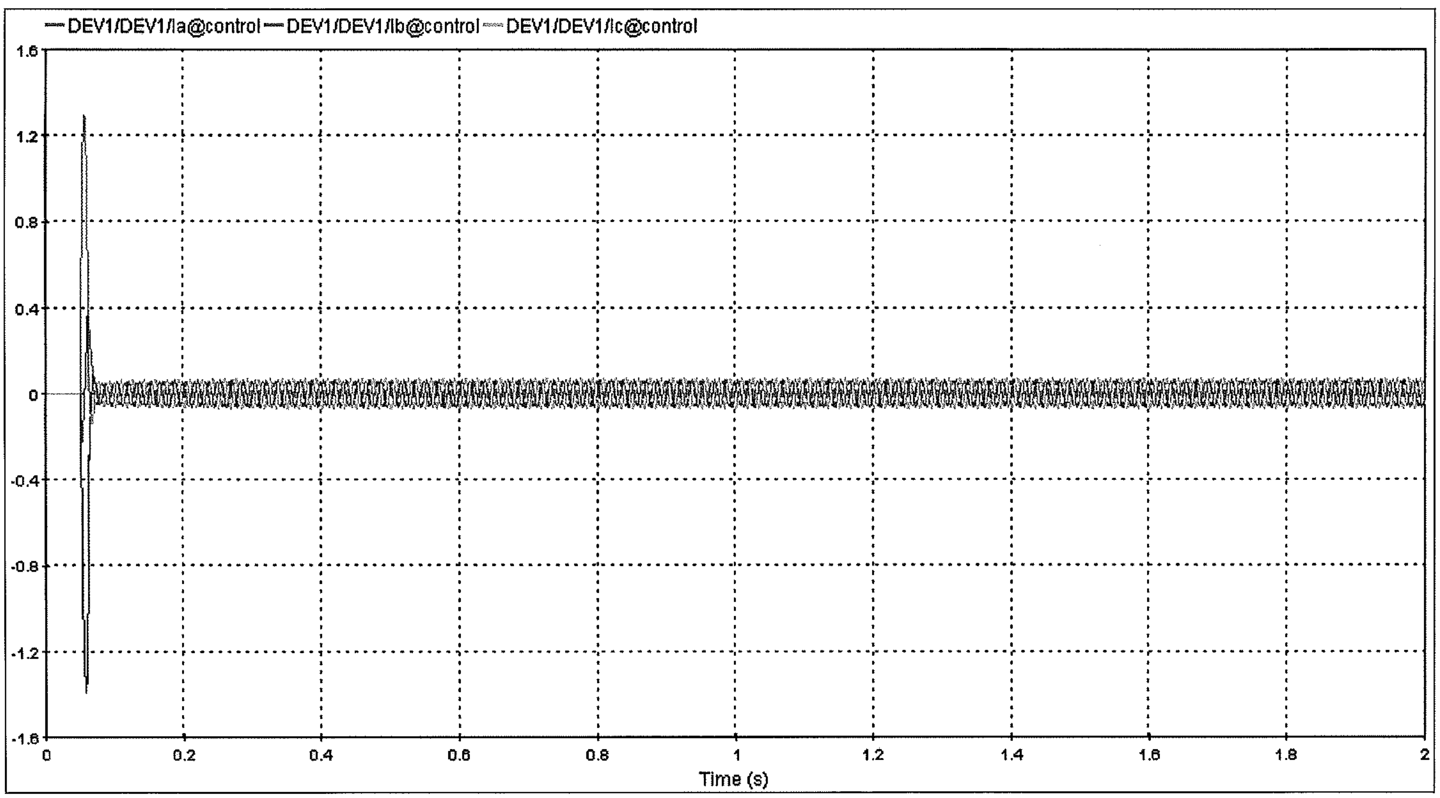

Figure 10. Output currents of the wind turbine model, showing initial startup transient. Vertical scale is in tens of kA.

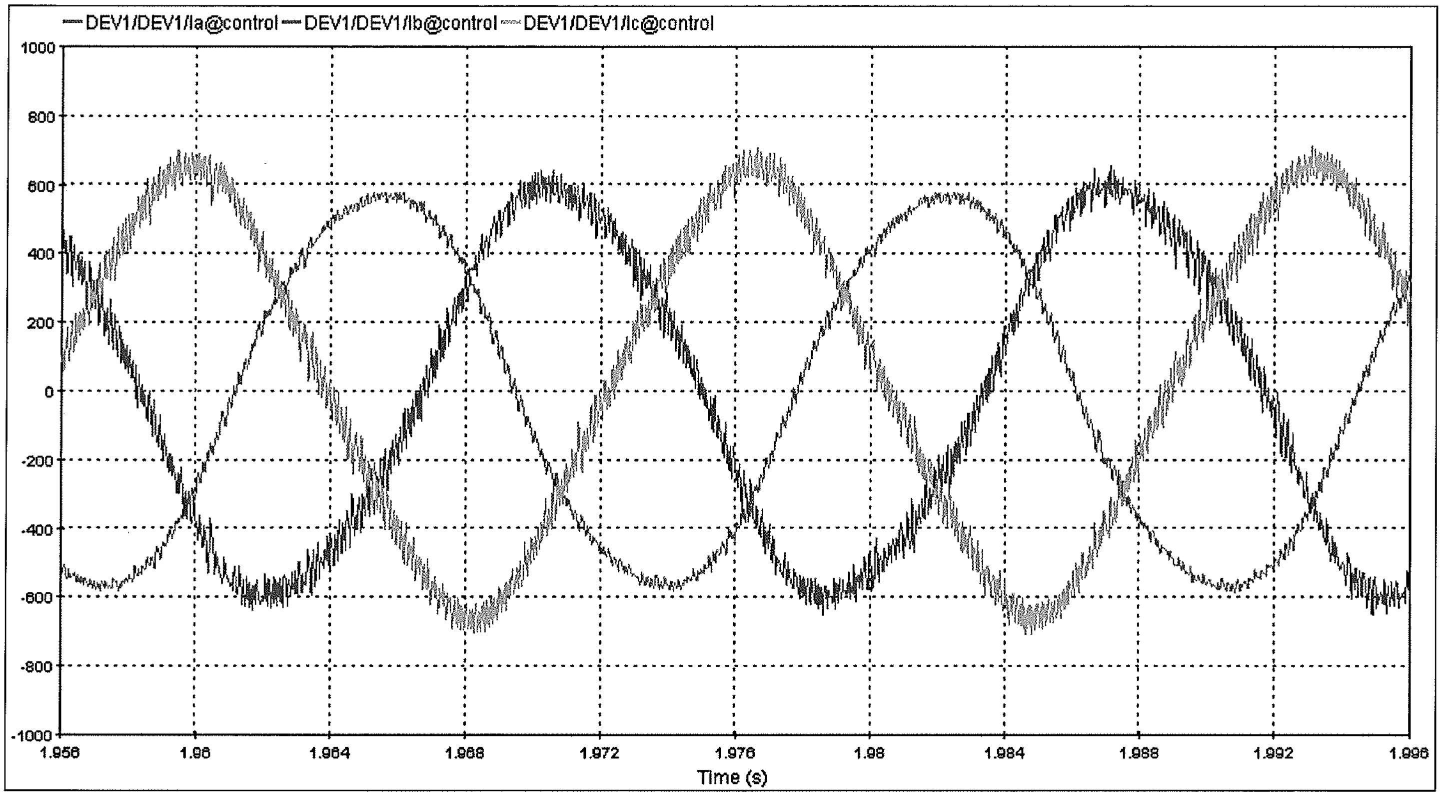

Figure 11. Zoomed-in version of Figure 10, showing hysteresis-controlled three-phase output currents. The switching action is clearly visible, and suggests that additional output filtering may be desirable.

Next steps

Next steps include:

- Completion of the model of a residential-scale wind turbine.
- Completion of the model of anaerobic digester-fired and similar generators, including site visits by NPPT personnel.
- Acquisition of grid frequency trajectory (frequency vs. time) at high time resolution.
- Conversion of the PV system model to include the actual switch bridge hardware.
- Completion of Xcel feeder data acquisition.

Second face-to-face coordination meeting

We held our second face-to-face coordination meeting in Knoxville, TN on December 14, 2009. We believe that we have shown good progress on all project objectives thus far. Also, we had an excellent open technical discussion of proposed solution methods for the ultimate problem to be solved by this project, namely enabling loss-of-mains detection by distributed generators without the use of positive feedback-based output perturbations. We are confident that all parties left the meeting with a) a good sense of the overall scope and objectives of the project; and b) an understanding of what each party must do next.

ADDITIONAL MILESTONES

Implementation of IEEE 13- and 34-bus feeder models (Milestones #5 and 6)

It is exceptionally difficult to define a "typical distribution feeder" because feeders use so many different conductor/crossarm configurations, capacitor deployments, conductor choices, feeder design philosophies, and load distributions. This greatly complicates the achievement of the goal of this project, namely to determine whether harmonics-based islanding prevention can be made to be useful at all points in the system and at all times.

We are using three types of feeder model to solve this problem: a) a generic, parametrized radial feeder; b) actual Xcel feeders; and c) two of the IEEE standard distribution feeders. We are working with Xcel engineers to determine the appropriate range of parameters for option 'a', and to obtain feeder data for option 'b' (this is discussed again below). In the meantime, NPPT and Enernex worked on implementing option 'c', the IEEE 13- and 34-bus feeder models, in the EMTP-RV software. The IEEE Power and Energy Society has archived data for four real-world feeders, along with the expected power flow solutions for these feeders. In this way, one can model a "realistic" feeder, and then verify the model in the power flow sense. Although these feeders cannot be considered typical, for the reasons discussed above, they are at least realistic in the sense that they represent what is actually in the field at four locations in the North American grid, and because the validation information is readily available, the models serve as a useful benchmark for a project like ours.

Enernex did some excellent background work on all four IEEE distribution feeders, to give context that assisted us in deciding which feeders to choose. The 13-bus feeder is an example of a relatively stiff urban feeder; the 34-bus feeder is rural, weaker (higher impedances, lower short circuit current strength), longer, and more nonuniformly loaded. Both feeders are strongly imbalanced.

The 34-bus feeder was entered and validated against the published power flow data. All power flow values are within 1% of the published solution, indicating that the model has been entered correctly and that the voltage regulator in this model is performing as expected. The IEEE 34-bus model with PV systems installed on all load nodes is shown in Figure 12 below. This system has been simulated and appears to be functioning correctly. (Note: in simulating this system, we realized that the data visualization software that comes with EMTP-RV has a file size limit, and that we had exceeded it. We can overcome this problem by eliminating storage of control signals that are useful for debugging but not needed at this system level, and also by decimation/downsampling.)

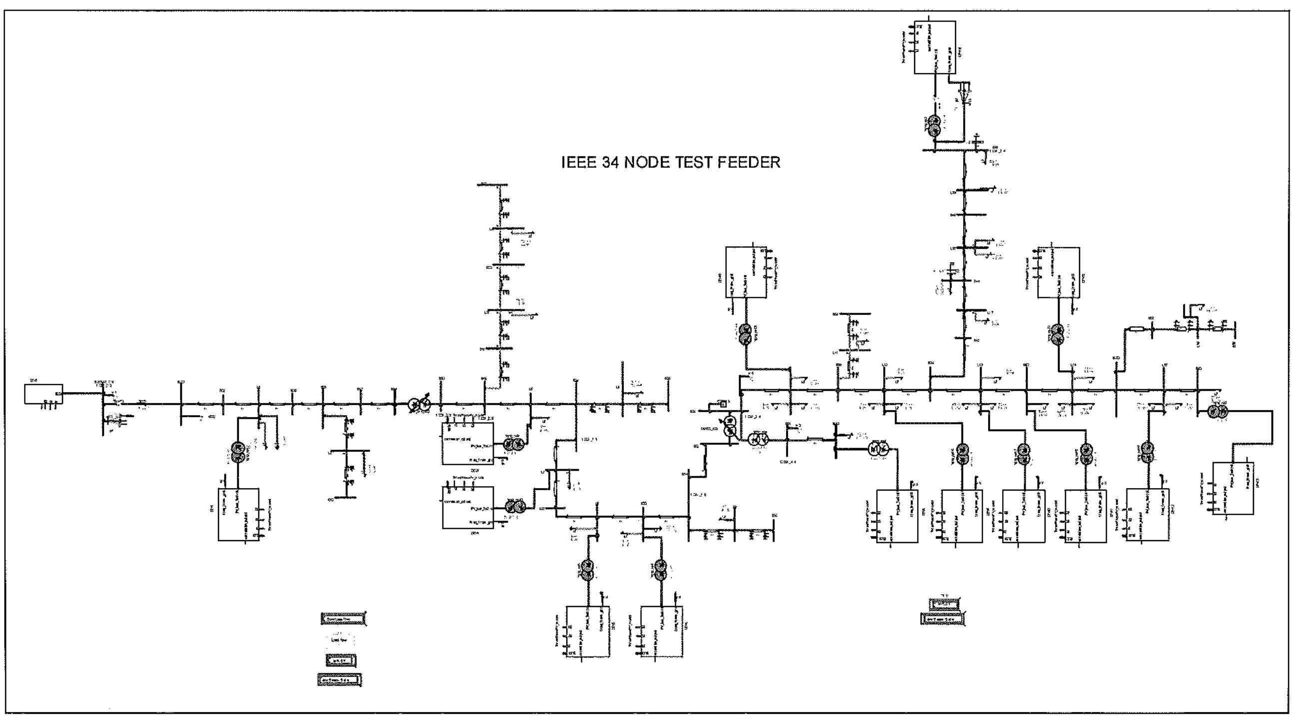

Figure 12. IEEE 34-bus distribution feeder with 13 PV systems added.

The 13-bus feeder has also been entered, and we are presently in the process of validating our power flow solution against the published one.

To ensure that the results of the project are of maximum value project sponsor Xcel Energy, we are seeking distribution feeder data specifically from Xcel Energy's NSP service territory). We will implement these models as well. We will work with Xcel's distribution engineers to determine what verification data may be available for the feeders we model.

Complete acquisition of all feeder data and test cases (Milestone #5)

As discussed above, we are currently working on obtaining data in two categories.

1.) We have begun the process of collecting the information we will need to be able to realistically program the synthetic source. These data include frequency trajectories (meaning, realistic frequency vs. time plots at resolution of ~ 1 sec) and Thevenin-equivalent impedances, most likely given in the form of a short-circuit current availability and an X/R ratio. As noted above, we now have a technical point of contact within Xcel that is assisting us in obtaining these data. We hope to obtain values from other utility systems as well, as time and availability permit.
2.) We are working with Xcel engineers to obtain impedance and load data for feeders in Xcel's northern system. These data will be used to establish the range of parameter values to be used in our generic feeder models (option 'a' above), and in addition we will model some of the actual Xcel feeders (option 'b') along with the IEEE standard feeders (option 'c').

Begin testing and evaluation of synchrophasor and harmonic models (Milestone #7)

We have begun early testing and validation of our models, as well as early evaluation of the synchrophasor method of loss-of-mains detection. Although it is too early to include results in this report, we are highly encouraged by what we are seeing thus far.

PROJECT STATUS

We are still about one month behind schedule. However, note that our previous report indicated that we were two months behind, so we are gaining ground. We expect to submit our March 01, 2010 milestone report (Milestone #4) on time.

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