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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: 4** **REPORT DATE: MARCH 31, 2010**

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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 December 15, 2009 to March 16, 2010, and describes our progress on Milestone 4. Milestone 4 has been completed, and substantial progress has been made on Milestones 5 and 6. Substantial accomplishments in this reporting period include:

- Completion of a behaviorally reasonable model of an engine-generator set, and development of parameter values for grid-tied and stand-alone application, in the EMTP-RV power system simulation software.
- Improvement of the photovoltaic system model in EMTP-RV.
- Improvement of the three-phase wind turbine model in EMTP-RV.
- Initiation of development of a single-phase wind turbine model in EMTP-RV.

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TECHNICAL PROGRESS

Milestone #4 consisted of: development of a model of combustion-driven rotating machines used in anaerobic digesters.

According to our literature and site surveys, there are two primary types of anaerobic digester-based generation equipment in use in the field. The first type uses microturbines or other similar equipment, the electrical generator operates asynchronously from the grid, and the interface to the grid is handled through an AC/DC/AC converter that is topologically much like a motor drive. (Type 3 and 4 wind turbines use the same type of converter.) The second type, and apparently the far more common type at this point in time, are generators that use a common internal combustion engine driving a synchronous generator.

Anaerobic digester model 1: inverter-based

Modeling these generators is very similar to modeling photovoltaic systems. The primary difference is in the dynamics of the DC source, but in both cases, the main effect that must be modeled is the rate at which the energy source can resupply the large DC buffer capacitor present in the converter. This can be understood by examining Figures 1 and 2.

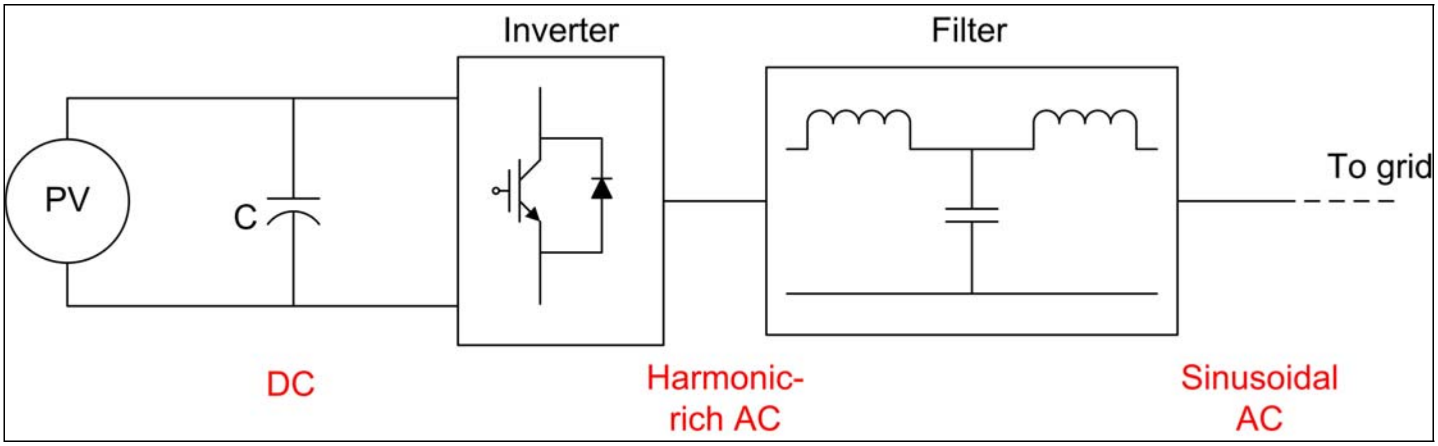

Figure 1. Schematic of a typical PV inverter. (Note that some PV inverters employ a DC-DC converter between the PV array and buffer capacitor.)

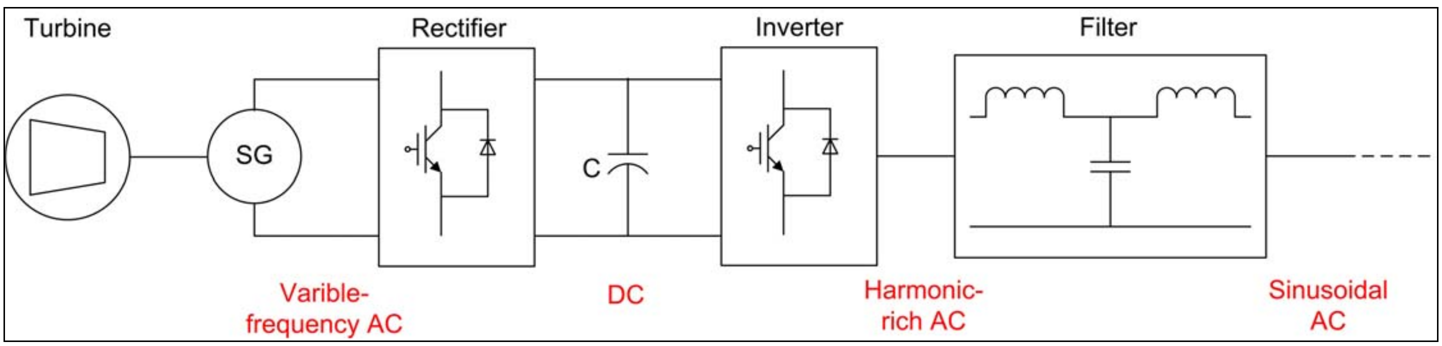

Figure 2. Schematic of an AC-DC-AC converter of the type used in microturbine-based generation systems.

Figure 1 shows a typical photovoltaic system configuration. The PV array produces DC power. There is a significant amount of energy storage in the form of a filter (shown in Figure 1 as a capacitor "C") that buffers the PV array from the switching waveforms of the inverter. If the filter were not there, the PV array would see a pulse width modulated current, and maximum power point tracking would not be possible. The inverter contains the switching transistors, and converts the DC into an AC waveform that contains some harmonics, with the harmonic levels being dependent on how the inverter is controlled. These harmonics are reduced to well below IEEE-519 allowable limits by a line filter, shown in Figure 1 as a T-filter, with the understanding that the final inductance of the T might actually be in the line interface transformer. Sinusoidal AC current then flows to the grid. Note that the PV system's output to the grid is a current, not a voltage.

For comparison, Figure 2 shows a diagram of a microturbine-based generation system feeding the grid through an inverter. The microturbine, at the far left, turns a standard electrical generator, which may be any of several types of machine (Figure 2 shows a synchronous generator, labeled "SG", although the literature suggests that the most common type used in this application is a permanent magnet synchronous generator, or PMSG). The output of this generator is AC, but its frequency is allowed to vary according to the operating point corresponding to the desired power setpoint. To make this variable-frequency AC output grid-compatible, it is first rectified to DC. A DC link capacitor ("C" in Figure 2) provides energy storage that supports the DC link voltage. This DC, like the DC from the PV array, is then inverted to 60 Hz and filtered to provide an IEEE 519-compliant output current.

Both the PV and microturbine inverters must utilize the same IEEE 1547-type protection and controls, so that portion of our model is borrowed directly from the PV system model described in our Milestone 3 report. The microturbine, permanent magnet synchronous generator, and the turbine governor and automatic voltage regulator (AVR) are represented using the model proposed in Reference 1. Governor and AVR parameters are being set via a tuning process performed in EMTP-RV.

We will continue to refine this model as we move into the next phase of this project. However, we have focused most of our efforts on the other type of anaerobic digester-based electrical generation, the engine-genset type, because a) it appears to be by far more common at this time than the microturbine type; and b) the direct-connected synchronous generator should be a much more challenging case for the islanding detection methods we are developing than the inverter-based type. This latter factor is key to this project; we need to ensure that the islanding prevention means developed here can operate for any combination of distributed generators, while simultaneously enabling grid support functions and bidirectional energy exchange. Thus, focusing on a worst case such as the direct-connected synchronous generator is appropriate.

<u>Anaerobic digester model 2: engine-based</u>

As noted earlier, the second type of electrical generator based on anaerobic digesters uses a standard internal combustion engine, and for the reasons noted above our work on Milestone 3 has focused on this type. If the proper pretreatment of the biogas is implemented, it seems that off-the-shelf engines designed to burn natural gas can run on biogas with little loss of performance, although the maintenance requirements are reported to be significantly greater with biogas.

For our purposes, there are four key elements in the model of this type of generator: the engine, the engine governor, the synchronous generator, and the generator's exciter and AVR. These are illustrated schematically in Figure 3.

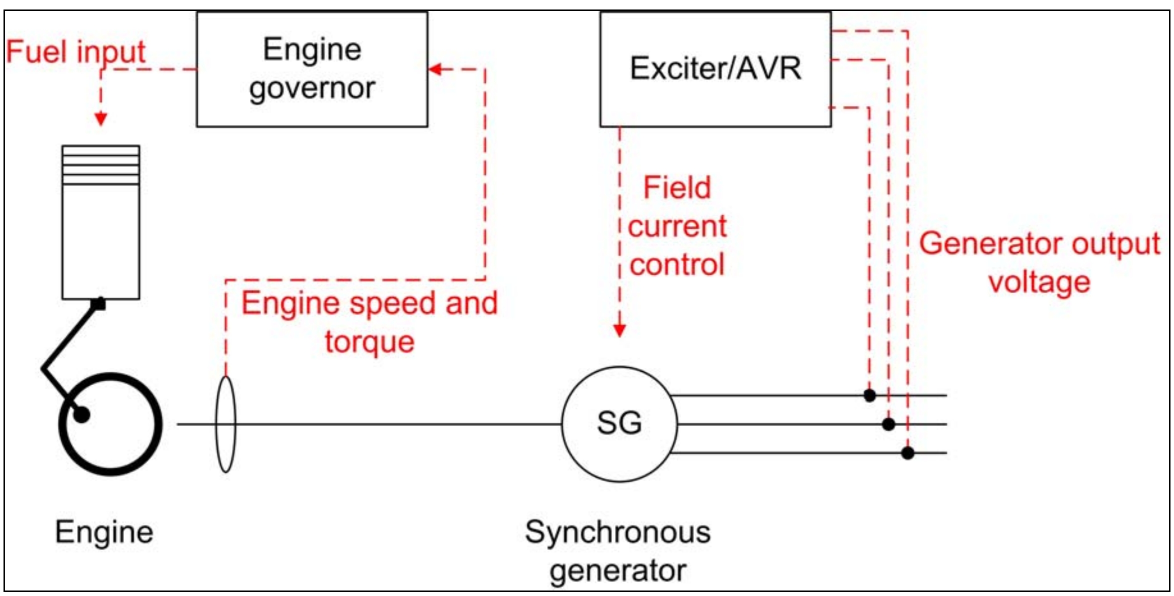

Figure 3. Schematic of the engine-genset and its key control elements.

For our purposes, we require models of the low-frequency dynamic behavior of the system. Many details can be omitted—for example, we do not need to model in detail the process of combustion of the fuel in the engine to derive power.

Theoretically, the modeling is fairly simple, but ensuring that it was accurate was a lengthy process. Our development of this model, including parameter determination, involved discussions with over two dozen manufacturers; a handful of experienced field engineers; several academic colleagues; investigators at the Distributed Energy Technologies

Laboratory at Sandia National Laboratories (Albuquerque, NM) and the National Renewable Energy Laboratory (Golden, CO); and an on-site visit to the Midwest Dairy Institute's 375-kW anaerobic digester plant.

Based on this background work, coupled with our own theoretical work and simulation results, we believe that adequate models for each component have now been determined. We obtained synchronous generator parameters from two different manufacturers, at 400 and 800 kW levels. For the engine itself, a simple first-order model was deemed adequate for this work. For the exciter/AVR, we have used an IEEE Standard Type 1 model, a model of which is already available in EMTP-RV. Starting parameter values were provided to us by manufacturers and field engineers, and from that point we used the EMTP-RV simulations to tune the values, which is consistent with how systems of this type are configured in the field. A similar process was followed for the engine governor; manufacturers provided us with a sufficient block diagram and starting parameters, and a tuning process was employed to bring the generator's performance into compliance with expectations.

The results are shown in Figures 4-6 below. Figure 4 shows the engine-generator system connected to a highly simplified power system that we used for testing and experience-gaining purposes. This model contains a 480 V_{L-L} synchronous generator (synchronous machine, labeled "SM"), engine governor, engine, and exciter (the "IEEEX1 (pu)" block). A 480 V_{L-L} utility source and series impedance are used, along with a system load represented by the P-Q block at the right. Note the switch next to the synchronous machine. That switch is present to allow the generator to come up to speed and synchronize, as is the case with actual generators. Figures 5-6 show representative results of simulations run with this simplified system, to assist in and verify tuning of parameters. This simulation uses the 400-kW generator.

In the field, synchronous generators have to be brought to a speed slightly higher than synchronous speed, then connected to the grid at a zero point of the "beat" waveform between the generator terminal voltage and the grid voltage [2]. That procedure is what is simulated in Figures 5 and 6. The generator is brought up to a speed of 1.0005 p.u. before being connected to the grid at t = 30 seconds. When the switch closes to connect the generator to the grid, we expect brief speed and voltage transients in which the generator output power quickly increases as its speed decreases to match the grid frequency. These transients should settle in a short time to their new steady-state values under the action of the governor and AVR, after which the governor slowly increases the speed to bring the generator up to its user-set power output. Figures 5-6 show that this is in fact what happens, so the simulation's behavior is physically reasonable.

We have developed several sets of tuning parameters for different machine sizes and will use these in the next phase of the project. We also continue to seek measurements from fielded systems that will enable us to better validate our models and parameter sets.

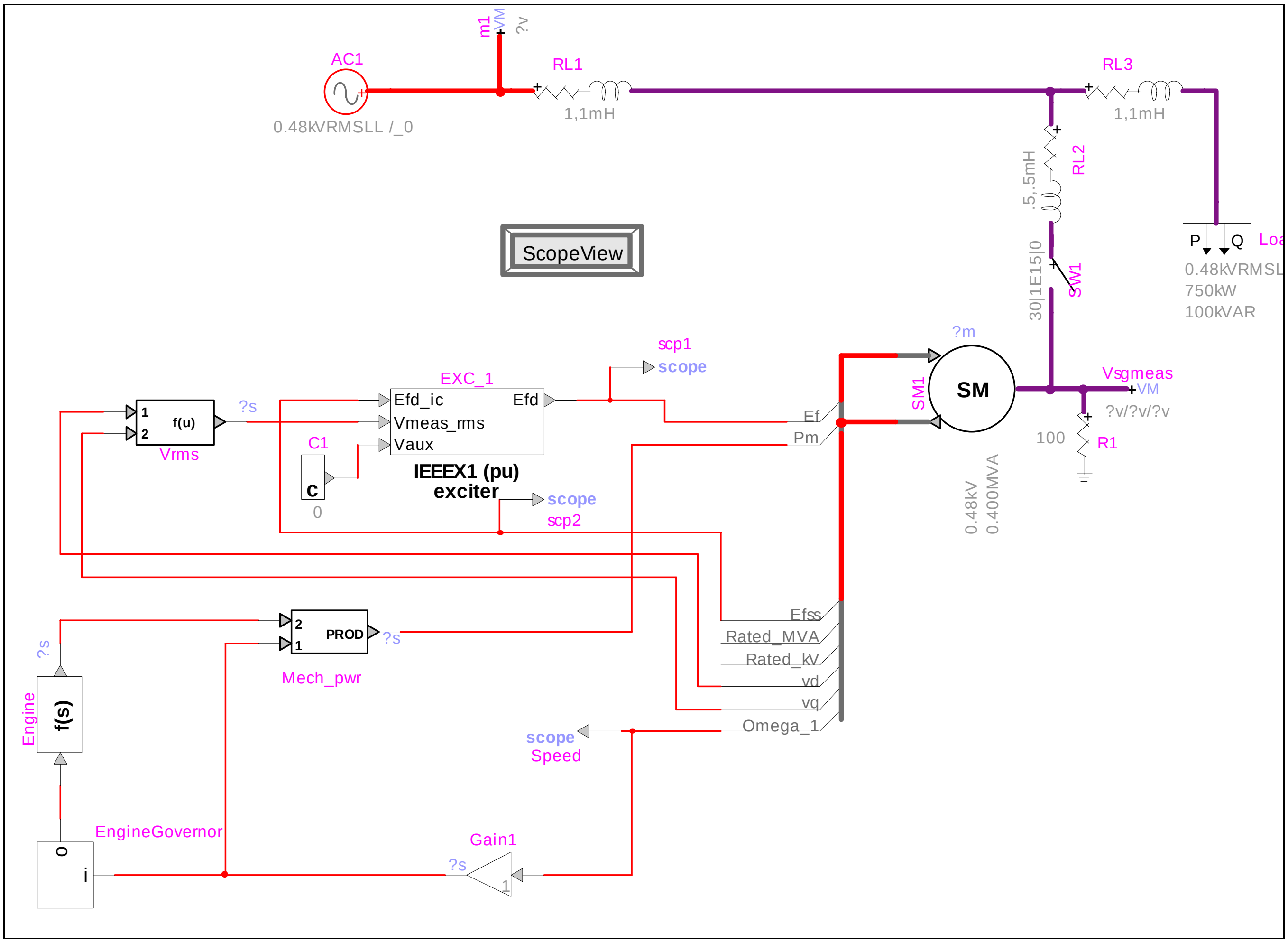

Figure 4. Screen shot of the engine-generator model test setup. The synchronous generator is the "SM" block at center right. The engine governor is at the far lower left corner, and the engine is just above it. The synchronous generator exciter is the "IEEEX1 (pu)" block near the center. The utility is represented by an ideal voltage source and series impedance at the top, and the system load is the P-Q block at the far right.

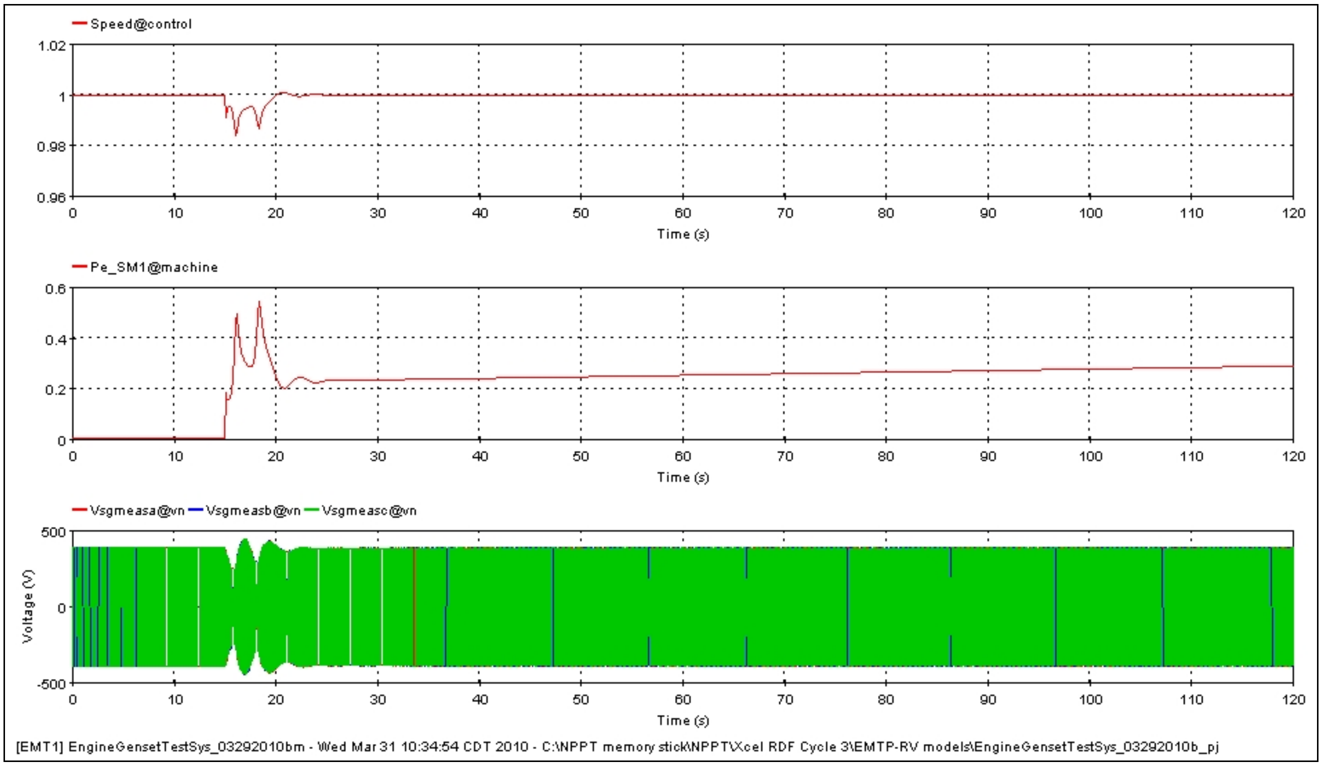

Figure 5. Simulation showing generator connection to the grid. The three plots show generator speed in per unit (top), electrical power output in MW (middle), and generator terminal voltage (bottom). The switch SW1 in Figure 4 is closed at 15 sec.

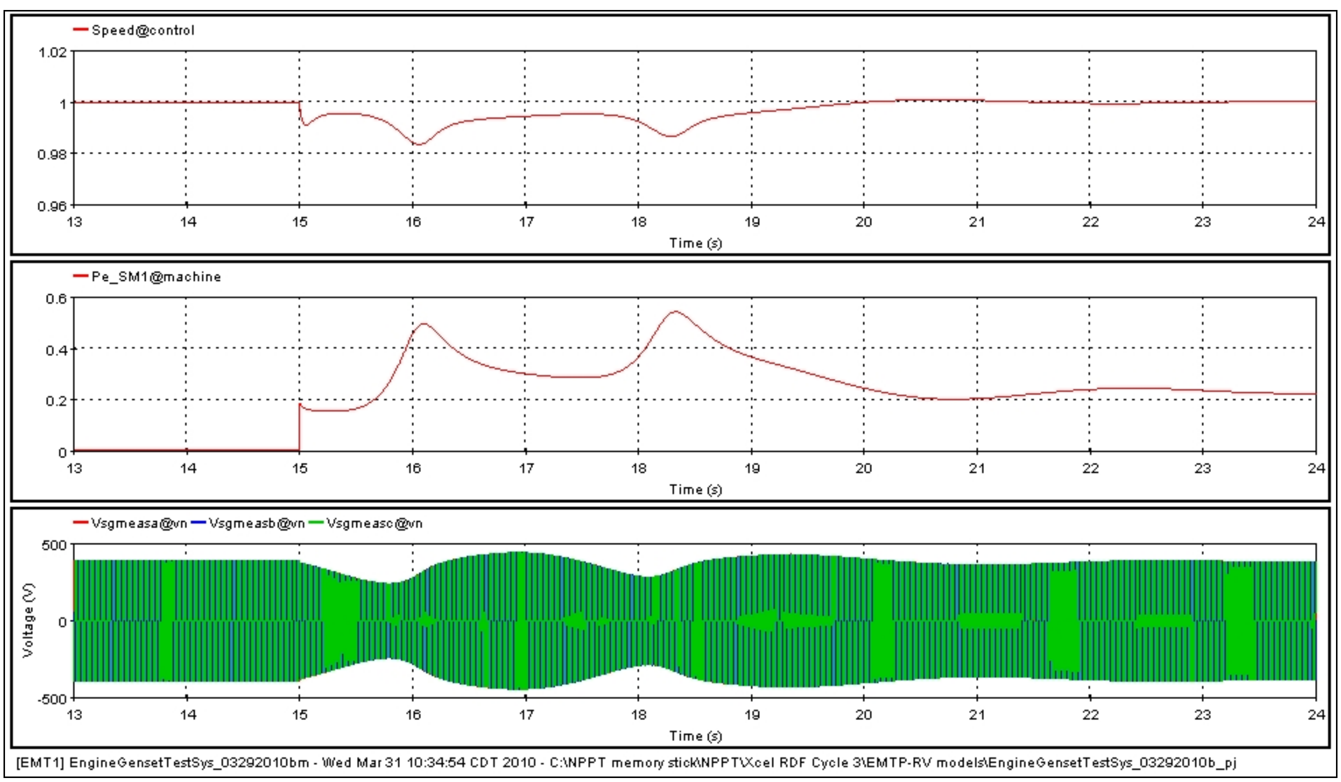

Figure 6. Zoomed in view of Figure 5, showing more detail of the time period right before and after the closing of switch SW1.

Project status

We continue to lag approximately one month behind schedule, but as has been previously reported we have already made significant progress on Milestones 5 and 6. We expect to submit those two milestone reports on time (note that these have the same scheduled due date).

Legal Notice

References

[1] R. Lasseter, "Dynamic Models for Micro-Turbines and Fuel Cells", Proceedings of the IEEE Power Engineering Society Summer Meeting 2001, vol. 2, pg. 761-766.

[2] L.L.J. Mahon, Diesel Generator Handbook, pub. Elsevier 1992, republished 2008, ISBN 0750611472.