HYBRID SIMULATION OF POWER DISTRIBUTION AND COMMUNICATIONS NETWORKS

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ABSTRACT

As the Smart Grid evolves it will become increasingly more important to simulate the communications networks and power delivery networks together. This paper demonstrates that premise with a hypothetical example using distributed storage units to compensate for solar PV generator output ramping due to cloud transients. The paper demonstrates how combined power and communications networks can prove useful for discovering unexpected results from Smart Grid applications.

INTRODUCTION

Communications networks are a key component of nearly all Smart Grid proposals. Power engineers have generally not been concerned with communications networks for the simulation of Smart Grid scenarios. The communication and control network is assumed to be able to perform its task almost instantaneously and flawlessly. Likewise, telecommunications engineers usually do not include power system behavior in simulations. Nutaro, et. al., [1] were perhaps the first to make a serious attempt to do this, combining the ns-2 Network Simulator with the *adevs* (A Discrete Event System) simulation package. [2] The combination of these systems allows the continuous dynamics of the power system to be combined with the discrete behavior of the communications network using advanced numerical computation techniques. This is key when modeling integrated communications and power systems networks.

A growing concern of engineers working on Smart Grid projects is whether or not the communications networks will be able to support next-generation power system applications. Many features envisioned for the Smart Grid, such as the real time dispatch of distributed generation and storage, will place heavy demands on communications networks. There are legitimate questions about whether communications networks can keep up with the needs of the power system to support the various Smart Grid functions being proposed. This is a special concern during contingencies when either or both networks might be damaged. There is a clear need to include communications network response with power system analysis to more accurately represent the behavior of the combined systems.

This paper describes a hybrid event-driven simulation of a power distribution system and communications network. Two open source simulators, one for power distribution networks and one for communications networks, were employed to perform a combined simulation. Not only were the two simulators written for different purposes, they were meant to run on different platforms. EPRI's Open Distribution System Simulator (OpenDSS) [3] was used to model the power distribution system and is designed for the Microsoft Windows environment. The ns-2 Network Simulator [4] was used to model communications networks and is designed for the Linux environment. The simulators were linked via a scripting mechanism. Both were run on a Windows computer with ns-2 being executed through the Cygwin environment.

THE EXAMPLE PROBLEM

The hybrid simulation is demonstrated with the solar PV ramping problem that is a concern of many power engineers as more large solar power units are interconnected with distribution systems. [5] Specifically, the simulation problem is to determine if distributed storage units could be dispatched quickly enough to compensate for solar PV power output that is dropping at 10% per second due to a cloud transient.

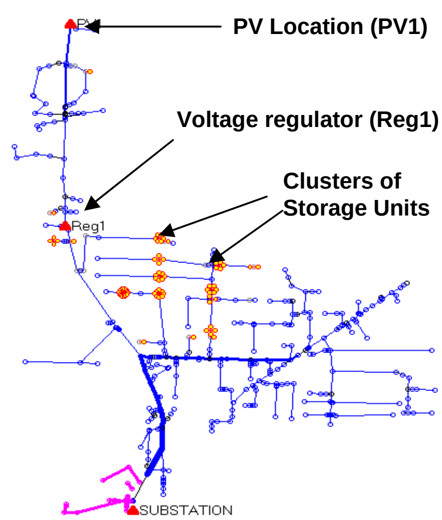

Figure 1. Distribution System One-Line Diagram

The example problem shown in Figure 1 is an actual distribution feeder modeled for a recent EPRI Smart Grid Demonstration project. A hypothetical 2500 kW solar PV generator was added to the end of the feeder model as shown. There were 84 storage units assumed installed on the LV side of customer service transformers in a residential area served by the feeder as indicated. Each storage unit was rated for 25 kW maximum power output, for a total of 2100 kW. These units were originally proposed for use to improve customer reliability and to assist with substation load management. This example explores how effective they might be to compensate for fluctuations in the output of the large solar PV generator caused by cloud transients. The key questions are:

- Can the storage units be controlled quickly enough?
- Are the storage units in a good enough location to be effective?

The solar ramping function template we have been using to evaluate the compatibility of large PV installations with distribution feeders is shown in Figure 2. This function has been found to exercise the voltage regulating equipment and expose voltage regulation problems on typical North American feeders.

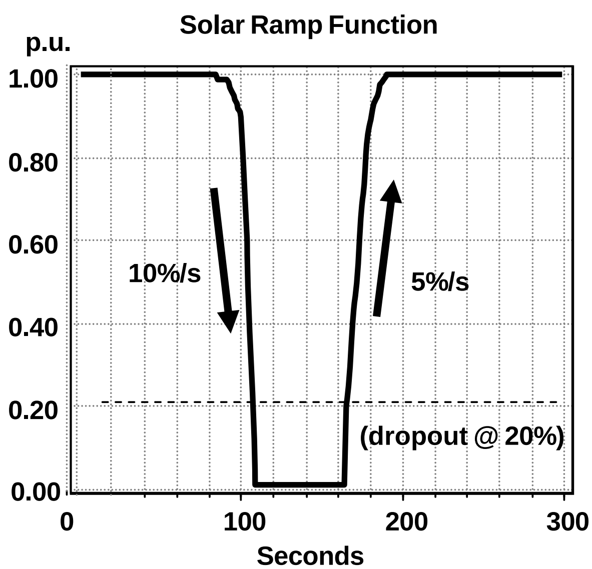

Figure 2. Solar Ramp Function Template

In this paper, we describe the simulation of only the initial down-ramp of 10% per second.

SIMULATION PROCESS

The data and process flow between the two simulators is depicted in Figure 3**Error! Reference source not found.**. [6] The wireless communications model is fed into the ns-2 program, which calculates message arrival times at the storage element nodes. The wireless model accurately represents the OFDM-based physical layer, taking into account transmitter power, path loss, and receiver sensitivity. These factors result in a probability that a given transmission will be received at the specified distance. The model also implements the 802.11 MAC. The MAC protocol expects an acknowledgement from each transmitted packet. If the acknowledgement is not received, the transmission will be retried (up to a limit). These retries result in increased arrival times for messages sent to nodes located near the maximum range at a given power and path loss. The messages are sent to all the nodes sequentially, by node number. The number of nodes within each distance zone in the model is given in Figure 4.

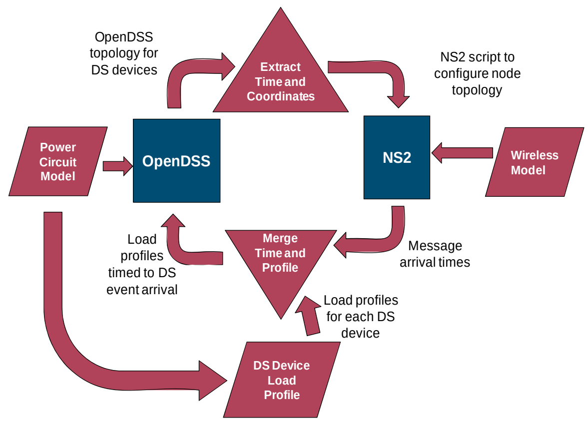

Figure 3. Data and Process Flow

The power network model is built in the OpenDSS program along with the load profiles, including the solar ramp function. The impact of the dispatch messages on the power system is simulated and simulation advanced to the next time that the power network control devices interact with the communications network. Then the cycle repeats.

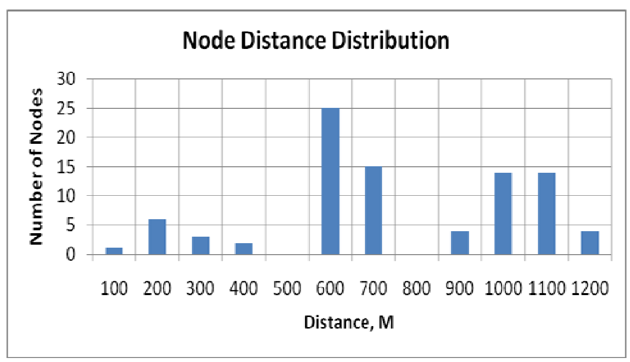

Figure 4. Number of Nodes Located in Distance Zones

The communications model simulates 802.11 OFDM radios operating in the 915MHz ISM band. Development of an IEEE standard for this band is currently underway in the 802.11ah Task Group. A 5 MHz channel width is chosen, resulting in a data rate of 1.5 Mbps. Several power levels are used to simulate wireless impairments such as propagation loss, fading, and interference. At lower power, the receiver has an increased probability of failing to receive a frame, and thus require retries.

All of the power levels are within the US regulations for the band, and could be implemented with "off the shelf" equipment. Figure 5 shows the range of results. At the highest power, all frames arrive sequentially without retries in about 120mS. At the lowest power, 30% of the packets are undeliverable, even after many retries, which extends the total time to over 1.5 seconds. For RF power levels over 100 mW, the wireless communication is fast and robust, and leaves a good margin for interference and fading. The inflection point for frame dropping due to retry timeout is at 30 mW.

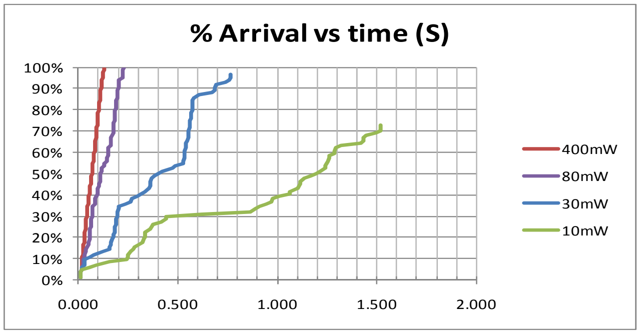

Figure 5. Frame Arrival Time

The ability to perform this detailed level of simulation for the communications is interesting for several reasons. First, we are able to simulate an emerging standard for which no commercial equipment is available, based on educated assumptions of the relevant parameters. Second, a wide variety of parameters in the communications model are easily altered to explore alternatives. Useful configurations that are discovered can be proposed for consideration by the 802.11 standards committee. Finally, the simulation environment allows research into the use of standards such as 802.11, which are not widely deployed today in this class of Smart Grid application.

OPENDSS SIMULATION SCRIPT

There are a number of ways we could have chosen to drive the OpenDSS program for this simulation, including:

- Explicit scripting of all actions,
- Generating loadshapes for the generator and each storage object, or
- Writing code in another program such as MATLAB or Excel VBA to drive the program through its COM interface.

Because the two simulators were running in different environments, the explicit scripting approach was the most straightforward to implement.
A portion of an OpenDSS script to perform the power system part of the simulation after computation of the message arrival time is:

```
! Start the ramp down at 5 sec
Set sec=5
Generator.PV1.kW=2500
Solve
Sample
Set sec=6
Generator.PV1.kW=2250
Solve
Sample
Set sec = 6.020834372 ! Unit 1
Generator.PV1.kW=2244.791407
storage.jo0235001304.state=discharging
~ %discharge=11.9
Solve
Sample
Set sec = 6.022028115 ! Unit 2
Generator.PV1.kW=2244.492971
storage.jo0235000257.state=discharging
~ %discharge=11.9
Solve
Sample
Set sec = 6.023158858 ! Unit 3
Generator.PV1.kW=2244.210286
storage.jo0235000265.state=discharging
~ %discharge=11.9
Solve
Sample
Set sec = 6.024604602 ! Unit 4
Generator.PV1.kW=2243.84885
storage.jo0235000268_1.state=discharging
~ %discharge=11.9
Solve
Sample
Set sec = 6.025738325 ! Unit 5
Generator.PV1.kW=2243.565419
storage.jo0235000268_2.dispmode=discharging
~ %discharge=11.9
Solve
Sample

(… etc.)
```

This script explicitly directs all actions of the simulator from decrementing the generator output to setting the discharge rate for each storage element. Each storage element is assumed to respond without delay once the dispatch message is received. Of course, this may not be a good assumption and could be a topic for further research into control and communications problem.
The script starts with the first 10% drop in the generator output from 2500 kW at 5 s to 2250 kW at 6 s. It is assumed that the control monitoring the PV array output samples the output once per second. A delay of 0.1 seconds is assumed before the controller begins sending messages to the storage units, and therefore the control sends out a dispatch message to all units sequentially starting at 6.01 s to compensate for the first 10 % drop. By the time the first message is received by a storage unit the solar generator output has dropped to approximately 2249 kW.
A message arrives at the first storage unit at 6.020834372 s into the simulation, setting its percent discharge rate at 11.9. It is assumed that the storage unit responds immediately. The PV generator output is updated and the power flow is recomputed and sampled. This is repeated for each of the 84 storage units.

RESULTS

This simulation results in the "sawtooth" voltage pattern in the voltage at the POC as shown in the solid line curves in Figure 6. The dashed line curves are the voltage that would have occurred for the down-ramp part of the cloud transient ramping characteristic without any storage to compensate. The results demonstrate a couple of issues that might arise with proposed Smart Grid concepts:

1. The voltage regulation may not be as smooth as desired due to communications limitations, and
2. The storage devices are not in optimal locations, nor do they have sufficient capacity, to fully compensate for the power fluctations.

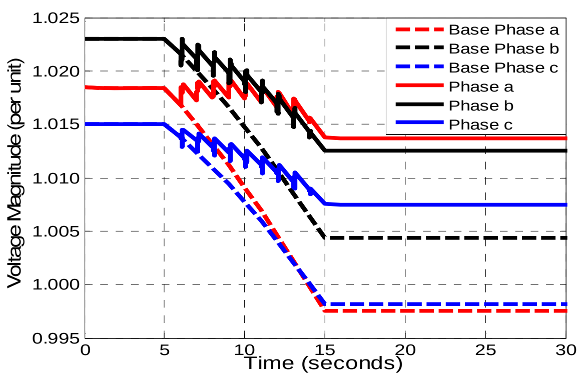

Figure 6. Voltages at PV Site for Initial Drop of Solar Ramp With and Without Dispersed Storage.

Obviously, one might be able to improve on this result with different control strategies and better placement of storage elements. For the purposes of this study, the results are sufficient to demonstrate the kind of imperfections engineers might expose when both the communications and power networks are simulated together.
There are other issues to expose in this simulation. One of the key ones is the assumption that the storage elements are able to respond immediately once the message arrives. The delay time for certain battery and inverter technologies may be larger than the communications delay.

CONCLUSIONS

The simulation showed that the scheme could be effective in reducing the voltage dip for a solar PV ramp to the minimum possible considering the distribution of the dispersed storage units if the communication system works well. The typical maximum communication delay simulated was 118 ms. A typical result is shown in Figure 6.
The sawtooth pattern in the response is a result of discrete control sampling and the communications delay. However, in other cases where there are dropped packets, many messages do not arrive at their destinations before it is time to take additional action. The hybrid simulation technique is shown to be valuable in determining a control and communications scheme that might function more acceptably.
One advantage of hybrid power and communications simulation particularly relevant to the Smart Grid is that engineers will be able to assess new equipment and the impact of standards even before commercial products exist. This showed reduce the number of costly false starts that accompany implementation of new technologies.
Research will continue in how to make such tools work together better and address other response issues (such as battery turn-on time) that were neglected in this simulation.

ACKNOWLEDGEMENT

The distribution system is an actual feeder being studied in an EPRI Smart Grid Demonstration project with American Electric Power Co., Inc. (AEP), Columbus, Ohio USA, to evaluate AEP's Community Energy Storage (CES) concept.

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