STORAGE SIMULATIONS FOR DISTRIBUTION SYSTEM ANALYSIS

Roger DUGAN
EPRI – US
rdugan@epri.com

Jason TAYLOR
EPRI – US
jtaylor@epri.com

Gauthier DELILLE
EDF R&D - FR
gauthier.delille@edf.fr

ABSTRACT

Storage is being proposed to solve many issues on distribution networks and distribution planners need tools to assess its impact on capacity, reliability, and power quality. Accurate analysis requires sequential-time simulation. This paper describes three types of storage simulations on distribution systems for three different time frames: capacity evaluations in 15-min intervals; renewable generation smoothing in 1-min intervals; and electromechanical dynamics analysis in intervals ranging from seconds down to microseconds. The illustrations come from recent research.

INTRODUCTION

Storage devices are being actively promoted to solve various operational and reliability problems on distribution networks. Distribution planners now face the challenge of accurately including the impact of storage in distribution planning. This paper describes some capabilities that planning tools will need to aid in understanding the interactions and limitations of storage with respect to capacity, reliability, and power quality.

Simulation modes identified for distribution system analysis of storage include:

Static: A solution of one power flow state with storage discharging or charging at specified rates or idling. This provides a partial picture of the situation by simulating limiting conditions but does not reveal issues that might be exposed through time-series simulation.
Time: Trigger ON at a specified time at a specified constant discharge or charge level.
Peak Shave: Discharges when load exceeds a specified value and attempts to limit the load current or power to the value. Charges at a scheduled time.
Load Following: Triggers ON at a specified time and attempts to limit the load to the value at that time by following the load.
Loadshape: Storage charge and discharge cycle is determined by a predefined shape.
Dynamics: For modeling fast-changing phenomena such as frequency control on microgrids.

EPRI has implemented versions of these simulation modes in its OpenDSS software (see [1]). The Dynamics model was adapted from a model developed by EDF R&D. A description of the implementation is contained in the recent EPRI report [2]

This paper describes three different classes of simulations of storage that differ mainly in the time step size:

1. Capacity evaluations: 10 minutes to 1 hour.
2. Compensating for renewable generation: 1 second to 1 minute.
3. Dynamics simulations: less than 1 second.

CAPACITY EVALUATIONS

Figure 1 shows the result of a simulation designed to determine the feasibility of using distributed battery storage, in 25 kWh units, to shave the peak feeder demand load each day using energy stored in off-peak hours. The simulation was performed using 15-minute demand data.

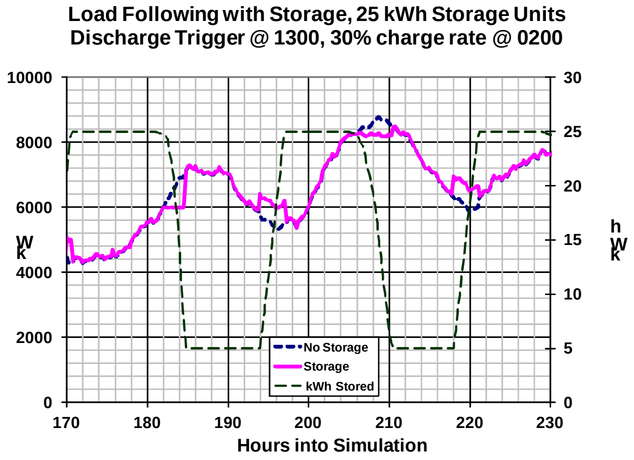

Figure 1. Using storage for daily peak shaving

This simulation illustrates the importance of forecasting the time of the daily peak when the storage resource is limited. This uses the “Load Following” control mode where the storage controller attempts to keep the feeder demand at, or below, the demand level at the time the storage is triggered ON. If the storage is triggered ON too quickly, the storage is depleted prior to the peak and not all the benefit from shaving the peak or having acquired stored energy at a substantially lower cost can be realized. This occurs on the first of the two days shown in Figure 1.

The storage model also represents the losses in the storage element whether charging, discharging, or idling. The reader can get a feel for this by observing the differences in the areas under the charging and discharging curves. In this case, there is approximately 20 % difference, which is visibly noticeable. In the simulation, each element takes care of computing its own losses. The energy meter at the head of the feeder records the net effect.

The discharge and charge states of all storage units for this application would be governed by a supervisory controller. In this example, discharging is started by a simple time control at 13:00 h each day. Then the controller manages the dispatch of each storage unit to maintain an approximately constant demand at the head of the feeder. A relatively simple deadband controller with a 2 % band around the target value is used. Discharging continues until either the feeder demand drops below the target or the storage elements have reached their minimum allowable level. In the OpenDSS implementation, the storage device models manage their own storage levels and cease to respond to the controller when the storage is depleted.

Charging is assumed to begin at 02:00 h and proceed at a rate of 30% of the power rating of the storage element.

FOR RENEWABLE GENERATION

Storage elements may be used for a variety of purposes on distribution systems. One commonly-cited example is to compensate for variable renewable generation. Example results are shown in Figure 2 for a 2 MWh storage device simulated at a one-minute resolution. The storage is charged during the peak solar PV output and then discharged at the load peak. This helps solve a common capacity problem faced by distribution planners: solar generation output frequently lacks about 2 h of meeting the peak load on residential feeders. Having the sequential-time simulation capability to analyze this problem will help planners better evaluate the true impact of such generation on system capacity.

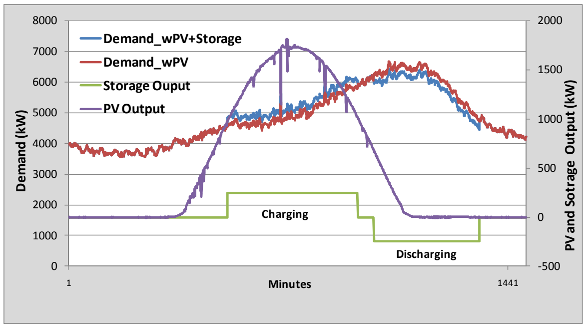

Figure 2. Using storage to shift PV generation

In the scenario shown in Figure 2 a Time based control is used to shift the energy output from the PV to higher demand periods. While this control may be simple and cost effective to implement, it is not as effective as the Peak Shave and Load Following methods. Without direct observation, the charge/discharge durations of the Time based method must be of sufficient length to capture the expected variations in both generation and peak demand. Consequently, the discharge/charging rate tends to be more shallow than may be achieved via other control types. Furthermore, this method performs a full discharge/charge cycle each day regardless of the energy generated or consumed.

The ability to evaluate the performance of different storage control options while accounting for interaction with renewable sources is an important design factor. Considering the storage and solar PV as a combined technology, the Time-based control of the storage was shown to reduce the effective energy supplied by the PV by 3.3 % due to the operational losses incurred by the storage unit each day. In contrast, a potential Peak Shave control was shown to decrease the effective PV generation by only 0.44 % while further reducing the peak demand by 740 kW beyond that achieved with the Time base control.

Another storage operation commonly considered when pairing with renewable generation is smoothing the fluctuations in the variable generation. In certain cases, these fluctuations can result in voltage concerns and increased voltage regulation device operations. Time-sequential simulations are again required to fully capture the system response to the proposed storage and control functionality.

The PV output with and without the storage is illustrated in Figure 3 for one potential control algorithm. In this case, the energy storage is dispatched based on a moving average target for the net output of both PV and storage.

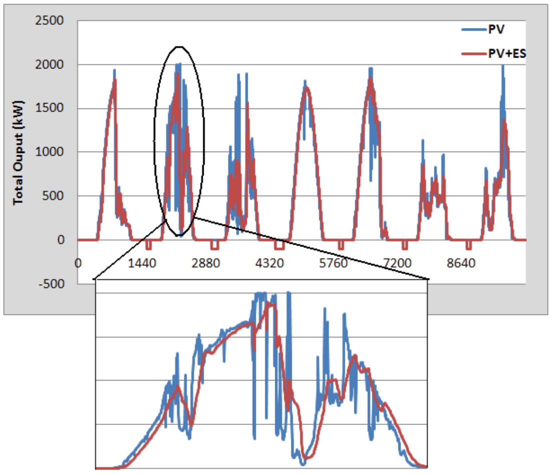

Figure 3. Smoothing variations in PV generation

The storage is emulated in OpenDSS based on a loadshape derived separately using the target value while also taking into account operational constraints including the rated kWh and kW associated with the modeled storage. The loadshape derived to emulate the smoothing operation is plotted in Figure 4. Note that this operation requires the storage unit to alternate between discharging and charging while the PV output is nonzero. In order to be able absorb or inject energy as needed, the storage unit is charged to half its rated capacity starting at 02:00 h and this charging is clearly visible in both Figure 3 and 4. Given the cyclical operation of the PV and the nature of smoothing functions, the amount of energy required to "top off" the storage device each evening is a direct function of the losses incurred during the previous day's operation. In this simulation, the losses incurred by the smoothing operation decreased the overall generation from the PV and storage by 1.8 %.

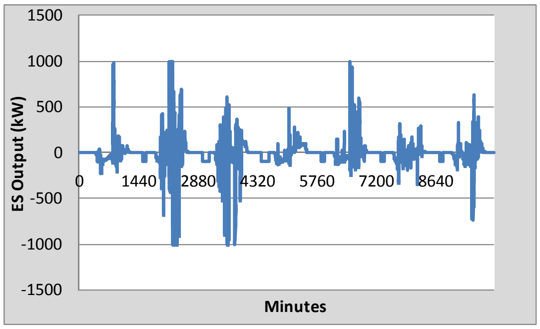

Figure 4. Power output smoothing operation

DYNAMICS SIMULATIONS

Most of the time-varying modes identified can be executed by supplying the load and power charging/discharging characteristic with power data in time steps ranging from a few seconds to one hour. To study the interaction of inverter-based storage devices during disturbances or for such things as frequency and stability control on microgrids requires dynamics analysis capability in very small times steps. EDF R&D has developed a library of dynamic models of distributed energy storage systems useable within the electromechanical transient simulation software Eurostag. The Dynamics model recently implemented by EPRI within OpenDSS software was adapted from one of these models. Some of their possible uses for distribution system analysis are described in the following paragraphs.

Analysis of the operation of storage units within distribution networks

Energy storage systems are expected by many to play an increasing role in future power systems. A significant part of these devices will probably be connected within distribution grids. In some cases, they will be fitted with very fast controls, able to respond for instance to major power system events through a continuous monitoring of system frequency and local voltage. These activities will impact the current flows and voltage profiles of the distribution systems. It is therefore critical to understand how the control algorithms of distributed energy storage systems will interact with the usual control devices of distribution grids, such as OLTC, capacitor banks and protection systems. Although part of these interactions can be identified using for instance sequential load-flow, dynamic simulations are the best way to identify any instability or oscillatory behavior.

Study of the compliance of storage systems with grid code requirements.

Dynamic models are interesting to study the compliance of DESS with relevant grid code requirements. For instance, the transient behavior of distributed storage systems during a fault can be studied through dynamic simulation. The library of dynamic models developed by EDF comprises the following DESS structure: storage media – chopper – voltage-controlled dc-bus – inverter – grid. In such a case, to be capable of being used for the analysis of the fault behavior of storage systems, the model should fairly describe the behavior of the dc-bus voltage. Indeed, it is the dc bus that transitorily has to store/release energy when it becomes suddenly more difficult to exchange power with the grid during the fault. For VSC-based DESS, the dc-bus voltage and the way it is controlled can therefore play an important role in the compliance with fault-ride through and recovery requirements. To illustrate this part, Figure 5 below shows the transient behavior of a distributed energy storage system during a fault.

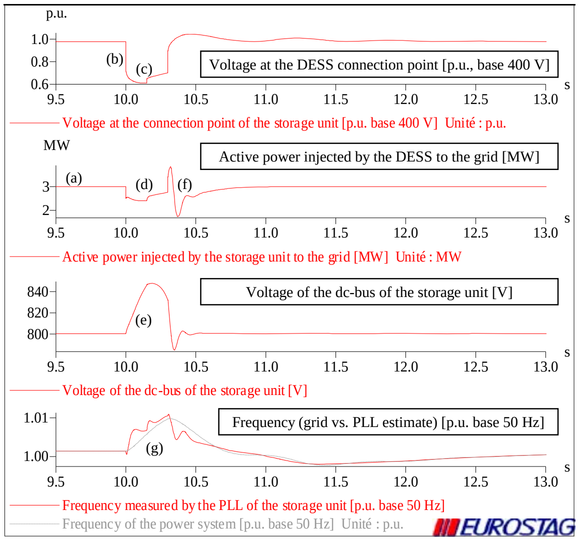

Figure 5. Dynamic simulation of a distributed energy storage system: transient behavior during a fault.

At the beginning at this simulation, the studies storage unit injects power to the grid at its rated power of 3 MW (a). A 3-phase fault occurs at time t = 10 seconds; the voltage at the connection point of the storage unit falls down to 0.6 p.u. (c). Due to its maximum current limit, the inverter of the DESS can no longer operate at rated power and, therefore, temporarily decreases the scheduled injection to the grid (d). Since the DESS power control loop, which regulates the power flow of the DESS through the chopper, requires some time to react, the dc bus continues to receive around 3 MW from the storage media but this power cannot be delivered to the grid. The amount of "in-excess" energy is charged in the capacitor of the dc bus, thus causing its voltage to increase (e). The extra energy stored into the dc-bus capacitor is injected to the grid immediately after the voltage recovery (f), which tends to make the DESS very difficult to control during a time delay of around 100 ms following a voltage sag. To prepare the simulation presented in Figure 5, the variable-step solver of Eurostag has varied the integration time step from 0,1 µs to 1 s.

Dynamics simulations to develop control algorithms and analyze some storage services

Dynamic models/simulations of storage systems can be used to develop control algorithms of DESS block diagrams and study their behavior under various operating conditions. Since electromechanical simulation of power system deal with phenomena in the range 0-10 Hz, the control systems that can be put in place this way do not include all the refinements that are required to make them ready to operate in the field. However, all the components of the control schemes that will respond to the usual changes in voltage, frequency, *etc*. –*i.e*. the components that carry the DESS services– can be properly designed.

The dynamic models fitted with these control algorithms can be used to study certain storage services, and notably those that have an impact on the dynamic behavior of the power system to which the considered DESS are connected (frequency control in isolated power systems such as in ref. [3], intentional islanding of parts of a distribution network, microgrids, *etc*.). The outputs of such a series of simulation can be conclusions regarding the feasibility of the studied services, an assessment of the required size of the storage unit or even a full technical/economic appraisal of the studied DESS for a given set of applications.

In addition, dynamics simulation of storage systems might become useful in the long term for training purposes of the DSO representatives, provided that this family of devices becomes widely developed.

DISCUSSION

Each of the sequential-time simulation modes presented requires more sophisticated models and more data than a simple static power flow evaluation with which most distribution planners are familiar.

Dynamics models of inverter-based storage may require values of more than 30 parameters. This is daunting for distribution planners. Some form of standard model framework must be developed to make this task easier and more attractive for distribution system analysts.

Time constants in inverter controls are frequently on the order of a few ms requiring simulation steps less than one ms. Figure 6 illustrates a dynamics simulation using the OpenDSS implementation of DESS. The model is attempting to finely control the power dispatch to meet a reference power signal on a microgrid, for example. It was performed at a fixed 0.2-ms time step, or 5000 steps per second. Simulation durations are much more limited than with the other two storage simulation modes presented due to the prodigious volume of results data produced. However, it can be quite important to determining the stability control algorithms for a microgrid.

The DESS output (blue line) lags a few ms behind the $P_{reference}$ signal (red line). In this case, the discharge and charge cycles are identical in magnitude and duration. Thus, the kWh stored is gradually decreasing due to losses represented in the model. A more intelligent controller would extend the charge cycle to ensure the storage level remains sufficiently high.

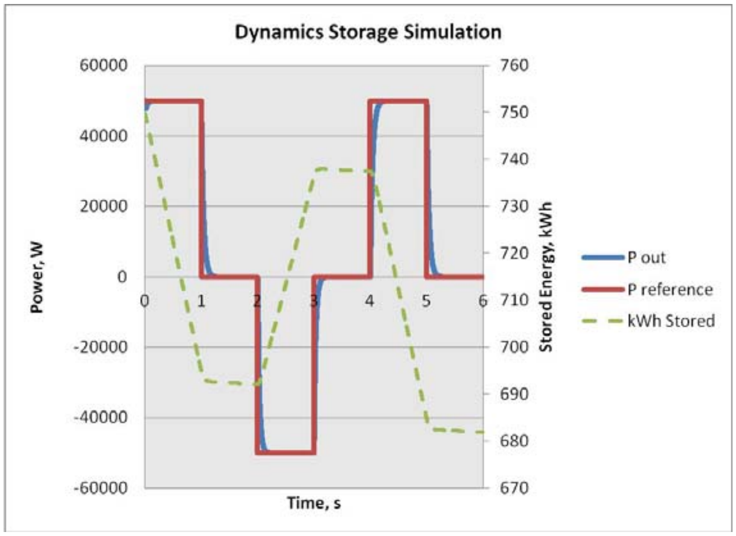

Figure 6. 6-s DESS simulation

REFERENCES

[1] EPRI, 2013, *OpenDSS Computer Program*, *Open-Source Distribution System Simulator*, Available on Sourceforge.Net, Ver 7.6.2.

[2] EPRI, 2012, *Analysis of Distribution System Effects of Energy Storage Through Simulation and Modeling*, Palo Alto, CA, US. 1024285.

[3] G. Delille, G. Malarange, B. François, 2012, "Dynamic Frequency Control Support by Energy Storage to Reduce the Impact of Wind and Solar Generation on Isolated Power System's Inertia", *IEEE Transactions on Sustainable Energy*, vol. 3, issue 4, pp. 931-939.