Enlisting Conventional Power Electronic Devices to Improve Stability and Security through Distributed Load Shedding and Energy Storage

W. Fadrhonec and J. Matamoros and P. Sood

Stem, Inc.
Millbrae, CA 94030, USA

Abstract—Load shedding is employed by grid operators when power demand abruptly exceeds generation supply. An additional layer of load shedding is now economically feasible to deploy at the end-customer level. The proliferation of conventional power electronic equipment, such as solar inverters and distributed energy devices, could enable fast, simple and secure distributed load shedding. Distributed load shedding schemes could augment existing centralized schemes and be deployed without communication or cybersecurity systems. This paper develops a control hierarchy for distributed load shedding and energy storage dispatch that is consistent with existing load shedding procedures. A transient simulation is developed that illustrates how these schemes could increase stability and reduce the risk and frequency of wide area load shedding events. In addition, the impact and efficacy of these schemes are examined in combination with distributed generation. Lastly, potential regulatory action and implementation activities to deploy such schemes are developed.

Index Terms—Demand response, distributed power generation, energy storage, load shedding, power electronics

I. INTRODUCTION

Load shedding (LS) is an established practice that has been utilized for decades by grid operators to respond to emergency conditions in which electric demand abruptly exceeds generation capacity. These emergency events can occur from the loss of a major transmission line or generator outage as examples. LS schemes are employed to reconcile an imbalance of supply and demand in order to restore system parameters to normal limits. There are mature and generally accepted practices and standards for LS implementation [1-2]. LS is typically implemented in layered schemes in which load is shed in discrete steps based on the degree to which and duration that the system is operating at below nominal system frequency. The objective of a LS scheme is to operate with an effective and appropriate response to below nominal system frequency.

Grid operators and regulatory bodies are responsible for deploying LS schemes today with limited customer involvement. Demand response (DR) programs are typically too slow to be utilized in LS schemes due to the speed of transient events. During a transient event in which LS is invoked, end-customers experience a momentary outage which has an economic cost and impact to distribution reliability metrics. Accordingly, there are conflicting risk minimization objectives for grid operators to weigh between shedding a sufficient level of load to arrest underfrequency events yet not shed too much load so as to interrupt customer service unnecessarily or adversely impact reliability operating metrics.

An increasing generation mix of distributed and renewable generation could result in additional LS events due to increased supply volatility. Inverter-based distributed generation (DG) complicates LS schemes due to interconnection standards that presently require disconnection during underfrequency events [3]. At increasing levels of DG penetration, the disconnection of DG during an underfrequency event could further exacerbate the event. Accordingly, there is activity underway to review the inverter standards with respect to coordination with LS schemes [4-6]. Lastly and critically, the speed and required response of transient events are in the order of cycles and seconds, not minutes and hours. There could be a significant benefit to implement centrally controlled and dispatched LS schemes, however, the required response speed, in addition to the communications and cybersecurity requirements, can make it challenging and costly to implement a highly centralized LS scheme.

II. IMPROVING GRID SECURITY: DISTRIBUTED LOAD SHEDDING AND ENERGY STORAGE

This paper examines the opportunity to deploy an additional level of grid security through the use of Distributed Load Shedding (DLS) and Distributed Energy Storage (DS). There are several technical schemes that have been formulated to augment LS that utilize distributed resources, improved algorithms and hierarchical control schemes [7-10]. The scope of this study relates to deploying a simple scheme that would have the least impact to existing LS schemes and require minimal resources to deploy. DLS is defined as a control scheme in which customer loads are shed automatically based on underfrequency conditions and without any dispatch or signaling from the grid operator. Eliminating the requirement for communication and cybersecurity by utilizing local frequency sensing and control simplifies implementation. In a DLS scheme, customers designate loads connected to frequency sensing devices that are most tolerable to shed, presumably focusing on non-critical loads.

DS is defined as fast responding energy storage equipment that has frequency response capabilities. DS assets could include UPS devices or other energy storage devices utilized in customer load management schemes.

Distributed load shedding schemes have been possible in the past, but have not been economically viable [11]. The cost to implement underfrequency relaying or energy storage has historically made such schemes impractical. However, in addition to their primary applications, certain power electronic devices, such as inverters, electric vehicle chargers
and distributed energy storage power converters can also instrument frequency thereby enabling DLS and DS schemes. Load management and control schemes could be integrated with these power electronic devices to utilize their frequency instrumentation capabilities. Power electronic devices may be increasingly able to measure frequency, in addition to voltage and apparent power, with higher degrees of accuracy and precision. The opportunity to deploy DLS and DS is especially effective for commercial and industrial customers for which more significant amounts of DLS and DS can be deployed per site.

Examples of DLS and DS schemes are shown in Figures 1 and 2. In Figure 1, the demand for an example customer is 125 KW during normal operations. This 125 KW represents net demand, but is actually composed of 50 KW in DG; 150 KW in Load; 25 KW in EV charging loads; in addition to 50 KW of available UPS and storage capacity that is not being charged or discharged in a normal state. Power electronics that may be able to detect underfrequency are also indicated in the figures.

**DLS and DS underfrequency settings and clearing times can be coordinated with LS schemes; in this paper, a simplified coordination example is developed with LS parameters that have been utilized in the Western Electricity Coordinating Council [12]. Please see Figure 3 for a baseline LS scheme and Figure 4 for the coordination of DS and DLS with baseline LS control.**

In Figure 2, the same example customer as in Figure 1 is illustrated during a load shedding event. Through deploying DLS and DS schemes, the customer demand is shed to net zero thereby supporting frequency response. The impact is significant even though there is no required net export of power during the underfrequency event for this example customer.
levels of DLS, termed DLS1 and DLS2, are modeled to represent two tiers (i.e., service levels) of customer designated loads to shed based on priority. Regarding DS availability given an unknown state of charge for energy storage devices, even if the storage device has a low state of charge or if the device is also utilized for UPS applications, the DS asset may still have sufficient energy for the short duration of transient events so long as the device can be reversed from a charging state to discharging state quickly.

III. SIMULATION

To evaluate the impact and efficacy of deploying DS and DLS, simulations were conducted using a low order system and simplified frequency response model utilizing a similar approach as employed in [13]. The model was developed utilizing MATLAB/SIMULINK. DG and DS are modeled as inverter based systems (non-rotating generation sources). The values for the system and model are shown in Figure 5.

\[
P_d + \sum P_a \frac{1}{2Hs + D} \Delta w = \frac{K_n (1 + F H T_k \Delta s)}{R(1 + T_k s)}
\]

\[
H = \text{Inertia Constant, seconds}
\]
\[
D = \text{Damping Factor}
\]
\[
R = \text{Regulation Constant, per unit}
\]
\[
P_d = \text{Sudden Load Disturbance, per unit}
\]
\[
\Delta w = \text{Speed Deviation, per unit}
\]
\[
P_m = \text{Turbine Mechanical Power, per unit}
\]
\[
P_i = \text{Accelerating Power, per unit}
\]
\[
K_m = \text{Mechanical Power Gain Factor}
\]
\[
F_H = \text{Fraction of power generated by HP turbine}
\]
\[
T_k = \text{Reheat Time Constant, seconds}
\]

\[
R = 0.05 \quad H = 4.0 \text{ seconds} \quad K_m = 0.95
\]
\[
F_H = 0.3 \quad T_k = 8.0 \text{ seconds} \quad D = 1.5
\]

where \( P_d < 0 \), signifies step increase in load and \( P_i > 0 \), signifies step increase in generation.

**Figure 5. System Model and Parameters**

The frequency response to a step disturbance at various levels was simulated. As illustrated in Figure 6, the simulation utilizes a six feeder model to represent an aggregate distribution system and existing LS schemes. There are five feeders which represent the buses subject to the sequential LS scheme: the sixth bus represents the balance of the net load which brings the entire system net load to 1 pu. DS, DG and DLS resources are assumed to be uniformly distributed throughout the distribution system based on the net pu load for each feeder. Figures 3 and 4 indicate the underfrequency cut-off points and clearing times for DS, DLS1 and DLS2.

The objective function of the control scheme is to minimize the LS level required to respond to a disturbance. Both the baseline LS scheme and a proposed LS/DLS/DS control schemes were simulated. Results are tabulated in Table 1 for both the schemes at varying levels of system disturbances. The first notable item is the increase in required LS level accompanying 0.2 pu DG versus a system with 0.0 pu DG. A DS level of 0.025 pu is utilized in the proposed model which is a level approximate to 1.3GW in energy storage [14] on a 52 GW load. The inclusion of non-critical DLS loads and DS has increased the system tolerance levels and reduces the likelihood of wide area LS.

**Table 1. Comparison of Baseline and Proposed UFLS Schemes**

<table>
<thead>
<tr>
<th>Disturbance (pu)</th>
<th>LS Only Baseline 0.00 pu DG</th>
<th>LS Only Baseline 0.20 pu DG</th>
<th>LS/DLS/DS Proposed 0.20 pu DG</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.05</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>-0.15</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>-0.20</td>
<td>1</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>-0.21</td>
<td>1</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>-0.25</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>-0.31</td>
<td>3</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>-0.39</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
</tbody>
</table>

In addition to examining the proposed scheme against a baseline, the impact and sensitivity to varying levels of DLS and DS was also simulated. For a 0.16 pu disturbance, one approximate in magnitude to an abrupt loss of the California-Oregon Intertie connection at peak loading for the CAISO [15], the required LS level response with varying levels DLS and DS is reported in Table 2.

**Table 2. Required LS Level Response with Varying Levels of DLS and DS (0.16 pu Disturbance)**

<table>
<thead>
<tr>
<th>DS (pu)</th>
<th>0.00</th>
<th>0.01</th>
<th>0.02</th>
<th>0.03</th>
<th>0.04</th>
<th>0.06</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>0.01</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>0.02</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.03</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.04</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.05</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
The mitigation impact is similar whether adding DLS and DS so long as either resource can respond early and quickly. DLS would not support the frequency response if the clearing time is too slow and LS schemes would have already triggered before response. DS devices may be able to ramp and act faster than DLS control. In addition, DS devices could also be utilized during above nominal frequency events in addition to supporting LS.

![Figure 7. Frequency Response: Zero DG, Baseline with DG, and Proposed Schemes](image)

Regarding response speed, the transient frequency response of the zero DG baseline scheme, the 0.20 pu DG baseline scheme and the 0.20 pu DG and proposed LS/DLS/DS scheme are plotted in Figure 7. The impact of the proposed scheme is that the frequency response results in both a higher minimum frequency and a faster arrest of frequency decay.

### IV. BENEFITS, IMPLEMENTATION, AND POLICY

From an economic and regulatory policy perspective, DLS and DS have distinct benefits; in addition, these schemes only augment, not replace, existing LS schemes. The proposed schemes are beneficial yet incremental, stability-enhancing, and simple to implement. As shown in Table 3, these schemes could be deployed as part of a more robust scheme employing DR along with market operations.

With LS, a grid operator cannot select the most economically efficient loads to shut down. Even with careful planning, critical loads could lose service during a LS event while less critical loads remain connected. Adding DLS and DS could help grid operators avoid unilaterally selecting loads to shed and allow customer engagement. Customers can designate non-critical loads to be shed and storage assets to be dispatched based on an economic trade-off analysis. This scheme creates economic choices for customers as opposed to a single, all-or-nothing decision made by grid operators.

Providing economic value to customers to opt-in to DLS and DS programs are necessary for adoption. Some utilities already have an incentive in place to enroll customers in load shedding schemes. For example, as part of the Base Interruptible Program at PG&E, customers can enroll in the Underfrequency Relay Program (UFR). Customers in the UFR agree to install a utility owned underfrequency relay at their site which will trip their load when frequency on the PG&E system drops below 59.65 Hz [16]. Customers who enroll receive a monthly credit to their demand charge which is measured in $/kW of sheddable load. The UFR program requires a complete load shed, not partial load shed, and requires implementation of utility-owned relaying, which has a cost and may limit customer adoption.

A recurring $/kW-year payment could compel customer enrollment in the DLS and DS programs. DLS and DS underfrequency schemes could use a simple payment mechanism, a credit against demand charges or other demand-related metric, to incentivize customers to opt-in. Payment could be based on the frequency at which load is shed, with higher payment for shedding at higher frequency since those events may occur more often. Lastly, normal utility metering could be used for verification and validation that DLS and DS are invoked during underfrequency events.

Utilities successfully manage DR and dynamic pricing programs already, which could serve as an additional guide for DLS and DS schemes. It would be challenging for DR or dynamic pricing, even with automated demand response (ADR), to respond to underfrequency events since the speed of LS events can occur on the order of cycles, not hours. While DR communications are likely too slow, customers could still employ the same relaying and load management equipment to participate in DLS, DS and DR schemes.

### Table 3. Demand Side Control Hierarchy with Distributed Storage and Distributed Load Shedding

<table>
<thead>
<tr>
<th>Control Time Domain</th>
<th>Cycles</th>
<th>Seconds</th>
<th>Minutes</th>
<th>Hour ahead</th>
<th>Day ahead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply Related Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fast Ramping Storage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generation Control</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spinning Reserves</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scheduled Resources</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand Related Components</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Underfrequency Load Shedding (LS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed Load Shedding (DLS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed Storage (DS)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Auto DR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DR</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic Pricing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication and controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Frequency Response</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed Topology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited communications</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dispatching Signal Response</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centralized Topology</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communications and Cybersecurity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand Side Policy and Economic Drivers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interruptible Tariffs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Standards</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price Signals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment Standards</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In addition to supporting LS schemes, there may be additional outage restoration benefits to deploying DS and DLS. Even if the DS and DLS are insufficient to arrest LS schemes, implementing DLS could still have the effect of leaving the DLS portion customer load devices in the “off” position rather than “on” position at the moment of a broader outage.

With respect to contingent reserves for frequency regulation, energy storage resources or load shedding can be deployed at either a distribution or transmission level, so long as the resources have fast enough response characteristics. Deploying assets at a distribution level provides additional value through enabling intentional islanding and reducing impact of transmission congestion, particularly if system topology changes during an emergency event. A form of distributed and automated frequency control at a customer level could be an important component to enable intentional islanding or microgrids in the future [17].

Enabling and promoting DLS and DS schemes will not require an overhaul of the electrical grid at the expense of grid operators or ratepayers. Similar to DR, DLS and DS equipment will operate on the customer side of the meter affecting the local load and not requiring export of power. DS equipment can be sized, standardized or regulated to prevent export across the point of common coupling should exporting adversely impact distribution circuits with compliance and performance verifiable by utility metering.

V. CONCLUSION

Load shedding is one of the last aspects of a centrally controlled and operated power system that has not been materially changed through either deregulation or the growing adoption of DG. By utilizing capabilities in distributed power electronics that will already be widely deployed at scale for other applications, grid operators can improve on successful and mature LS schemes and provide additional transient stability even amid an increase in distributed generation.

VI. REFERENCES


VII. BIOGRAPHIES

Willem Fadrhonc is the Manager of Grid Solutions at Stem, Inc., a distributed energy storage and analytics company. Willem’s background is in electric power markets policy and economics and he has a Masters Degree from Duke University in Environmental Management.

Joseph Matamoros is the Vice President of Commercial Operations at Stem, Inc., a distributed energy storage and analytics company. Joseph’s background is in electrical equipment and power systems and has a Masters Degree in Energy and Power Systems from Arizona State University.

Puneet Sood previously worked at Stem, Inc. and is currently a graduate student pursuing a Masters Degree in Energy and Power Systems from Arizona State University. His primary area of focus is distribution systems and power system stability.