Grid Energy Storage Services for High PV Penetration Systems

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***Abstract*—Integration of renewable energy resources in microgrids has been increasing in recent decades in response to concerns of climate change and rising fuel prices. Due to the randomness in renewable resources such as solar and wind, the actual power generated can deviate from forecasted values. This variation may cause extra operating costs for committing costly reserve units or penalty costs for shedding load, especially in high PV penetration systems. In addition, it is often desired to charge/discharge and coordinate the energy storage units in an efficient and economical way. To meet the energy storage requirements of a high PV penetration system, a suitable cost/benefit scenario must be developed. This paper addresses some of the system considerations.**

***Index Terms*—microgrids, renewable energy, energy storage**

I. INTRODUCTION

THE increased penetration of variable renewable resources is often predicated on the assumption of sufficient energy storage. At present, the U.S. has about 24.6GW (approximately 2.3% of total electric production capacity) of grid storage, the majority of which is pumped hydro [1]. Many European countries and Japan have notably higher fractions of grid storage. Microgrids with integrated renewable resources are emerging as a solution for reducing the dependency on conventional fossil fuel and reducing emissions in distribution systems. The variability of renewable power sources requires quick response and highly efficient storage devices with larger power and energy density, which creates a challenge in developing renewable energy-based microgrids in large scale. Although many new energy storage technologies are reaching the consumer market, there is little field experience to support their adoption, especially in microgrid applications.

Numerous technologies currently exist for energy storage. Pumped hydro constitutes the largest share of the energy storage market at nearly 95% of all energy storage installations. Pumped hydro is attractive due to its larger unit sizes, ease of technology, and longer history. Newer technologies include compressed air energy storage, thermal energy storage, batteries, and flywheels. These technologies constitute the remaining 5% of overall storage capability. However, the rapid development of power electronics has spurred increased interest in electrochemical technologies (batteries) by enabling more efficient balance of plant systems.

Electrochemical battery technologies are better suited for microgrid applications due to their relatively small footprint and installation mobility. Much of the technological development in electrochemical batteries has been driven, in part, by the increased interest in plug-in electric vehicles. Several electrochemical technologies include lithium-ion, sodium sulfur, and lead acid batteries, including lead carbon batteries. Because Li-ion batteries do not handle cyclical deep-discharges well, they are better suited for power management applications that require only short duration power exchanges. Sodium-sulfur, iron-chromium, Zinc-bromine, and lead-acid batteries can maintain longer discharges (four to eight hours) and may be more suitable for load leveling and price arbitrage operations. Flow batteries are a newer technology that have been developed expressly for grid-scale energy needs. These batteries have limited commercial availability, but are accruing increased interest as a result of numerous demonstrations projects in the US and abroad.

Faced with this plethora of types, chemistries, and attributes, it is increasingly difficult for consumers and utilities to determine whether a proposed installation will be cost competitive. Given the range of applications and services, it is difficult to develop a generalized approach to evaluating energy storage. A generalized approach for evaluating energy storage should include [2]:

- An assessment of the storage requirements and value originating from the locational needs of grid operators and planners;
- Assessment of benefits; and
- Draw a distinction between quantifiable and monetizable services and direct and incidental benefits.

II. ENERGY STORAGE APPLICATIONS

Energy storage can be used for many applications in bulk power systems. In this paper, we focus on benefits realizable specifically for distribution systems with a high-penetration of renewables. These application/benefit areas may be roughly categorized as:

1) Regulation
2) Power Quality
3) Voltage Support
4) Load Shaping
5) Arbitrage

Benefit areas 1-3 are primarily *power* applications, whereas areas 4 and 5 are primarily *energy* applications. Applications such as infrastructure deferral and (transient) stability improvement are not implicitly considered because of the localized

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nature of a microgrid. Power applications are those that require the energy storage system (ESS) to have fast response and typically complete their charge/discharge cycle in the order of micro-seconds to minutes. Energy applications are those that require charge/discharge cycles in the order of minutes to hours and typically have a large variation in the state-of-charge of the battery.

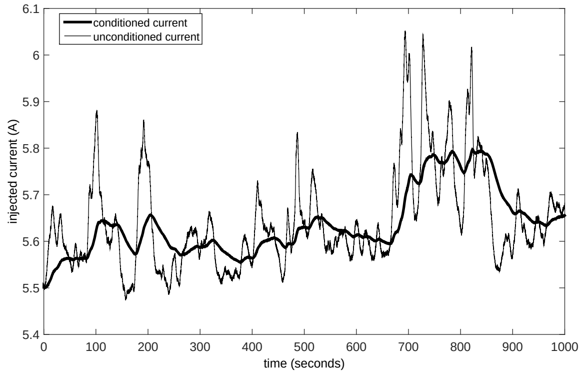

Fig. 1. Load current with and without regulation

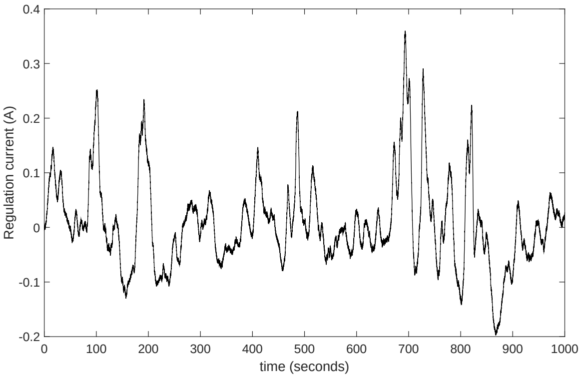

Fig. 2. Regulation current injection

A. Regulation

Regulation is the ability of the energy storage to charge and discharge rapidly in antipathy with mismatch between load and generation. Due to the intermittency of wind speed or solar insolation, renewable generation output power can be highly variable. Resulting power fluctuations may cause severe power quality problems when connected to the grid. The large variability in wind turbine output power can adversely impact local loads that are sensitive to pulsating power, posing a challenge to the use of wind power extensively. The rapid growth of renewable generation and its immense potential as a future energy source may required methods to smooth the line power variability. Energy storage technologies can be used to improve the quality of the line power [3] [4]. Fig. 1 shows the impact of wind power on the load observed at the point of common coupling. If the renewable generation (in this case a small wind turbine) is at the end of a feeder or in a weak microgrid, the impact of the variation on the consumer can be significant. Fig. 2 shows the current injection/absorption required to produce the smoothed output shown in Fig. 1.

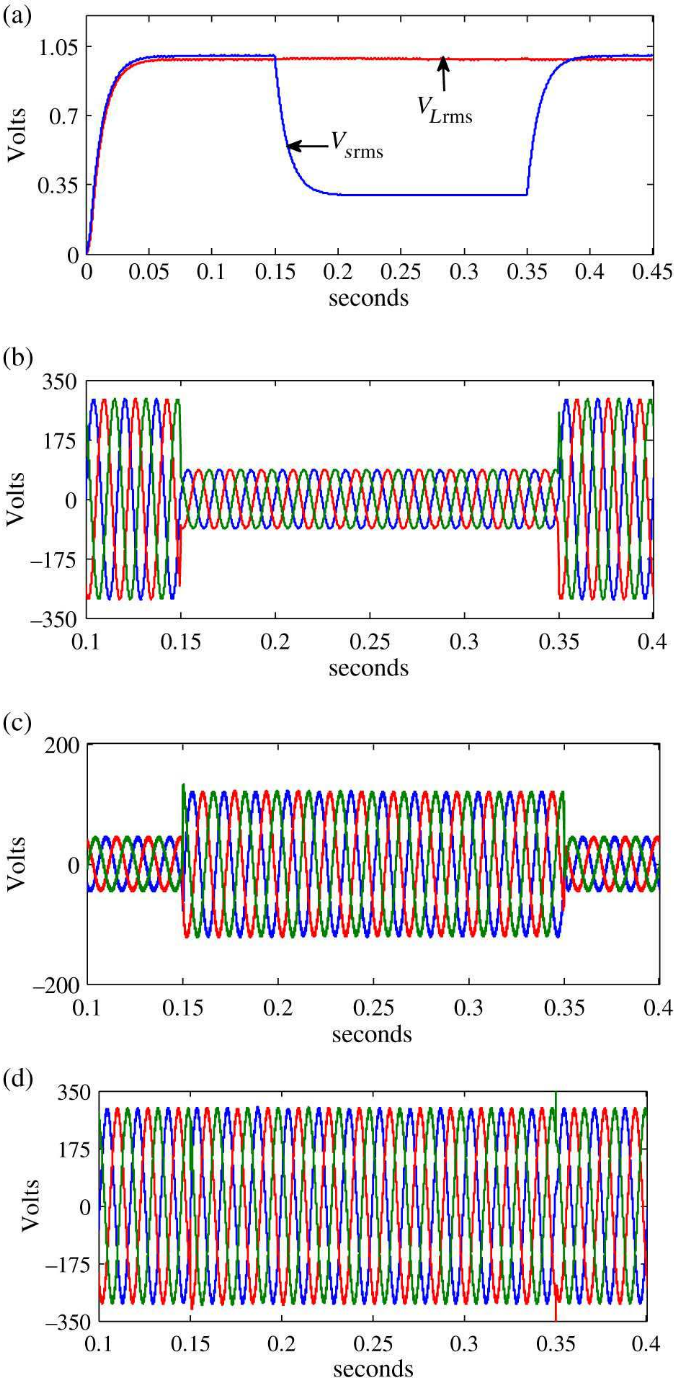

Fig. 3. (a) Source and load rms voltages $V_{s,rms}$ and $V_{L,rms}$ during sag (b) Source voltages during sag (c) Injected voltages from ESS during sag (d) Load voltages during sag

B. Power Quality Improvement

In addition to the renewable intermittency smoothing application, voltage sags and swells are power quality problems in the distribution grid that can mitigated through the use of energy storage systems. As opposed to the intermittency smoothing application in which the ESS supports the grid, in the power quality improvement application, the energy storage systems supports the customer load. In the sag/swell compensation mode, the ESS system is designed to protect sensitive loads from disturbances on the supply-side. These disturbances require short-term energy storage. The ESS will discharge to meet the active power requirements during a voltage sag and to be able absorb active power in a stable fashion during a voltage swell event. Fig. 3 shows the response of the system and ESS during a voltage sag on the system side of the ESS. The sag lasts of 0.1 seconds and reaches a minimum RMS voltage of 0.36 pu. The top figure shows the RMS voltages of the sag on the system and the relatively unaffected voltage at the load. The phase voltages of the source and ESS are given in the middle two plots, and the phase voltages are shown in the lower plot. Fig. 4 indicates that the active power to the load remains nearly unchanged.

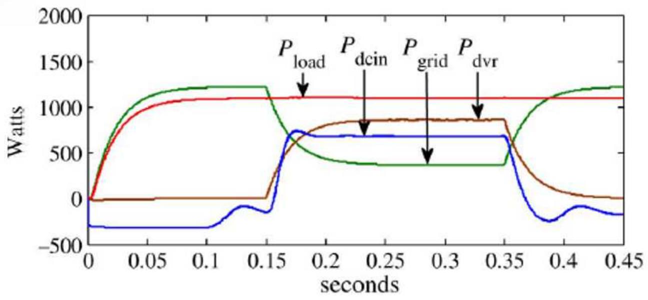

Fig. 4. Active power injection during sag

C. Voltage Support

The power conversion system (PCS) of most ESS requires a bi-directional converter to integrate the ESS, which may be either DC or AC at various voltages, to the synchronous AC grid. This converter also has the capability to independently inject/absorb reactive power up to the capacity of the converter. The PCS of the ESS used for voltage support must be capable of operating at a non-unity power factor. In the application, active power is not necessarily required from the battery in this mode of operation. With four quadrant operation capability, the ESS can absorb or inject reactive power simultaneously with active power charge or discharge.

The load varies throughout the day in accordance with the normalized load curve shown in Fig. 5, which represents a typical residential load. The solar insolation at each pilot bus is shown in Fig. 6.

Fig.7 shows the results of the algorithm on the c-phase voltage magnitude at bus 890. Note that without volt-var control, the competing effects of the diurnal load and the solar insolation cause the uncontrolled voltages to violate both the minimum and maximum voltage limits. However, once the VVC algorithm is implemented, the voltages are maintained within the operational boundaries.

To see the impact of the proposed volt-var control at the substation, the active and reactive power measured at the substation with and without control is shown in Fig. 8. Note that due to the high penetration of solar power, the active power at the substation goes negative indicating that the distribution feeder is supplying active power through the substation to the remainder of the network. Note that without VVC, the power factor at the substation is maintained at near unity as a design feature of the SSTs. However, as the SST pilot buses assume volt-var control, the reactive power changes to accommodate the commanded controls. However, even with the proposed VVC, the power factor is still near unity.

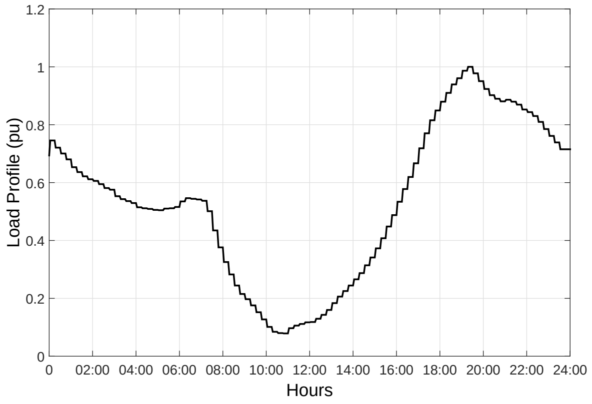

Fig. 5. Daily load profile

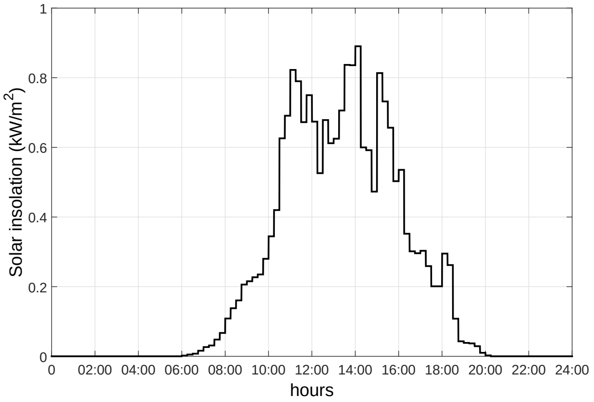

Fig. 6. Daily solar profile

D. Load Shaping

Electric energy load-shaping involves purchasing inexpensive electric energy, available during periods when prices or system marginal costs are low, to charge the storage system so that the stored energy can be used or sold at a later time when the price or costs are high. Alternatively, storage can provide similar time-shift duty by storing excess energy production, which would otherwise be curtailed, from renewable sources such as wind or photovoltaic (PV). The functional operation of the storage system is similar in both cases, and they are treated interchangeably in this discussion. Fig. 10 shows a typical daily load curve in which the load peak is lowered (peak-shaving) by storing energy during the night (valley-filling). Load shaping is most effective when there is a cost-incentive to offset the roundtrip ESS losses. This process can be incentivized by utility time-of-use rates.

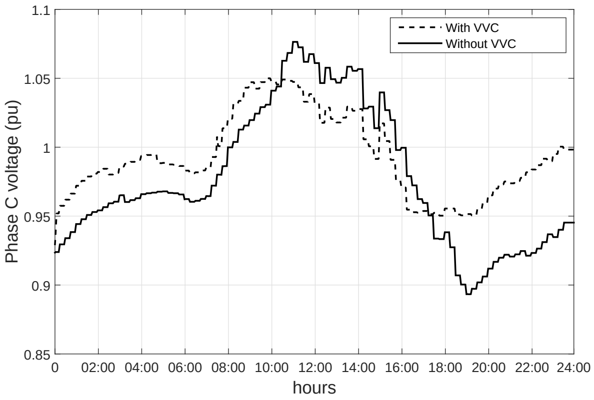

Fig. 7. Voltage of phase C at ESS

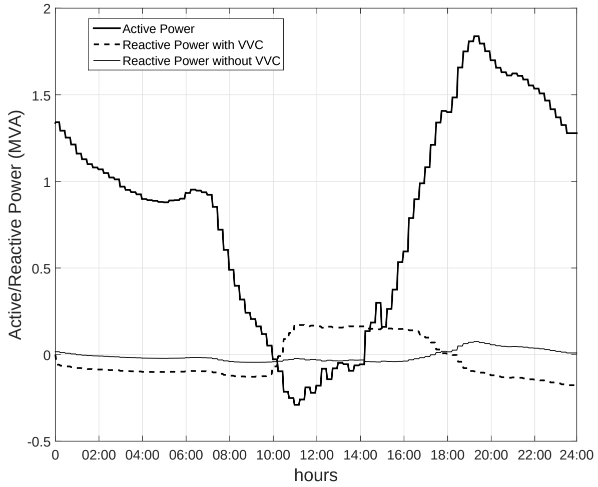

Fig. 8. Substation active and reactive with with and without volt-var control

E. Arbitrage

In arbitrage, price differences between two different time periods are exploited to reduce electricity costs to the consumer. Utilities across the US have adopted different time of use rates to incentivize customers to better manage their energy use. Most TOU rates are two (on-peak and off-peak) or three different rates (on- peak, part-peak, off-peak). Fig. 11 shows the TOU rates for several US utilities (in 2013) [5]-[11].

III. ENERGY STORAGE TECHNOLOGIES

To realize the benefits discussed previously in both terms of performance and economics, the ESS must be selected based on the needs of the consumer and the economic case. With recent renewed interest in energy storage, there have been many new technologies introduced in the market in the past decade as well as numerous technologies still in development. Each technology has its own performance characteristics that makes it optimally suitable for certain grid services and less so for other grid applications. The best business case will be achieved for installations that can address more than one of

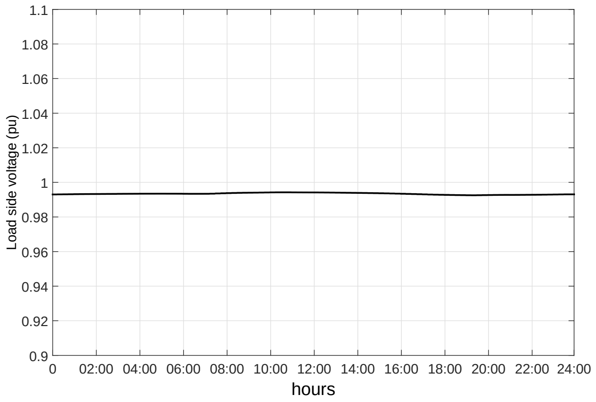

Fig. 9. Load side voltage

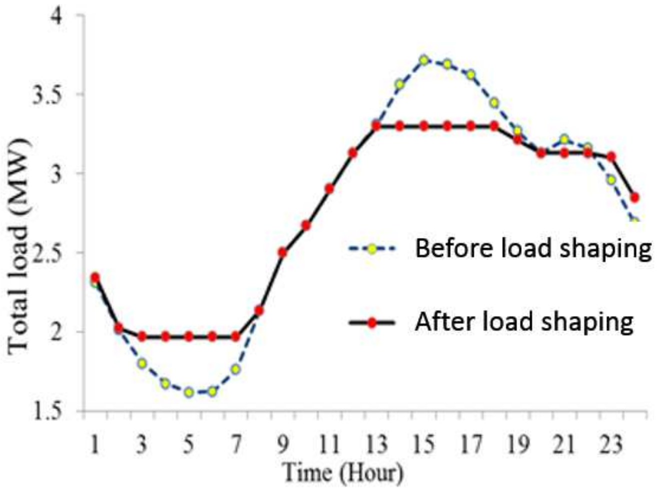

Fig. 10. Daily Load

the application benefits. Recent entries to the commercial market include flow-batteries, Superconducting Magnetic Energy Storage (SMES), and ultracapacitors [1]. Table I compares some of the more common battery types used in microgrids.

IV. ENERGY STORAGE VALUATION TOOLS

Currently, there are two primary energy storage evaluation tools for analyzing the business case. They are the “Energy Storage Valuation Tool” (ESVT) developed by EPRI and the “Energy Storage Computational Tool” (ESCT) developed by DOE. The ESCT is a free Microsoft Excel-based tool that is

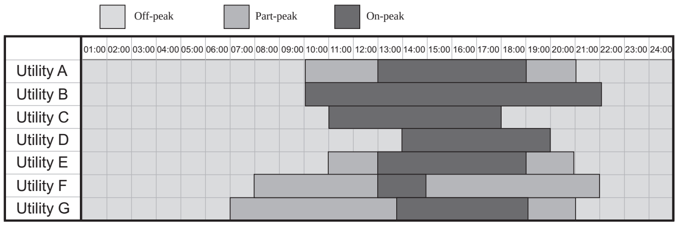

Fig. 11. Time of Use Rate Structures

TABLE I
COMPARISON OF TYPICAL BATTERIES [12] [13]

Type	power cost ($\$/kW$)	energy cost ($\$/kWh$)	eff. (%)	cycle life (no.)	energy density (Wh/L)
Lead-acid	175-600	150-400	70-82	100-2000	50-80
VRB	175-1500	150-1000	60-85	12000-14000	16-33
Li-ion	175-4000	500-2500	85-98	1000-10,000	200-500
Na-S	150-3000	250-500	70-90	2500	150-250

available for download from the DOE website [14]. The ESVT is a financial simulation model that allows the user to evaluate the cost-effectiveness of technically feasible grid-connected energy storage system use cases and multiple stakeholder business cases. Both software platforms provide default values for a variety of users and energy storage systems.

V. CONCLUSIONS

Renewable energy resources such as wind and solar are reaching high penetrations in many systems worldwide. Furthermore, aging infrastructure and environmental concerns can cause large variation in the cost of electricity to the consumer. In both of these cases, energy storage provides an option to improve the technology and economic performance of the system. However, to achieve the greatest benefits from the energy storage system, the ESS must be selected and sized for the application. It is more likely to reap positive benefits, if more than one application area can be addressed by the ESS. Unfortunately, there is not much experience by either the consumer or the utility in designing systems that optimize the business case. Several recent tools have been developed to assist in analyzing the business case.

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