DEVELOPMENT OF DIMENSIONING AND ALLOCATION ALGORITHMS FOR DIFFERENT APPLICATIONS OF BATTERY STORAGE UNITS

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ABSTRACT

In scope of this paper, the question of how to optimally utilize, dimension and allocate a battery storage unit (BSU) has been briefly addressed. Based on a novel generic BSU model, three main application fields of BSU are explored: market arbitrage, renewable firming, and network support. Main obstacles of modelling and simulation are identified in the process, and practical solution and applicable examples are analyzed to address these topics.

INTRODUCTION

Under current global transition towards smart grid era, the generation, transmission and distribution sectors of power industry are expected to change drastically over the coming decades. Rising levels of renewable penetration in power grid and the imminent picture of massive electric vehicles adoption would inevitably call for an increasing number of battery storage units (BSU) [1] to be installed in coming years.

In comparison with peer storage technologies, BSU has the general advantage of much lower geographic and space requirements in comparison with pumped hydro and compressed air energy storage options; and it also excels over fly wheel and super capacitor technologies by providing a much higher level of energy content, thus standing out as applicable to both short-term power applications and long-term energy applications [8].

Traditionally, the application of electric storage devices in power industry has been largely limited to niche markets such as balancing reserve, frequency support, and other ancillary service sectors. However, as the advents of smart grid and E-car industries are expected to speed up commercial maturity and cost reduction [3] [4] of most BSU technologies, a much larger variety of application fields for BSU can be envisaged in near future. In scope of this paper, the following three typical applications are selected and analyzed as an early attempt to reveal the potential consequences of BSU design and operation:

1. Market arbitrage application
2. Renewable firming (i.e. balancing) application
3. Network support (i.e. loading and voltage) application

One important feature of BSU, when compared to traditional power system components, is that its design process cannot be performed as a stand-alone task that is separated from its daily operation routines. In fact, the designer of a BSU must have a very clear understanding of its prospective operation pattern so as to properly dimension [2] and allocate [4] it optimally.

In ensuing sections, the operation, dimensioning, and allocation aspects of BSU are respectively addressed by the proposed three typical application fields. In order to properly account for physical limitations of BSU, a generic steady state BSU model has been adopted and is briefly explained first to facilitate understanding.

THE GENERIC BSU MODEL

Concurrently, BSU applications have a multitude of battery technology options to choose from, namely: lead acid, nickel metal hydrate, NaS, Redox, and lithium ion batteries etc. Lithium ion batteries are normally preferred due to their high loading capacity and remarkable lifecycle performance [1] [3] (i.e. despite safety and cost concerns). However, as studies performed within this paper can be considered as applicable to not just lithium ion but also alternative battery technologies, a generic BSU model is needed to minimize the impact of battery technology choice and BSU system configuration on developed dimensioning and allocation algorithms.

In Figure 1, the proposed generic BSU model is shown together with a simplified BSU configuration diagram. It can be seen that the generic model is developed as a highly abstract concept, which is largely decoupled from the actual physical configuration of a BSU system. The most important feature of this generic model is the introduction of a virtual internal 'ideal' AC source, which acts as an ideal storage unit with zero losses and absolute linearity.

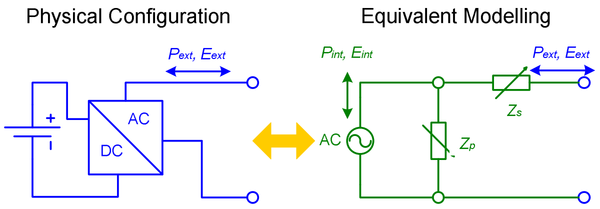

Figure 1: Equivalent Modelling of BSU Applications

Unlike classical battery modelling approaches , the generic model proposed in this paper does not seek to settle upon a fixed set of equivalent parallel and series impedance (i.e. R_p and R_s) values—instead, the generic model treats them as 'black boxes' as their values are mostly likely subject to changes under varying BSU operating conditions. Thus the input-output characteristics of the generic model is alternatively described by a set of functional correlations between internal (P_{int}, E_{int}) and external (P_{ext}, E_{ext}) powers and energies (i.e. real power). In general, three levels of modelling—ideal, linear, and nonlinear—can be assumed for this correlation as follows:

$$\begin{aligned}
&\text{Level 1: Ideal Modelling}\\
&\quad P_{\text{int}} = P_{ext} \quad \Leftrightarrow \quad P_{ext} = P_{\text{int}}\\
&\text{Level 2: Linear Modelling } (\eta_C \text{ and } \eta_D \text{ are charge / discharge efficiencies})\\
&\quad \begin{cases} \text{Charge:} & P_{\text{int}} = \eta_C \cdot P_{ext} \quad \Leftrightarrow \quad P_{ext} = P_{\text{int}} / \eta_C \\ \text{Discharge:} & P_{\text{int}} = P_{ext} / \eta_D \quad \Leftrightarrow \quad P_{ext} = P_{\text{int}} \cdot \eta_D \end{cases}\\
&\text{Level 3: Nonlinear Modelling } (a, b, c, \text{ and } d \text{ are equiavlent parameters})\\
&\quad \begin{cases} \text{Charge:} & P_{\text{int}} = \sqrt{a \cdot P_{ext} + b^2} - b \quad \Leftrightarrow \quad P_{ext} = \frac{1}{a} \cdot P_{\text{int}}^2 + \frac{2b}{a} \cdot P_{\text{int}} \\ \text{Discharge:} & P_{\text{int}} = c \cdot P_{ext}^2 + d \cdot P_{ext} \quad \Leftrightarrow \quad P_{ext} = \sqrt{\frac{1}{c} \cdot P_{\text{int}} + \left(\frac{d}{2c}\right)^2} - \frac{d}{2c} \end{cases}
\end{aligned} \tag{1}$$

The three models in Equation (1) are further visualized by Figure 2. For most preliminary storage dimensioning and allocation tasks, the linear model is normally sufficient with constant charge / discharge efficiency figures. The nonlinear model, however, has gone one step further to address the specific phenomenon of battery capacity variation under different charge / discharge speeds.

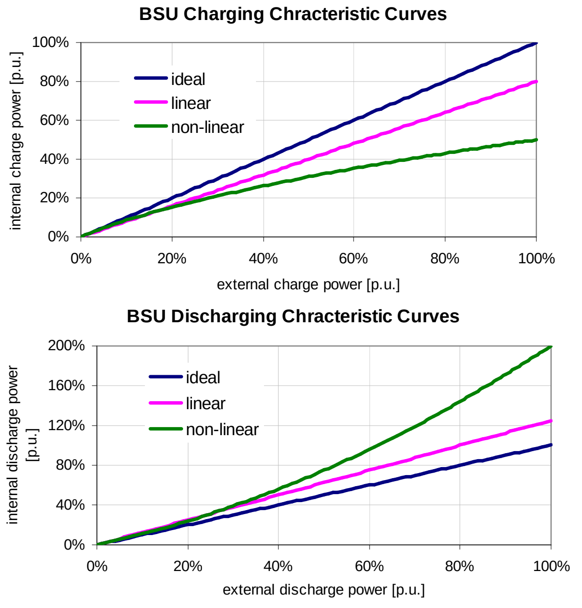

Figure 2: Charge / Discharge Features of BSU Models

Note that self-discharge and ageing effects are modelled separately and not accounted for in Equation (1). Ensuing application cases are analyzed based on the linear model.

APPLICATION 1: MARKET ARBITRAGE

A BSU is effectively an 'arbitrager' when it attempts to gain revenues from electricity market via taking advantage of real-time price differences in a day. Under current market conditions, profitability of this type of application is still not high enough to justify installation of BSU. Nonetheless, it already shows great commercial potentials as BSU cost goes down in future.

The basic principles of market arbitrage operation for BSU can be seen from Figure 3. A review of existing BSU arbitrager simulation tools [4] shows major focus of design for this type of application stays to be operation in nature, as profitability of an arbitrager BSU does not rely heavily on its location or size (i.e. per-kWh profitability stays relatively constant under same arbitrager strategy).

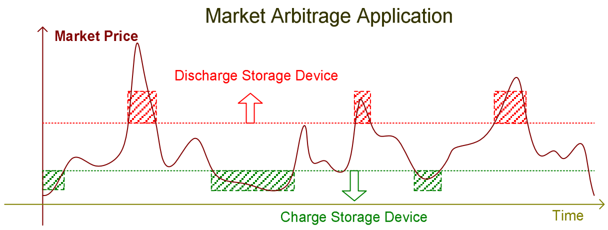

Figure 3: Illustration of Market Arbitrage Application

The BSU arbitrager operation routine needs to firstly convert physical variables into an equivalent ideal storage framework using linear / nonlinear transformation of Equation (1); then a dispatch algorithm should be executed to obtain the amount of charge / discharge energy within each sampled time slot (one hour); and finally the dispatch result should be converted back to physical (i.e. 'external') values. The arbitrager dispatch algorithm can be described by the following optimization problem (ideal framework, thus no loss or efficiency terms should apply):

$$\begin{aligned}
&\text{Maximize} \quad h = \sum_{t=1}^{T} \left[q_t \cdot (y_t - x_t) - k_x \cdot x_t - k_y \cdot y_t \right], \quad \forall t \in [1, T]\\
&\text{s.t.} \quad \begin{cases} E_t = E_{\text{int}} + \sum_{v=1}^{t} x_v - \sum_{v=Tb}^{t} y_v \\ 0 \le x_t \le PX_{\max}, \quad 0 \le y_t \le PY_{\max}, \\ E_{\min} \le E_t \le E_{\max} \\ E_T = E_{end} \end{cases}
\end{aligned} \tag{2}$$

where:

h is the total arbitraging profit of BSU in a day;
x_t is the amount of purchased energy at time t;
y_t is the amount of sold energy at time t;
q_t is the market electricity price at time t;
k_x and k_y are leveraged per-kWh charging/ discharging costs;
E_t is available energy level in BSU at time t;
PX_{max} and PY_{max} are maximum charging/ discharging powers;
E_{min} and E_{max} are minimum/maximum BSU energy levels;
E_{int} and E_{end} are initial/final BSU energy levels in a day.

In general, linear programming technique is sufficient for handling the optimization problem of Equation (2)—although admittedly an iterative process is needed to fix buy / sell decisions in each hour. In Figure 4, the dispatch result of a sample arbitrager BSU application is shown.

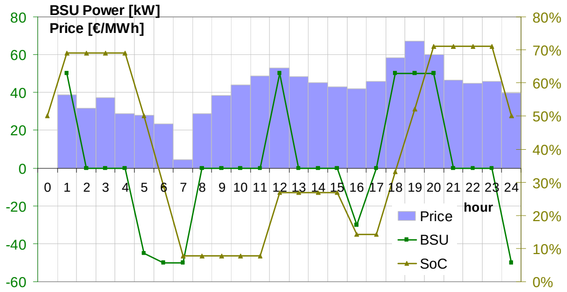

Figure 4: Sample Market Arbitrage Dispatch Result

One interesting discovery of arbitrager BSU application is that prospective advent of commercial BSU adoption may exhibit a very abrupt ‘outburst’ period, as shown by Figure 5. Note that drastic increase of BSU usage ratio (hence profit) is observed for a leveraged BSU usage cost range between 9 €/kWh and 10 €/kWh (this range is only used for discussion purpose and thus should not be applied to real world applications).

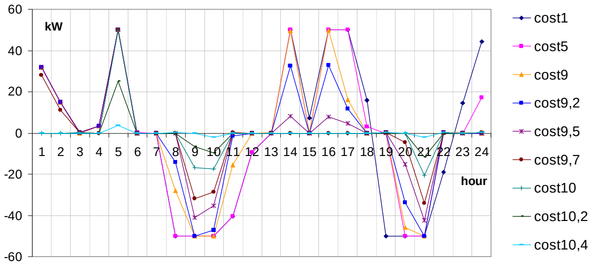

Figure 5: BSU Dispatch Result under Different Costs

APPLICATION 2: RENEWABLE FIRMING

A renewable firming BSU system is in effect an energy balancing application that attempts to minimize the power / energy fluctuations caused by renewable energy sources [5] in a given region of a grid or in an island. This type of algorithm is developed with the aim of minimizing potential total cost of dispatching controllable generator(s) in the same time. Figure 6 shows the basic principles of renewable firming BSU operation as a reference.

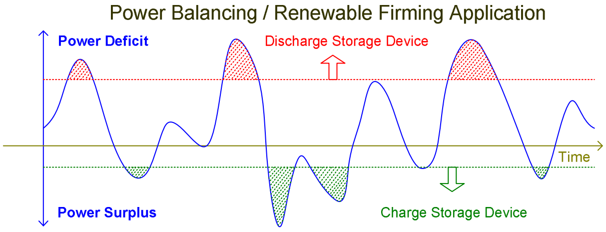

Figure 6: Illustration of Renewable Firming Application

The most challenging task of designing a BSU system for renewable forming purpose is obviously the dimensioning of BSU. This dimensioning algorithm, however, has to be based on a correlating dispatch algorithm first—in Equation (3), this renewable firming dispatch algorithm is formulated as an optimization problem (ideal framework):

$$\text{Let} \quad z_t = p_t + x_t - y_t, \quad \bar{z} = \frac{1}{T}\sum_{t=1}^{T} z_t$$

$$\text{Minimize} \quad f = \sum_{t=1}^{T}\left[(\bar{z} - z_t)^2\right], \quad \forall t \in [1, T] \tag{3}$$

$$s.t. \begin{cases} E_t = E_{\text{int}} + \sum_{v=1}^{t} x_v - \sum_{v=Tb}^{t} y_v \\ 0 \le x_t \le PX_{\max}, \quad 0 \le y_t \le PY_{\max}, \\ E_{\min} \le E_t \le E_{\max} \\ E_T = E_{end} \end{cases}$$

where:

f is the fluctuation level of demand curve after applying BSU;
p_t is the residual load demand (load minus RES) at time *t*;
z_t is the modified load demand (after applying BSU) at time *t*;
x_t is the amount of purchased energy at time *t*;
y_t is the amount of sold energy at time *t*;
All constraint variables have same definitions as Equation (2).

A combination of both quadratic and linear programming techniques is required (i.e. iterative process) to solve the renewable firming dispatch problem of Equation (3). On top of physical / ideal framework transformations for the generic BSU model, an extra layer of segmentation algorithm is needed to facilitate renewable firming operation, which can be roughly explained by Figure 7.

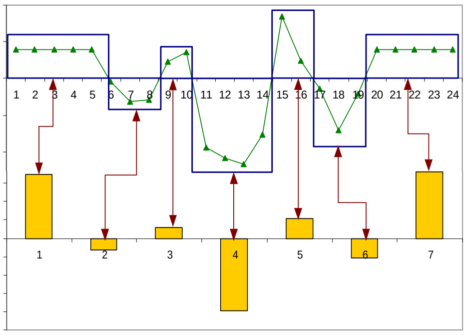

Figure 7: Segmentation Method for Balancing Application

The main purpose of segmentation operation is to provide a preliminary list of charge / discharge decisions for each hour, once an estimated average of modified load demand is known. In Figure 8, a sample dispatch result is shown.

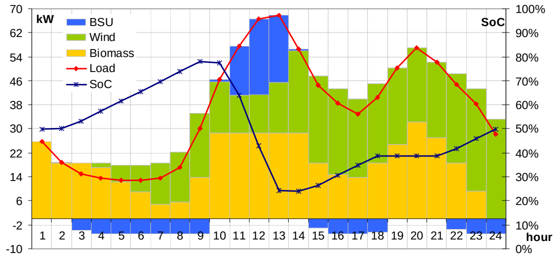

Figure 8: Sample Renewable Firming Dispatch Result

BSU dimensioning task for renewable firming application can be thus performed by calling the dispatch routine for a number of varying BSU / generator sizing settings, out of which scenarios of minimal cost can be chosen as eventual solution. Different reliability requirements may lead to varying dimensioning results, as shown by Figure 9.

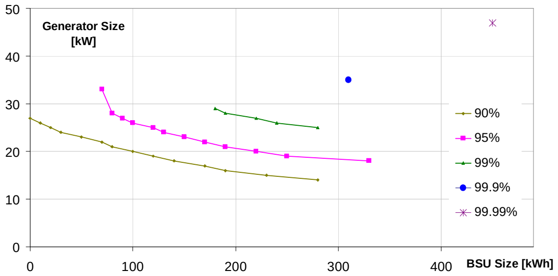

Figure 9: Sample Dimensioning Result of Island System

APPLICATION 3: NETWORK SUPPORT

The network support application of BSU mainly aims at solving network issues such as overloaded lines [6] and/or breaching of voltage band limit [7] at certain locations via installing one or more BSU ('s). Basic principles of this application can be explained by Figure 10.

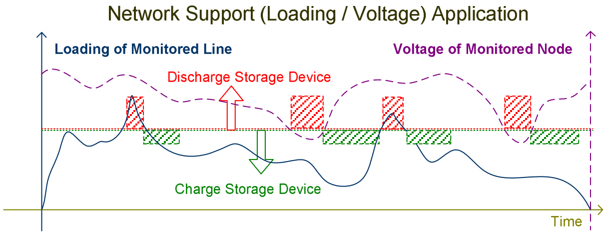

Figure 10: Illustration of Network Support Application

For a network supporting BSU, operation, dimension and allocation are all important topics to consider. This type of BSU application differs from previous two in the sense that no strong operation cycles exist—instead, the operation of a network supporting BSU is more dependent on its real-time impact on the network, as shown by the linearized load flow [8] Equation (4):

$$
\begin{aligned}
&Write\ \vec{x} = \left[\vec{p}_{BSU}^{\,T} \quad \vec{q}_{BSU}^{\,T}\right]^T, \quad then: \\
&\Rightarrow \vec{i}_{link} = \sqrt{\left(\vec{A}_{ip}\cdot\vec{x}+\vec{B}_{ip}\right)^2 + \left(\vec{A}_{iq}\cdot\vec{x}+\vec{B}_{iq}\right)^2} \qquad (4) \\
&\Rightarrow \vec{u}_{node} = \vec{A}_u\cdot\vec{x}+\vec{B}_u \\
&\Rightarrow p_{loss} = \vec{x}^T\cdot\vec{A}_l\cdot\vec{x}+\vec{B}_l\cdot\vec{x}+\vec{C}_l
\end{aligned}
$$

where:

- p_{BSU} and q_{BSU} are BSU active / reactive power vectors;
- i_{link} is thermal loading vector of all lines and transformers;
- u_{node} is nodal voltage magnitude vector;
- p_{loss} is total power loss in the grid;
- A_{xxx} , B_{xxx}, and C_{xxx} are network parameter matrices/vectors

Equation (4) shows that component thermal loading level, nodal voltage magnitude and total grid power loss can be deducted as linear or quadratic functions of BSU active / reactive power outputs. Thus an iterative NtL load flow [8] plus linear/ quadratic programming routine can be used to optimize both operation and allocation of BSU's to achieve loading reduction and voltage support goals, as can be seen from Figure 11 (results based on study [9]):

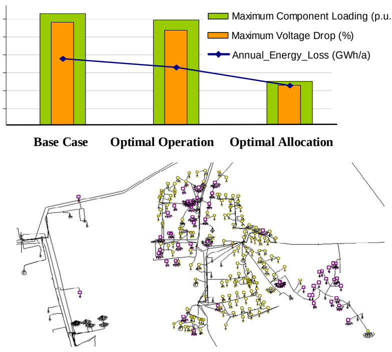

Figure 11: Sample BSU Benefits and Allocation Result

CONCLUSIONS

This paper has presented potential challenges and viable solutions for three typical BSU applications: market arbitrage, renewable firming, and network support. Practical dimensioning and allocation algorithms for BSU are proposed and tested under realistic test network conditions using a generic BSU model. The presented ideas should serve as a reasonable basis for future research efforts.

REFERENCES

[1] Jean-Philippe Macary, Dr. Andreja Rasic et al, June 2011, "Smart Power Applications and Peak Power Management in Distribution Networks with Energy Storage Solutions", *CIRED 2011*, paper 0512

[2] Chandu Venu, Yann Riffonneau et al, June 2009, " Battery Storage System Sizing in Distribution Feeders with Distributed Photovoltaic Systems", IEEE Bucharest Power Tech Conference

[3] Jarno D. Dogger, Bart Roossien et al, March 2011, "Characterization of Li-Ion Batteries for Intelligent Management of Distributed Grid-Connected Storage", IEEE Transactions on Energy conversion, vol. 26, No. 1

[4] MG Hoffman, A Sadovsky et al, September 2010, " Analysis Tools for Sizing and Placement of Energy Storage in Grid Applications: A Literature Review ", Pacific Northwest National Laboratory Report, Prepared for US Department of Energy

[5] Federick Geth, Jeroen Tant et al, July 2010, "Integration of Energy Storage in Distribution Grids", IEEE Power and Energy Society General Meeting, Minneapolis

[6] G. Koeppel, M. Geidl et al, November 2004, "Value of Storage Devices in Congestion Constrained Distribution Networks", International Conference on Power System Technology-POWERCON, Singapore

[7] M.A. Kashema and G. Ledwich, March 2006, " Energy Requirement for Distributed Energy Resources with Battery Energy Storage for Voltage Support in Three-Phase Distribution Lines", Electric Power Systems Research 77 (2007) 10–23

[8] Christine Schwaegerl, Liang Tao et al, Dec 2009, "Report on the Technical, Social, Economic, and Environmental Benefits Provided by Microgrids on Power System Operation", EU Project "More Microgrids", Deliverable DG3

[9] Mattias Hable.; Christine Schwaegerl et al, 2010, "Requirements on Electrical Power Infrastructure by Electric Vehicles", Emobility-Electrical Power Train, VDE Congress ETG-PELS, Lepzig