Sizing Energy Storage to Accommodate High Penetration of Variable Energy Resources

Yuri V. Makarov, Michael C.W. Kintner-Meyer, Pengwei Du, Chunlian Jin, and Howard F. Illian

***Abstract*—The variability and non-dispatchable nature of wind and solar energy production presents substantial challenges for maintaining system balance. Depending on the economical considerations, energy storage can be a viable solution to balance energy production against its consumption. This paper proposes to use discrete Fourier transform (DFT) to decompose the required balancing power into different time-varying periodic components, i.e., intra-week, intra-day, intra-hour, and real-time. Each component can be used to quantify the maximum energy storage requirement for different types of energy storage. This maximum requirement is the physical limit that could be theoretically accommodated by a power system. The actual energy storage capacity can be further quantified within this limit by the cost-benefit analysis (future work). The proposed approach has been successfully used in a study conducted for the 2030 Western Electricity Coordinating Council (WECC) system model. Some results of this study are provided in this paper.**

Index Terms—Imbalance power, energy storage, integration of variable resources, discrete Fourier transform, WECC System.

I. Introduction

High penetrations of variable energy resources create significant uncertainty in required power generation, needed to balance the energy production against the consumption [1-2]. New technologies, such as new wind and solar forecasting tools, demand-side control, fast start-up units, and many others have been proposed to address this balancing issue [1]. Among those options, energy storage can be a viable solution because of its fast response and control flexibility [3-4].

A. *Energy Storage as an Ancillary Service Resource*

Today, many electricity storage technologies, including pumped hydro, various batteries, compressed air, flywheels, capacitors, and others are proposed or already used to control the grid [3-6]. Energy storage (ES) systems can be used to follow the net load changes, stabilize voltage and frequency, manage peak loads, improve power quality, and ultimately support renewable integration. A summary of performance requirements needed for a variety of energy storage applications can be found in [6].

Wind and solar power variations are hard to predict and cause multiple impacts including the impact on system reliability. To maintain balance between generation and load, costly flexible generation resources that have sufficient start up time, ramping speed, and capacity may be employed.

Alternatively, energy storage for periods from days to less than 1 hour can help to smooth out unpredicted power fluctuations. For the intra-hour variations, energy storage can provide essential ancillary services such as fast regulation and load following. This would have great advantages because fast regulation may be twice as effective as gas turbines and 20 times more effective than steam turbines [7]. Therefore, the short-term ES represents a new perspective class of ancillary service resource.

The 2007 FERC[1] Order No. 890 allows so-called “non-generation” resources like energy storage to participate in regulation markets on a non-discriminatory basis. Since then, new market rules have been developed by some Independent System Operators (ISOs). For example, the New York ISO already started to support the integration of limited energy storage resources (LESR) [8].

The balancing ancillary services represent an attractive business opportunity for ES. Numerous research and demonstration projects in this area have been planned or currently under development. For example, Beacon Power Corporation is constructing the grid-scale 20 MW flywheel plant in Stephentown, New York, in an attempt to provide approximately 10% of New York's overall frequency regulation needs. AES has tested an Altairnano lithium-titanate battery (2MW/500kWh) in a pilot program with California ISO. Furthermore, the Department of Energy’s American Recovery and Reinvestment Act

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[1] FERC stands for Federal Energy Regulatory Commission

(ARRA) stimulus funding is sponsoring 37 projects with a combined value of 637 million dollars, which combine smart grid and energy storage functionality [9]. This will greatly accelerate the entrance of ES into the power grid, in particular, the module, distributed ES (e.g. community energy storage, plug-in hybrid electric vehicles). If modeled and controlled properly, these aggregated small-size ESs can provide the ancillary services cost-effectively. In view of these, it can be envisioned that ES will become more integral to the grid operation, and play a key role in providing ancillary service to enable a high penetration of wind power and other renewable resources [9].

B. Sizing of Energy Storage

Among other characteristics, an energy storage can be characterized by its energy capacity (MWh), power capacity (MW), round-trip efficiency, and ramping capability. The capital cost of energy storage consists of an energy component ($/MWh) and a power component ($/MW). The former represents the cost of the storage medium, and the latter represents the cost associated with the power electronics. The current cost for energy storage is still relatively high. However, as mentioned above, several companies are exploring the competitiveness of their novel storage technologies in very specific high-value markets. These markets usually require short duration energy storage, which power output can be sustained at the rated power capacity level from 15 to 20 minutes. Longer duration energy storage (for over several hours or for a day) are generally pumped hydro or compressed air energy storage technologies, which generally are less flexible in their placement compared to battery or flywheel energy storage. Both from a transmission planning and technology development points of view it is of interest to estimate the total market size for different energy storage systems.

In this context, the optimal operation and sizing of ES is a subject of intensive research work. Stochastic optimization has been proposed to find the optimal sizing of energy storage so as to maximize the expected operation profit (or minimize the cost) while taking into account transmission constraints [10-15]. In [16], battery energy storage (BES) is used in conjunction with a wind farm. The capacity of BES is determined to ensure constant dispatched power to the grid while the voltage level across the dc-link of the buffer is kept within preset limits. Some authors used probabilistic methods to model the operation of energy storage [6]. They evaluated two potential control strategies, i.e., the energy is released as soon as the local network can absorb it, or the energy is stored and is sold when the price of electricity is higher. The value of storage in relation to power rating and energy capacity was investigated so as to facilitate appropriate sizing. The BES storage device can be used to reinforce the dc bus during transients, thereby enhancing its low-voltage ride through capability. When properly sized, it can effectively damp short-term power oscillations, and provide superior transient performance over a number of seconds [17]. Using a BES unit to provide frequency regulation was discussed in [11].

State-of-the-art ES models that would be appropriate for transmission and distribution uses were reviewed in [9]. They can be used for optimizing storage size for ancillary services.

C. Need for Sizing Tools for Power Systems Planners

This paper presents a novel perspective on the sizing issue of grid-scale ES for utilities which are concerned with the system flexibility characteristics needed to mitigate the volatility of wind and solar power. Essentially, the maximum size of ES can be decided upon the cycling components of the required balancing power. Previous research work conducted at the Pacific Northwest National Laboratory (PNNL) studied the capacity requirement of energy storage in WECC for year 2030 [2] [18]. The follow-up work reported in this paper aims at determining the maximum feasible size of energy storage by identifying different cycling components of the balancing power. This proposed approach does not use either production cost models or comprehensive storage models. It is based on the fact that an energy storage cycles energy within certain frequency range. For example, a flywheel can cycle energy 4 cycles per hour or even faster if the full energy capacity is used. To find the maximum cycling requirements at different frequencies, a frequency decomposition of the balancing power signal is used in the paper. The components of this decomposition are periodic signals with zero total energy, representing the cycling job for the energy storage. These periodic components also indicate the duration requirements for storage technologies. Ultimately an optimal allocation of storage technologies can be determined based on this cycling analysis.

This paper is organized as follows. Section II discusses the basic methodology to decompose the

[2] Internal PNNL study that estimated the technical potential of the energy storage for meeting new balancing requirements in the WECC for a 88 GW wind power scenario.

balancing power using discrete Fourier transform (DFT). Section III presents the simulation results for the 2030 WECC system model. Section IV provides the final discussion and conclusions.

II. Decomposition of Balancing Power Using DFT

The balancing process consists of several components, including scheduling, load following, and regulation. While the scheduling component usually reflect hourly dispatches of generation units providing most of the energy to the load, the load following and regulation components help to achieve intra-hour balance by covering the gap between the hourly schedules and minute-by-minute system load.

A. Balancing Power

The power system control objective is to minimize area control error (ACE) to the extent sufficient to comply with the North American Electric Reliability Corporation (NERC) Control Performance Standards (CPS). Therefore, regulation and load following signals are signals that oppose deviations of ACE from zero:

$$-ACE = -(I_a - I_s) + 10B(F_a - F_s) \quad (1)$$

where subscript a denotes actual, s denotes schedule, I stands for interchange between control areas, F stands for system frequency, and B is the system frequency bias (MW/0.1 Hz, a negative value).

The generation output consists of two components:

$$G_a = G_s + G_{dev} \quad (2)$$

where subscript s refers to hour-ahead schedule[3], and dev refers to the deviation from the schedule.

Similarly, the load can be separated into two components as follows:

$$L_a = L_{f\_ha} + L_{dev} \quad (3)$$

where L_{f_ha} is hour-ahead load forecast.

Based on the assumption that

$$G_s = L_{f\_ha} \quad (4)$$

the difference between the actual load, L_a, and the forecasted load, L_{f_ha}, represents the load deviation that is compensated by generators (or energy storage) procured for load following and regulation processes.

$$L_{dev} = L_a - L_{f\_ha} = L_a - G_s \quad (5)$$

Wind and solar generation can be treated as negative load.

$$G_a^w = G_{f\_ha}^w + G_{dev}^w \quad (6)$$

where G_a^w is the actual wind power, $G_{f\_ha}^w$ is hour-ahead wind power forecast, and G_{dev}^w is the deviation from the forecast.

Therefore, similarly to the situation without wind, the balancing power can be expressed as follows:

$$G_s = L_{f\_ha} - G_{f\_ha}^w \quad (7)$$

$$L_{dev} = (L_a - G_a^w) - G^s = L_a - L_{f\_ha} - (G_a^w - G_{f\_ha}^w) \quad (8)$$

Fig. 1 shows the imbalance power in the WECC model for August 2030. The balancing power needed in the system is opposite to the imbalance. It is assumed that the peak load in 2030 will have grown to 205 GW, and the installed wind capacity will be 88 GW (up from about 7 GW in 2008 [18]). The highly fluctuating imbalance signal is attributable to the high variability of wind power. It also represents the gap between the scheduled generation and actual load. By utilizing energy storage, the imbalance can be reduced by charging the energy storage whenever there is over-generation (imbalance signal is above zero) and discharging the storage during periods of under-generation (imbalance signal is negative). Periodic zero total energy components of the imbalance signal in Fig. 1 correspond to the maximum charging/discharging job that can be allocated to the energy storage.

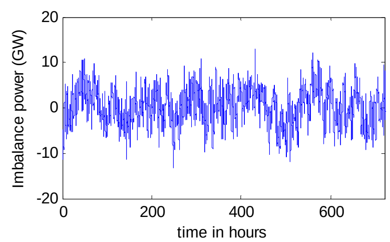

Fig. 1. Imbalance power imposed by load and wind variability for assumed 88 GW of installed wind capacity (WECC model for Aug. 2030).

B. DFT Analysis

Different energy storage technologies are best suited for operation over different time periods. The imbalance power, shown in Fig. 1, can be broken down into the components spanning different frequency ranges. This decomposition can be achieved by using DFT. Each component of the periodic signal, except for the zero frequency component, represents cycling energy that averages to zero over each cycle.

Generally, in a discrete form, the DFT analysis and synthesis equations are written as follows [19]:

[3] Please note that the hour-ahead schedule can be implemented differently in the different markets.

Analysis equation (fast Fourier transform)

$$X[f] = \sum_{t=0}^{N-1} x[t] W_N^{tf} \quad f = 0,\dots,N-1 \tag{9}$$

Synthesis equation (inverse Fourier transform)

$$x[t] = \frac{1}{N}\sum_{f=0}^{N-1} X[f] W_N^{-tf} \quad t = 0,\dots,N-1 \tag{10}$$

where N is the number of the data points in the sequence ($x[0]$, $x[1]$, $\cdots$, $x[N\text{-}1]$), and $W_N^{tf} = e^{-j(2\pi/N)tf}$.

The basic approach to decompose the imbalance signal using DFT consists of five steps, as shown in Table 1.

Four different frequency ranges are selected, and the signal is decomposed into four categories: slow cycling, intra-day, intra-hour and real-time components. The band-pass filter applied to the spectrum is a rectangular window with unit magnitude within the band and zero magnitude outside of the band, as illustrated in Fig. 2 and Table 2. It is symmetric around one half of the sampling frequency.

Table 1: Procedures of applying DFT for cycling analysis

Steps	Description
1	Assume that the data sampling $x(t)$ is sampled each minute (or 0.0167 Hz). The data window selected for DFT analysis is 2 days (2880 samples), which starts at 0:00 and ends at 48:00.
2	The data points are increased to 5760 sample with zero padding.
3	The spectrum, $X(f)$, is obtained by DFT. A band-pass filter (see Fig. 2) is applied to the spectrum, $X(f)$.
4	The filtered spectrum is converted back to the time-domain signal, $x'(t)$, by using inverse DFT.
5	The time-domain signal $x'(t)$ is characterized by the magnitude and periodicity.

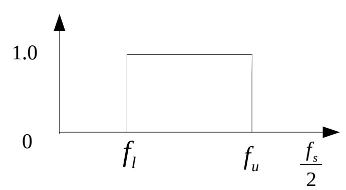

Fig. 2. Band-pass applied to the signal spectrum (the cutoff frequencies are f_l and f_u, and the filter is symmetrical about the half of the sampling frequency, $f_s/2$)

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Table 2: Specifications of frequency bands of the balancing signal components

Component	f_l (Hz)	f_u(Hz)
Slow cycling	0	2.315e-5
Intra-day	2.315e-5	9.259e-5
Intra-hour	9.259e-5	0.00333
Real-time	0.00333	0.00833

The frequency ranges given in Table 2 have no a strict definition and they are loosely connected to the dispatch intervals. The reason is that a dispatch interval can contain half cycle, the entire cycle, two cycles, and so on depending on researchers' judgment. Currently they are set for periods of 3-12 hours (intra-day), 5 minutes –3 hours (intra-hour), and 2–5 minutes (real time).

C. Simulation Results

The DFT method described in Section II was applied to a simulated WECC system imbalance power model reflecting a future high wind penetration scenario for 2030. Several simplifying assumptions were made to determine the balancing requirements curve. The balancing requirement was derived from the uncertainty in the load and wind forecasting. The scenario assumed 88 GW of wind capacity in the WECC system. Furthermore, it was assumed a consolidation of all WECC balancing areas into one single balancing area. This model was derived in a previous PNNL project analyzing the energy storage potential applications in the WECC system [18].

D. Decomposition of Balancing Power for a Particular Day

Fig. 3 shows the one-day imbalance power signal (top) and the corresponding spectrum (bottom). Most of the energy is concentrated in the low and middle frequency bands.

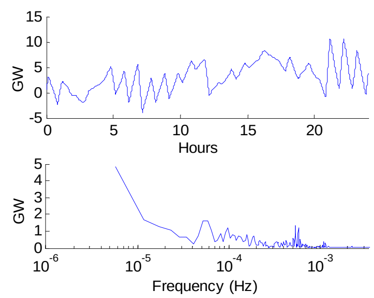
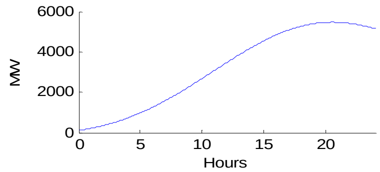


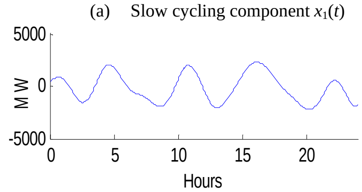
Fig. 3. Imbalance power for a day in August 2030

By applying the filters shown in Fig. 2 and Table 2, in Fig. 4 the imbalance power, $x(t)$, is decomposed into four components, namely, into slow cycling, intra-day, intra-hour, and real time components, $x_1(t)$, $x_2(t)$, $x_3(t)$ and $x_4(t)$. By summation of these components, we can reconstruct the original time-domain signal. The reconstructed imbalance power matches well with the original signal, as shown in Fig. 5.

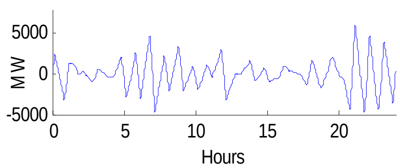
The frequency and magnitude of the decomposed signal play an important role in determining the required energy storage characteristics as well as technologies appropriate for each application.



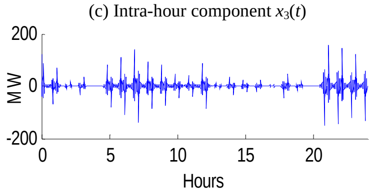
(a) Slow cycling component $x_1(t)$



(b) Intra-day component $x_2(t)$



(c) Intra-hour component $x_3(t)$



(d) Real-time component $x_4(t)$

Fig. 4. Decomposition of imbalance signal for a day in August 2030

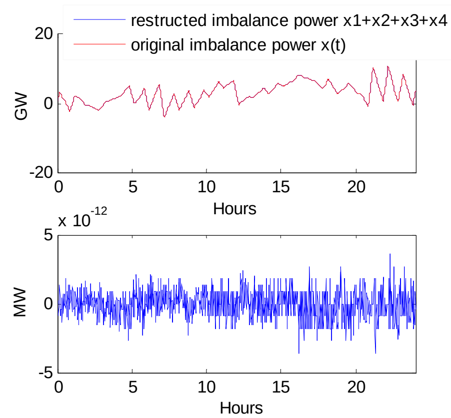


Fig. 5. Comparison between original signal and reconstructed signal.

The frequency of cycling increases for intra-hour and real time components. This means that the energy capacity requirements are decreasing, while the cycling requirements are increasing. The cycling requirement has implication for the life time of the energy storage.

The energy storage power capacity requirement is associated with the magnitude of the cycles. On this particular day, the imbalance power swings between 10.7 GW and -4.1 GW, while intra-hour component swings between 6.1 GW and -4.8 GW, and real-time component swings between 154 MW and -153 MW[4]. Therefore, the intra-day balancing process requires more ES power capacity than the intra-hour process by 43. The same fact has also been observed for other days as described below.

E. Sizing of Energy Storage

To determine the size of energy storage for slow-cycling, intra-day, and intra-hour balancing processes, the method described in Section II was applied. We assumed a depth of discharge for the ES of 80%. Table 3 shows both the power and energy capacities for the energy storage.

In the full balance scenario (second column), the energy storage compensates for all the imbalance power. In the partial balance scenario (third column), the energy storage compensates for only intra-hour and real-time components. In the fourth column, the reduction in ES requirements between the full balance and partial balance is shown.

[4] Despite the asymmetric power capacity requirement, the energy requirement remains symmetric (the positive and negative energy are equal), which is important for the energy storage applications.

Table 3: Comparison of the full balance and partial balance scenarios

Energy storage size	Full balance	Partial balance	Reduction in ES requirements
Power	13.4 GW	7.7 GW	42.6%
Energy	68.1 GWh	4.3 GWh	93.6%

A very significant ES energy capacity (68.1 GWh) would be required in the full balance scenario. The state of charge of ES in this scenario is shown in Fig. 6. The size of the energy storage can be reduced to 3.8 GWh for the intra-hour component and to 568 MWh for the real-time component as shown in Fig. 7.

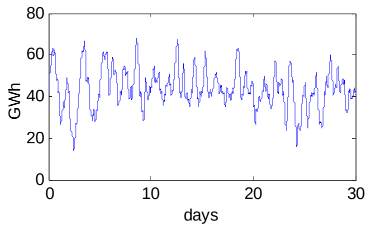
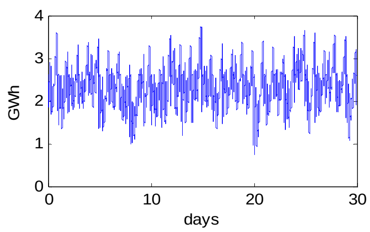
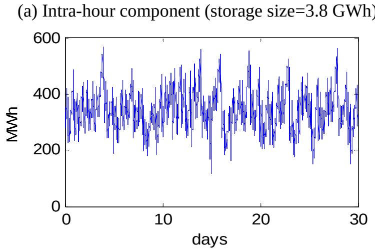


Fig. 6. State of charge profile for energy storage in Aug 2030 (storage size=68.05 GWh)



(a) Intra-hour component (storage size=3.8 GWh)



(b) Real-time component (storage size=568 MWh)

Fig. 7. State of charge profile for intra-hour and real-time components in August 2030

III. Conclusions

This paper presents a novel methodology of characterizing maximum energy storage requirements for a balancing area or their interconnection. The approach is particularly useful for the system planning community as well as for the energy storage providers. The introduction of a cycling taxonomy (slow-cycle, intra-day, intra-hour, intra-minute and real-time) offers a new way to characterize the key features of energy storage technologies needed in the system.

IV. Reference

Comment [YM2]: Make them all consistent with the IEEE standards

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