



## Grid-side control technology research on the distributed hybrid energy storage system

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### Abstract

The ever increasing trend of renewable energy sources (RES) into the power system has increased the uncertainty in the operation and control of power system. The vulnerability of RES towards the unforeseeable variation of meteorological conditions demands additional resources to support. In such instance, energy storage systems (ESS) are inevitable as they are one among the various resources to support RES penetration. However, ESS has limited ability to fulfill all the requirements of a certain application. So, hybridization of multiple ESS to form a composite ESS is a potential solution. While integrating these different ESS, their power sharing control plays a crucial role to exploit the complementary characteristics of each other. Therefore, this article attempts to bring the numerous control strategies proposed in the literature at one place. Various control techniques implemented for HESS are critically reviewed and the notable observations are tabulated for better insights. Furthermore, the control techniques are classified into broad categories and they are briefly discussed with their limitations. From the carried-out analysis, the challenges faced towards the implementation of HESS for standalone and grid connected micro grid systems are presented. Finally, the future directions are laid out for the researchers to carry out the research and implementation of HESS technologies. Overall, this article would serve as a thorough guide on various control techniques implemented for HESS including their features, limitations and real-time applications.

The distributed energy storage (DES) segment of the energy storage market currently has the highest growth rate in the sector. As incentives for development and deployment have been introduced and costs have fallen, the number of DES projects both in the United States and globally has increased significantly (see Figure 1). The growth of DES is closely linked to the rapid deployment of behind-the-meter solar, high commercial/industrial tariff demand charges, demand management incentives, and self-generation incentives. Recent announcements by major manufacturers have brought DES further into the spotlight. For example, in mid-2015, Tesla launched a DES product line and battery factory to deploy DES in large volumes. Tesla's low-cost home battery pack, the Power wall, reportedly captures and stores up to 10kWh of energy from wind or solar and retails for up to \$3,500. In the first week alone, Tesla received orders for the Power wall worth greater than \$200 million in revenue. Other major manufacturers have made similar announcements with expanded DES product offerings, including Samsung<sup>3</sup>, LG Chem<sup>4</sup>, and Saft<sup>5</sup>. Due to this rapid evolution of DES, the U.S. Department of Energy (DOE) Electricity Advisory Committee (EAC) undertook a review of the DES market. Two of the EAC's subcommittees—the Smart Grid Subcommittee and the Energy Storage Subcommittee—spearheaded the review and on the basis of this assessment will make joint recommendations to DOE regarding its DES strategy and activities. Members from both Subcommittees contributed to the working group for this review.

**Keywords:** Energy management and operational control, grid battery energy storage systems, dynamic energy management, hybrid energy storage system, power management in micro grid

### Introduction

Smart grid technologies bring the functionality of computers and communication systems to bear on the power supply network. There are a number of ways in which smart grid technologies can be used to help maintain system stability. One of the most important is through automated demand management. By setting up rapid communication systems that link the grid operator to the consumers, signals can be passed from one to the other to control the loads that are connected at different times.

At an industrial level, certain large consumers will agree to a reduced tariff with the condition that if demand begins to outstrip supply, they will temporarily shut down some or all of their operations in order to reduce the system load. This type of demand management can be fully automated with shutdown activated at different trigger points. However, in many cases, the companies involved will require notice of an impending cutoff in order to shut down in a controlled manner. Similar control can, in principle, be introduced at

the domestic level too, allowing a considerable level of control over demand. One way that this can be implemented is through smart domestic meters which communicate directly with the system controller. These meters, in turn, have control of certain types of domestic appliance such as washing machines or air conditioning systems. With two-way communication, the system control center can ask these appliances to shut down temporarily when demand is high. Equally importantly though, some devices may also be asked to switch on when there is a surplus of supply over demand, as for example when there is excess wind power on a system.

Smart technologies can also help with the supply side of the grid. One simple application is the use of advanced weather forecasting to predict the output of wind and solar plants attached to the grid. With these forecasts in place, the system controller can schedule additional capacity to come online when output from these renewable plants is expected to be low and plan to take these additional units off line

when output rises again. By providing a longer time frame for this type of scheduling to take place, forecasting can reduce the cost attached to adding or removing capacity.

Another useful tool is the virtual power plant. With sufficient communication capacity, it is possible, for example, to aggregate wind plants from different geographical locations and operate them as if they were a single power plant. While wind is unpredictable, the level of unpredictability is much smaller when averaged over a large geographic area. A virtual wind farm of this type will therefore provide a much more reliable output than a single wind farm at specific location. Moreover, different types of power plant can be aggregated: wind and solar plants are often complementary over a long time scale, for example, with wind output greater in the winter while solar output is higher in summer. The more reliable the output from these virtual plants, the more valuable the power and the higher the price that can be charged for delivery of the power.

Smart grid technologies utilize recent cyber advancements to increase control and monitoring functions throughout the electric power grid. The smart grid incorporates various individual technical initiatives

Such as:

Advanced Metering Infrastructure (AMI),

Demand Response (DR),

Wide-Area Monitoring, Protection and Control systems (WAMPAC) based on Phasor Measurement Units (PMU),

Large scale renewable integration in the form of wind and solar generation, and

Plug-in Hybrid Electric Vehicles (PHEV).

Of these initiatives, AMI and WAMPAC depend heavily on the cyber infrastructure and its data transported through several communication protocols to utility control centers and the consumers.

Wide Area Monitoring, Protection and Control systems (WAMPAC), leverages the Phasor Measurements Units (PMUs) to gain real-time awareness of current grid operations and also provides real-time protection and control functions such as Special Protection Schemes (SPS) and Automatic Generation Control (AGC), besides other emerging applications such as oscillation detection, and transient stability predictions.

While communication is the key to a smarter grid, developing and securing the appropriate cyber infrastructures and their communication protocols is crucial. WAMPAC can be subdivided further into its constituent components namely, Wide- Area Monitoring Systems (WAMS), Wide-Area Protection Systems (WAP), and Wide-Area Control (WAC). PMUs utilize high sampling rates and accurate GPS- based timing to provide very accurate, synchronized grid readings. While PMUs provide increasingly accurate situational awareness capabilities, their full potential will not be realized unless these measurement data can be shared among other utilities and regulators. Additionally, power system applications need to be reexamined to determine the extent to which these enhancements can improve the grid efficiency and reliability. The development of advanced control applications will depend on WAMS that can effectively distribute information in (WAP), but the most common one

among them is Special Protection Schemes (SPSs). The North American Electric Reliability Council (NERC) defines SPS as an automatic protection system designed to detect abnormal or predetermined system conditions, and takes corrective actions other than and/or in addition to the isolation of faulted components to maintain system reliability. Such action may include changes in demand, generation (MW and MVAR), or system configuration to maintain system stability, acceptable voltage, or power flows. Some of the most common SPS applications are as follows: generator rejection, load rejection, under frequency load shedding, under voltage load shedding, out of step relaying, VAR compensation, discrete excitation control, HVDC controls.

Until the advent of PMUs, the only major Wide-Area Control mechanism in the power grid was Automatic Generation Control (AGC). The AGC functions with the help of tie line flow measurements, frequency and generation data obtained from Supervisory Control and Data Acquisition (SCADA) infrastructure. The purpose of the AGC in a power system is to correct system generation in accordance with load changes in order to maintain grid frequency at 60 Hz. Currently, the concept of real-time WAC using PMU data is still in its infancy and there are no standardized applications that are widely deployed on a system wide scale, though there are several pilot projects in that area. Some of the potential WAC applications are secondary voltage control using PMU data, Static VAR Compensator (SVC) control using PMUs, and inter-area oscillation damping.

### Cyber-attack Taxonomy

A generic Wide-Area Monitoring, Protection and Control (WAMPAC) architecture is shown in Figure along with the various components involved. The system conditions are measured using measurement devices (mostly PMUs), these measurements are communicated to a logic processor to determine corrective actions for each contingency, and then appropriate actions are initiated, usually through high-speed communication links. The inherent wide-area nature of these schemes presents several vulnerabilities in terms of possible cyber intrusions to hinder or alter the normal functioning of these schemes. Even though SPSs are designed to cause minimal or no impact to the power system under failures, they are not designed to handle failures due to malicious events like cyber-attacks. Also, as more and more SPSs are added in the power system, it introduces unexpected dependencies in the operation of the various schemes and this increases the risk of increased impacts like system wide collapse, due to a cyber-attack. It therefore becomes critical to reexamine the design of the Wide-Area Protection schemes with a specific focus on cyber physical system security.

Also presented in the figure is a control systems view of the power system and the wide-area protection scheme. The power system is the plant under control, where the parameters like currents and voltages at different places are measured using sensors (PMUs) and sent through the high-speed communication network to the Wide-Area Protection controller for appropriate decision making.

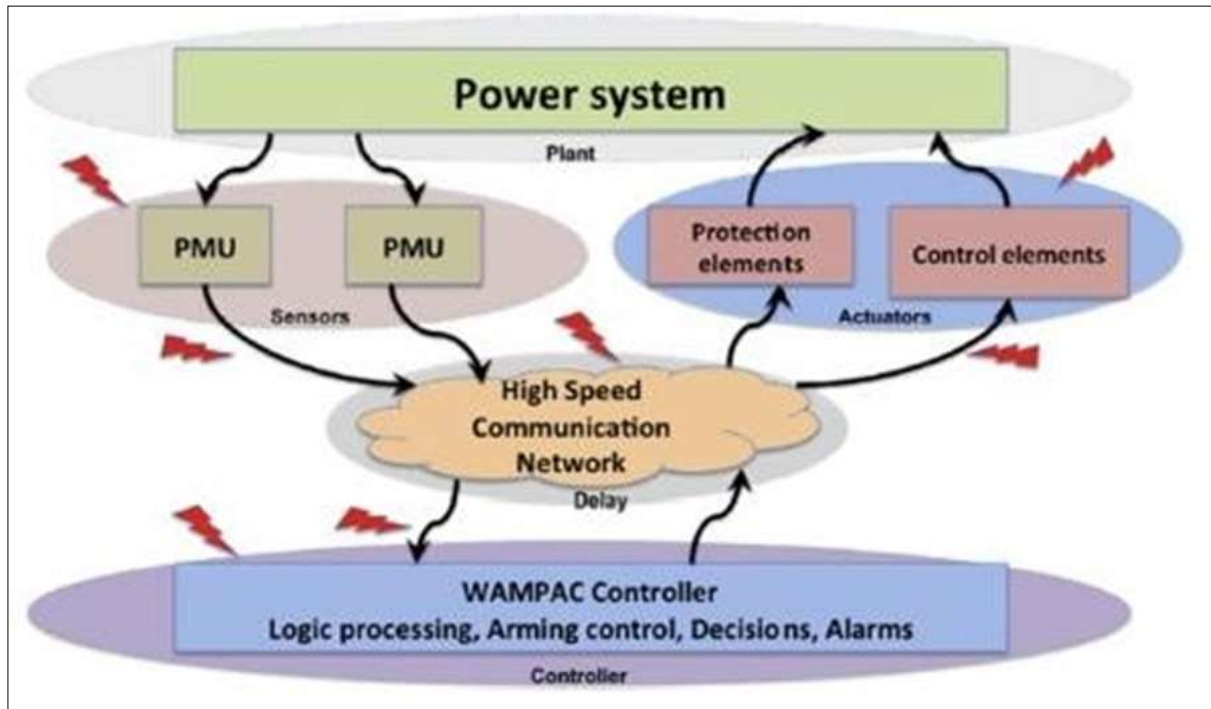


Fig 1

The controller decides based on the system conditions and sends corresponding commands to the actuators which are the protection elements and VAR control elements like SVC and FACTS devices for voltage control related applications. There are different places where a cyber-attack can take place in this control system model. The cyber-attack could affect the delays experienced in the forward or the feedback path or it could directly affect the data corresponding to sensors, the actuators or the controller.

### Grid Battery Energy Storage Systems

Battery energy storage systems (BESSs) are an important method to store energy with their flexible configurations for different application requirements without geographical conditions. Their fast responses can simultaneously input or output active and/or reactive power. Compared with other energy systems, BESS has relatively higher energy efficiency. The said advantages make BESS an irreplaceable option in centralized and distributed new energy integration, and ancillary grid operations. With the rapid development in recent years of the electric vehicle (EV) industry, battery manufacturing and application related technologies have made great progress. Battery life and cost issues have further improved, making battery storage the most popular and fastest-growing type of energy storage technology. Currently, the application scale and scenarios of a BESS is larger, and more diverse. The emergence of a 100-megawatt BESS contributes a positive role in the large-scale integration of this new energy along with the safe and stable operation of the power grid. Distributed and mobile energy storage is also a rapidly developing technology in the field of distribution network smart management of a renewable energy power resource, and intelligent transportation. With

their rapid development and improvement, energy storage systems with large-scale integration and distributed applications are expected to have multiple application modes and diverse applications. Ensuring the positive role of a centralized or distributed BESS in the new energy integration support and grid safety control, achieving multiple objectives, multi-level collaborative optimization control and efficient operation is an important goal for the future development of a BESS. This paper reviews the research results and developmental status of a BESS at the power supply side, grid side and power distribution side. A forecast of the key technologies, application prospects, and operation modes of a BESS is included in this study. This paper is organized as follows. Section II presents an overview of BESS monitoring and applications. Section III presents a BESS in the power supply side. Section IV describes a BESS in the power grid side.

Applications of a BESS in the power distribution side are discussed in Section V. Section VI presents the conclusions and future directions for grid BESSs.

### Overview of bess monitoring and Applications

Lithium-ion, lead-carbon, sodium-sulfur, and redox-flow batteries are the main battery technologies that are used for energy storage. With the continuous release of support policies and improvements of the manufacturing processes, the energy storage battery technology has developed rapidly. Its key technical indicators, such as battery safety, cycle life, and energy density, have greatly improved. On the other hand, the application costs have dropped significantly. On this basis, the scale of global energy storage applications has maintained its rapid growth (see Fig. 1) creating an optimistic prospect for the technology.

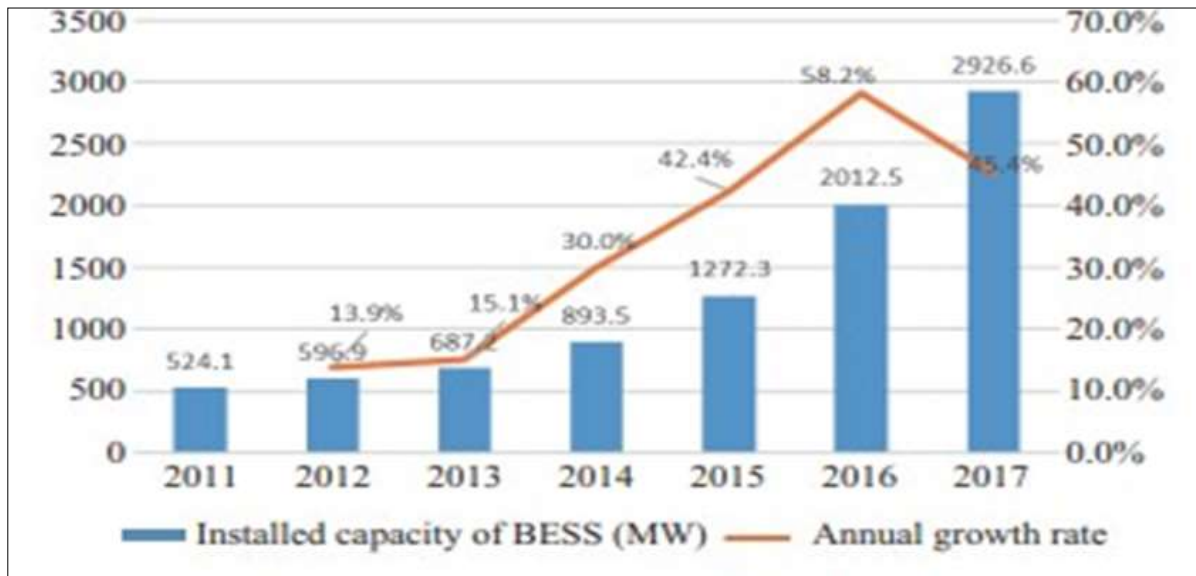


Fig 1: Global BESS application scale in recent years (Source: CNEA)

BESSs have been widely used in all aspects of power systems and have become a new focus in the development of the power industry. According to the experience of global energy storage applications, the energy storage application scenarios can be divided into three categories and 16 types according to the power supply side, the power grid side.

#### Applications of a bess in the power grid side

The application of a BESS in the power grid side has higher requirements for equipment and network architecture. It is necessary to establish an independent communication loop to directly communicate with the PCS as a BESS needs to perform various functions such as emergency power support. A typical network architecture of a BESS at the power grid side is shown in Fig. 8.

#### Verification of the Proposed ESOC Evaluation Method

To verify the proposed ESOC evaluation method, a simplified model consists of a cascaded HESS unit connected to a load is built in the Matlab/Simulink platform. The HESS unit switches between different modes and the ESOC is calculated in real-time. The rated capacity and initial SOC condition of the battery and supercapacitor in this HESS unit is shown in the Table

Table: The rated capacity and initial SOC condition of the battery and super capacitor in this HESS unit.

The simulation was taken in four stages (0–3, 3–5, 5–10, 10–20 min), corresponding to operation mode 1, 2, 1 and 3 respectively. The details of the three operation modes are introduced in Section II (a). Figure 6 shows the changes in ESOC and its normalized value  $\langle \text{ESOC} \rangle$  during the four stages.

The HESS unit was operating in mode 1 from 0 to 3 min and from 5 to 10 min. In these time periods, only the batteries inject power to the load and the super capacitor is standing by. That means that the remaining energy in the HESS unit totally depends on the remaining energy in the battery. Therefore, the remaining energy in the ESOC is completely determined by the SOC of the battery.

The HESS unit was operating in mode 2 from 3 to 5 min, in the time period when instantaneous extreme high power demand occurs. The provided power from HESS to the load almost all comes from the super capacitors. Thus, the

remaining energy in the HESS unit totally depends on the remaining energy in the super capacitors.

The capacity of the super capacitors is much smaller than that of the battery, so there is a significant drop in ESOC.

Figure: Simulation result

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