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Utilization of Battery Energy Storage Systems (BESS) in Smart Grid : A Review

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Abstract

The uncertainty in fuel cost, the ageing of most existing grid, the lack of utilities' supply capacity to respond to the increasing load demand, and the lack of automatically power restoration, accelerate the need to modernize the distribution network by introducing new technologies, putting the smart grid (SG) on spot. The aim of this paper is to carry out a detailed survey of the major requirements of (SG) and discuss the operational challenges arising from the integration of distributed generation (DG) in distribution networks (DN). These requirements dictate the necessity to review the energy and communication infrastructure, the automatic control, metering and monitoring systems, and highlight the features of smart protection system for a robust and efficient distribution grid. In addition, the paper aims to classify the energy storage systems (ESS) and explain their role for utilities, consumers and for environment. This includes the pumped hydro systems (PHS) and compressed air systems (CAS), battery energy storage systems (BESSs), double layer and superconductive capacitors, and electric vehicles (EVs). Since BESSs emerged as one of the most promising technology for several power applications, the paper presents an overview of their main features, management and control systems and operational modes. A survey about the utilization of BESSs in power system is presented.

Key words

Smart Grid (SG), Energy Storage systems (ESS), Battery Energy Storage Systems (BESS), Battery Management Systems (BMS), Battery Storage Applications.

1. Introduction

Existing power grids are generally unidirectional , used to carry power from central generating stations to area with a large number of customers. Most generating stations operate at low efficiency not exceeding 40% and without recovering wasted heat. This hierarchical topology of power network, coupled with lagging investments in infrastructures could decrease the system stability in case of any rise in electric demand. The fluctuation in fuels cost, together with the inability of the of utility companies to expand their generation capacity in line with the rising demand for electricity, accelerate the need to modernize the distribution network by introducing new technologies that can help with the demand side management and revenue protection making the network smarter to operate. Smart grid is a network that uses information, cyber secure, communication technologies, and computational intelligence to create an automated and distributed advanced energy delivery network to achieve a safe, reliable, efficient, and sustainable system. It coordinates the need and capabilities of all generators, grid operators, end users, and electricity market stakeholders to operate all part of the system as efficiently as possible, minimizing costs and environmental impacts while maximizing system reliability, and stability [1].The "Two way flow of electric power'', which is one of the major characteristic of this kind networks, means that the electricity could be generated in the distribution grid benefiting from power generation by using solar panels ,wind turbines or other sources of renewable energy. By this way, the electricity can also fed back into the grid by users. The SG could respond to events that occur anywhere in the grid, such as power generation, transmission, distribution, and consumption, and adopt the corresponding strategies [2,3].Table I gives a comparison between existing grid and SG .

Table I. Comparison between existing and smart grid

	Traditional Grid	Smart Grid
Communication	One Way	Two Way
Generation	Centralized	Distributed
Sensors	Few	Throughout
Monitoring	Manual	Self
Restoration	Manual	Self
Reliability	less	reliable
Efficiency	less	high
Oil consumption	high	less
CO2 emission	high	less
Consumers Choices	Few	Many
Cost	less	high
Protection	Failures and Blackouts	Adaptive and islanding

The paper is organized as follows: compression between current and the suggested smart grid. A highlight of the main requirements of a smart grid. It also gives an explanation of the role of energy storage systems in power system application for utilities, environment as well as for consumers. It classifies the different categories of energy storage systems and an overview of battery energy storage system. A section explains the features of a battery management system and finally a review of the different applications of battery storage schemes in power system.

2. Smart Grid Requirements

A SG consists of five subsystems: Energy Infrastructure, Smart Metering System, Communication System, Monitoring, Management and Automation system and Smart Protection system [3]. Each subsystem will be briefly discussed in the following sections.

A. Energy Infrastructure

The bidirectional flow of power in Smart grid does not only lie on the conventional generation stations, but also it introduces the concept of generation in distribution system. In spite of this increases the flexibility and reliability of the system, it complicates the power flow. Distributed generations (DGs), virtual power plants (VPP) and micro grid (MG) are considered to be the main elements of SG energy infrastructure. A brief description of each element is given below.

1) Distributed Generation (DGs)

The DG takes advantages of distributed energy resources (DER), such as wind and solar panels, with aim to improve the power quality. Each DER is connected to the power grid via power electronic devices and a switching power interface to control the current drawn to the SG [4]. DG has their own associated devices for communication, power flow monitoring, smart metering systems, protection equipment, energy storage systems, automatic voltage control, and dynamic line rating. Nonetheless, the integration of DGs in the power network is not problem free. Their high integration could cause wide fluctuations resulting from the renewable resources on one hand, and insulation damage to equipment when the voltage increases on the other hand.

2) Virtual Power Plants (VPP)

Due to the associated operational problems of DGs integration, it is necessary to develop active control strategies to facilitate their integration. Otherwise; the distribution network could face a lot of operational problems. For such reason, the Virtual Power Plant (VPP) is presented to facilitate and control the DGs in the distribution network.VPP, represented in figure 1 is an information and communication system with centralized control over an aggregation of distributed generation, controlled loads, and storage devices .Its main role is the management of the electric flow of energy within the main grid [5]

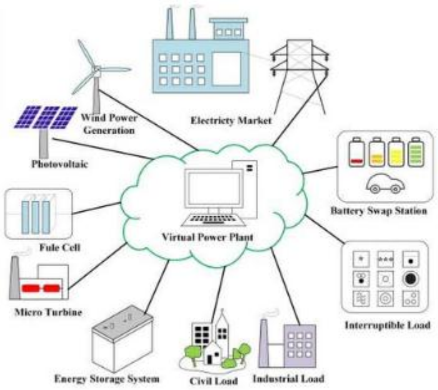

Figure 1 Virtual Power Plant

3) Micro grid (MG)

Another requirement for DGs integration, is the micro grid (MG), as shown in figure 2, which consists of different distributed power sources at low voltage side of the distribution network, which could be operated into two modes [3,6]. The first is in grid mode, where the customers share power generated from their DGs with the main grid. The second mode is islanded mode. In case of emergency or power shortage, the MG shift to islanded mode automatically, where the customers are disconnected from the main grid, but still could be supplied from their DGs. This ability of islanding mode could provide a high level of reliability in case of any disturbances. However, the control of large number of DGs is facing many operational and technical problems such as the bidirectional power flow in grid connected mode, the frequent change of voltage and frequency during the connection and disconnection of DGs, and few others. For this reason, many control schemes [6] and protection approaches [7] should be investigated to maintain a high level of power quality, stability, power flow balancing and reliability.

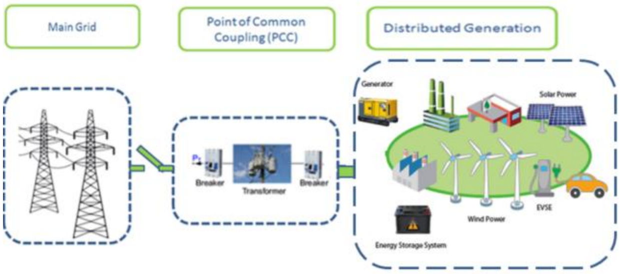

Figure 2 Micro-grid

B. Smart Metering System

In SG, power consumption information need to be gathered, integrated and analyzed for optimum decision making on both consumer and utility side. Therefore, metering, monitoring and communication systems should be upgraded and modified for a secured, précised information system. Automatic Meter Reading (AMR) is introduced for one way communication grid, for automatically collecting the consumption and the data from the energy meters and sending them to a central data base for billing, troubleshooting and analyzing [2, 3]. Due to its one way communication, the utilities could not take any online corrective action based on the measurements received from the meters. Thus, this type of meter does not support the transition to smart grid. Automatic Meter Infrastructure (AMI) is then introduced for two way communication systems. By this way, utilities can meet their basic target of load management and instantaneous information about load demand for a better power system operation. Smart Meters (SM) are similar to AMI, and sometimes they could be considered the most essential component of the AMI. They record information hourly or sub- hourly and send the gathered data to utilities for power generation and distribution decision making with information feedback to encourage customer to reduce consumption.

C. Communication System

Communication systems in SG should support the bidirectional flow of power and information between the different sections in SG, as it enables system sensing and monitoring , utility and customers' linkage to detect the real time demand, and self-correction capability in case of any failure. The main requirements and the challenges of communication systems in SG, such as the quality of service, reliability, security, and scalability are discussed in [4]. SG communication systems could be wired or wireless. Installing large wired communication system for monitoring the power grid costs time and money. Moreover, whenever any fault occurs in the system, communication becomes difficult, sometimes even impossible. Only wireless sensor network can resolve this kind of problems. Low cost wireless sensor has paved the way for grid automation, real time monitoring and remote control of system elements such as primary and secondary sub stations, power lines, capacitor banks, feeder switches, fault indications and other physical facilities. Wireless Sensor Networks (WSNs) with their affordable low cost and numerous desirable features enable utilities to monitor their remote facilities any time with applications such as Supervisor Control and Data acquisition System (SCADA).

D. Smart Monitoring, distributed automation and management System

Distributed automation (DA) is the use of SCADA for the remote monitoring and control of the distribution network [8]. It also integrates the real time operation information, grid structure, equipment status, customer automation control, data communication and information management, that realize the efficiency and reliability improvement on one hand and the management of distribution grid on the other hand due to the flexible control. Network reconfiguration, fault Identification, service restoration, load management, load shedding and others are the application of distributed automation in SG [8]. Management in SG is an essential application of DA in SG. It mainly focus is onto three goals: the first goal is energy efficient and demand profile improvement through shifting, scheduling or reducing the demand in order to reshape the demand profile in peak hours [3], the second goal is minimizing the energy losses which is very challenging due to the integration of renewable resources and distributed generation, the third goal is the reduction of CO2 emission for a secured green environment, through an optimized cost for utilities. However, minimizing generation cost is not directly equivalent to minimum emission as the cost of renewable energy source is not always the lowest. In order to realize the previous management objectives, optimization and intelligent systems, and others tools are reviewed in [3].

E. Smart Protection System

A smart protection system should have many characteristics to improve the reliability, the stability and the security of power system [3]. A smart protection system should have:

1. Predictive ability to prevent failures from happening by expecting the weak points in the network such as the failures due to load fluctuation, the thermal capacities of generators and others.
2. Self-correction capability after a fault by locating the fault and isolating it to avoid cascade failures.
3. Automatic network reconfiguration by finding all the plans to supply the customers to avoid outage considering the radial configuration, minimum losses and the minimum time of restoration through changing the state of the switches by employing optimization and intelligent techniques.
4. Maintain the power system reliability by reducing the impact of DGs on the grid without scarifying the system reliability.
5. MG protection, as they could work in two modes in grid and in islanded mode. New protection schemes are developed in this area [7]
6. The ensure security and privacy to prevent attackers from penetrating the software and getting access of control to destabilize the grid in unpredictable way.

3. Energy Storage System Role

This section discuss the features of integrating the advanced electric energy storage technologies for both utilities and consumers side, taking into account the impact on the consumer the environment, as represented in figure 3. The following points highlight the benefits aimed to be achieved through energy storage systems [9]:

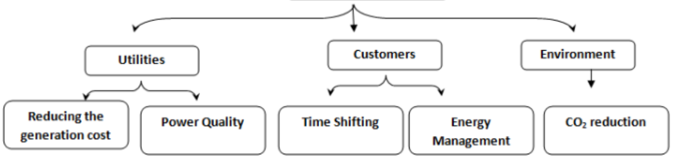

Figure 3 EES role in power system

1. Reducing generation cost is one of the major benefits of the integration of ESS into the

utilities, by storing the electric power generated of the less cost plants during night, and discharge them during peak hours maintaining a secured continuous supply for all customers .

2. Another target of ESS, is keeping the reliability and the continuity of power supply. Many electric utilities proposed the renewable energy resources as alternative resources. The uncertainty of these resources is considered one of their main challenges, as they depend on weather conditions. Then ESS could store the energy when it is available and used when it is needed. By this way they could minimize the environmental impacts caused by the combustion of fossil fuels during the traditional generation process, reducing the fuel used on one hand, an reducing the environmental and the global warming problems on the other.
3. ESSs could also be used by the utilities to ensure the electric power system stability under the unexpected load demand and generation conditions. They could replace the online spinning reserve that is synchronized to the grid and supplied by part loaded generators operating at reduced efficiency, thus, reducing the thermal losses and the inefficient operation of the part loaded generators.
4. In addition, ESSs are not used only to mitigate the short term power loss as they are commercially available and cost effective such as uninterruptable power supply (UPS), but also they could be installed as a substitute for emergency generators during an outage.
5. Furthermore, considering the consumers side, they could also benefit by using the electric storage systems in the off peak as low price tariff, and discharging the energy when the demand is high. This is known by electrical energy time shifting. This could lead to an efficient utilization of energy as they could reduce the cost of their electric consumption bill on one hand, and it is known by End User Energy Management. On the other hand, ESS system owners could benefit by selling the stored energy to other customers or to the electric utilities in the peak hours, which they could benefit financially from their storage batteries.

4. Energy Storage Systems Selection and Classification

Currently, there are two factors that characterize the selection of an ESS [10]. The first is the energy that could be stored in the device. The second is the rate at which the energy could be transferred in or out the device. The appropriate selection is based mainly on the application requirements response time, energy storage, efficiency required and life time as illustrated in table II.

According to [9], the ESS is classified into 5 categories: mechanical, electrochemical, chemicals, electrical and thermal as shown in figure 4. The following section discusses the most common three storage systems used for power applications.

Table II ESS selection consideration [11]

	Matching Power demand	Providing back up power	Enabling the RE	Power quality
Discharged power	(1:100) MW	(1:200)MW	20kW:10MW	<10ms :10
Response time	<10 min	10ms:10 min	<1ms	<20ms
Energy Stored	(1:1000) MWh	(1:1000) MWh	(10kWh:200MWh)	50kWh: 500kWh
Efficiency	High	Medium	High	Low
Life time	High	High	High	Low

A. Mechanical Energy Storage system

1) Pumped Hydro System (PHS)

PHS, shown in figure 5(a), uses two water reservoir storage areas, one above the other, to store energy. This is done by pumping water from the lower one to the upper one during off-peak periods and then, during peak-load hours, allowing the water to flow from the upper reservoir to the lower one, turning a generator and converting the hydro-potential energy into electricity .Their long life time and their high efficiency are the main advantages. However, the dependence on topographical conditions and large land use are considered the main drawbacks [9, 10, and 12].

2) Compressed Air Energy System (CAES)

CAES, shown in figure 5(b), uses excess power generated by power stations to compress air during off peak periods. During peak periods this air is then decompressed in a compression chamber before being fed to turbines, increasing energy production during peak periods [9, 12]. Their advantages could be summarized in their large capacity to store the electric energy, their low trip efficiency and their geographic locations are their main disadvantages [9].

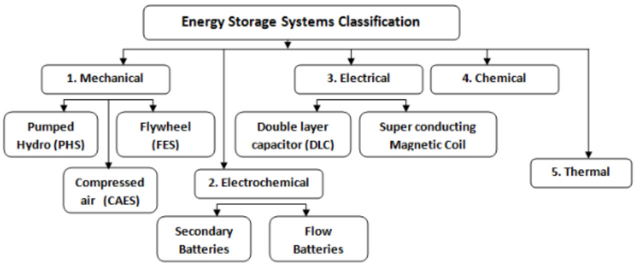

Figure 4 ESS Classification

3) Flywheels

Flywheels, shown in figure 5(c), uses off peak energy to rotate a rotor attached to a wheel within a vacuum. Energy is conserved in kinetic energy until it is needed during high demand period; this energy is used to generate power [12]. They take up relatively little space, have lower maintenance requirements compared to batteries, and have a long life span [13]. However, flywheels have a high level of self-discharge due to air resistance and bearing losses and they suffer from low current efficiency [9].

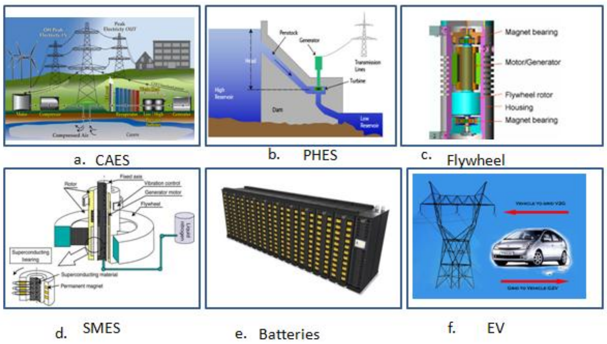
a. CAES b. PHES c. Flywheel d. SMES e. Batteries f. EV

Figure 5 ESS Categories

B. Electrochemical Storage Systems

Electrochemical storage systems, shown in figure 5 (d), are divided in two types: secondary battery, and flow batteries. Secondary batteries store energy in chemical during charging and discharge electrical energy when connected to a load. Flow batteries are rechargeable ones. The electrolyte are stored separately in tanks and pumped through an electrochemical cell that converts chemical energy to electric and vice versa. The amount of energy stored in the battery depends on the volume and the size of the electrolyte in the tanks, while the power depends mainly on the speed of ion transfer across the membrane [14]. Lead Acid (LA), Nickel Cadmium (NiCd), Lithium ion (Li ion), Sodium Sulphur (NaS), and Sodium Nickel Chloride (NaNiCl) are the different kinds of secondary batteries. Vanadium Redox, Hybrid and Zinc Bromine are the main common types of Flow batteries. Based on [9,15,12,13,16]], a comparison between the different types of batteries is given in table III .

C. Electrical Storage Systems

Double layer Capacitor (DLC) and Superconductive Magnetic Energy Storage system (SMES) represent the electrical category for ESS. Super capacitors are electrochemical double layer capacitors that store energy into the electric field. They do not require any heating or cooling, they do not need any maintenance as they do not have any moving parts and their life time is measured in decades, so that they are considered very efficient [13]. They have high power density, but relatively low storage ability when compared to batteries. Superconducting magnetic energy storage (SMES), shown in figure 6 (e), is a type of EES that store energy in the magnetic field created by the flow of dc current in a superconducting coil [11,12,13]. The coil can discharge very quickly when it is necessary. They are very efficient and have very fast response .On the other hand; they are very expensive due to the superconductive material and need cooling, thus they are used for short duration energy storage applications such as power quality [9, 11, and 13].

Table III BESS Comparison

	Applications	**Advantages**	**Disadvantages**
LA	-Emergency power supply -Standalone systems with PV, wind. -Starter batteries for vehicles	Low Cost	-Low Energy density -Their capacity decrease when large power is discharged
NiCd	-Power tools -Mobile phones -laptops	-Low maintenance cost -Resistance to high temperatures -Long life span	Expensive toxic
Li ion	-Cell phones -Electric bicycles -Electric cars -Laptops	-High energy density -Long life span -Low maintenance	Too Expensive
NaS	-Combined power quality -Time shifting - renewable integration	-High power -High energy density -Low cost	As their operating temperature reachs [300 - 350 °C], then they require a heat source, thus reducing the battery performance, efficiency and increase their cost
VRFB	large power applications -Power quality control	Large capacity Long life span Low cost Fast response	Low energy density
Zn/Br	Still new technology	High power High energy density	Toxic

D. Electric Vehicles

Electric vehicles (EV), shown in figure 5(f), are developing in recent years. They are connected to grid and can retrieve and inject a controlled amount of electric energy. On one hand they could be considered as active load that increases the demand during charging mode. On the other hand they could be operated as storage units to supply the customers while they are parking during discharging mode. Coordinated charging schedules could minimize the annual peak load, decreases the system losses and increase the power factor of the distribution grid [17].

5. Battery Energy Storage Overview

A typical BESS consists of a battery bank where multiple batteries are connected in series parallel configuration to provide the desired storage capacity. A bidirectional power electronic converter could be attached to the battery bank. Thus both real and reactive power can be delivered or absorbed independently according to the power system demand requirements. The inverted voltage from the dc battery source is always different than the grid voltage. Therefore, a transformer is used to convert the BESS output to match the transmission and distribution voltage level [18-20]. Therefore, the operation of each of them is coordinated by a battery management system (BMS), while the overall operation of all the system is coordinated by a supervisor control.

6. Battery Management System

To help the BESS to operate in optimum conditions , BMS is required for the following reasons [15]:

1. Reading all the collected data during the operation, such as the current, the voltage, the temperature through the supervisor control. Based on this information, it could in turn estimate many variables, such as battery state of charge (SOC) and battery state of health (SOH) based on physics based models. SOC represents how much charges is left in a battery over a single cycle, while SOH represents how much the battery capacity remains for the present cycle compared to the original battery capacity.
2. Estimating the time remaining based on the applied load profile.
3. Providing optimal charging pattern.
4. Allowing a safe operation of BESS based on the thermal management and by maintaining the safe operation between the current and the voltage limits.

7. BESS application in power system

Many industry experts believe that the use of energy storage technologies including the batteries, are crucial for many application as summarized in figure 6.

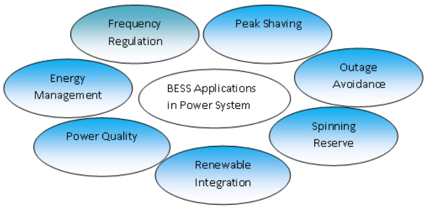

Figure 6 BESS Applications

A. Frequency Control

Due to the inversely proportional relation between the frequency and the load, any significant increase in load cause the frequency to slow down, as the frequency is measured through the rotating speed of the generator shaft. Similarly, the frequency may increase in case of load loss due to any threshold. Thus keeping the frequency within a tight tolerance requires the amount of power produced at any time match the demand. A certain amount of active power, usually called frequency control reserve, is kept available to perform this control. Three levels of control are generally used to maintain this balance between load and generation: primary, secondary and tertiary control [21]. Primary frequency control is a local automatic control that adjusts the active power generation of the generating units and the consumption of controllable loads to restore quickly the balance between load and generation and counteract frequency variations. All the generators that are located in a synchronous zone are fitted with a speed governor to perform this control automatically. In particular, it is designed to stabilize the frequency following large generation or load outages. While primary control limits and stops frequency excursions, secondary frequency control is suggested to bring the frequency back to its target value through a centralized automatic control schemes. Only the generating units located in the area where the imbalance originated should participate in this control. It is mainly used in all large interconnected systems because manual control does not remove overloads on the tie lines quickly enough. Tertiary frequency control refers to manual changes in the dispatching and commitment of generating units. This control is used to restore the primary and secondary frequency control reserves, to manage congestions in the transmission network, and to bring the frequency and the interchanges back to their target value when the secondary control is unable to perform this last task. BESS are not only used due to their fast response in providing the active power compensation during under frequency events, but also they are used to save real power in over frequency situations. Comparing with conventional generating units, the capacities and the location of BESS are flexible and also their precise control can be much superior to conventional ones [22]

B. Renewable Energy Integration and Outage Avoidance

The integration of renewable energy resources into the power grid is driven, by environmental and economical regulations aiming for reducing the carbon emission resulting from fuel combustion during conventional electric generation on one hand, and reducing the rising price of fuels on other hand Integration of large amounts of renewable resources presents important challenges in terms of load dispatch, reserves and ramping requirements. The uncertainty of renewable energy produced is another problem that affects their large scale integration in the power grid. Solar and wind energy are considered the two largest sources of renewable energy used. Both are unpredictable and weather depended; hence their output can vary significantly. Therefore, a sudden loss of renewable generation could potentially lead to a collapse of voltage and frequency which could have its effect on the power grid stability. Also this variability will cause undesired ramps in the output which create further integration challenges for the grid operators. To tackle these drawbacks, energy storage systems are one of the suggested solutions to integrate renewable energy generation to the existing power networks. By smoothing out the fluctuations and the sudden load changes, the battery energy storage systems could serve as back up sources during transmission line or large generation loss to avoid blackouts which are one of the main concerns of utilities. A research carried out in [23] to study the role of BESS in outage avoidance. A survey on the different controls techniques for BESS for renewable smoothing applications is presented in [24].

C. Energy Management and Peak Shaving

The major role of BESS is to enable the time shifting of energy by storing the energy during off peaks and using it when the demand increases during on peak. By this way, electric energy production will be maintained in constant level. This technique is very efficient for both customers and utilities, as it ensures power quality through the continuous power delivery to the customers on one hand, and realizes the energy management during on peak on the other hand. Many references studied the BESS application in energy management such as [25], where a BESS is proposed for integration of 3kW wind energy to facilitate the match between the energy demand and supply of the household for a better energy management.

8. Conclusion

In this paper, smart grid requirements have been reviewed and the most common energy storage systems have been stated. A comparison between the different battery storage systems has been presented, as they are one of the most promising technologies for several power applications. The features, and the management system for BESS have been explained. Frequency regulation, RES integration, outage avoidance, and energy management are reviewed .

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