Dynamic energy storage for smart grids

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Abstract

Purpose – This paper presents the world's first high voltage utility-scale battery energy storage system in the multi megawatt range.

Design/methodology/approach – The objectives are achieved by the series connection of switching semiconductor devices of the type Insulated Gate Bipolar Transistor (IGBT) and the series and parallel connection of Li-ion batteries.

Findings – After tests at ABB laboratories, where its performance to specification was confirmed, a first pilot will be installed in the field, in EDF Energy Networks' distribution network in the United Kingdom during 2010 to demonstrate its capability under a variety of network conditions, including operation with nearby wind generation.

Practical implications – This holds the development of a distributed dc breaker, the diagnostics of detecting fault locations as well as fault isolation and the balancing of the batteries.

Originality/value – The paper presents the world's first high voltage utility-scale battery energy storage system in the multi megawatt range suitable for a number of applications in today's and future transmission and distribution systems.

Keywords High voltage, Electric cells, Energy supply systems, United Kingdom

Paper type Research paper

1. Introduction

Modern society depends heavily upon electricity. With deregulation and privatization, electricity is becoming a commodity among others. At the same time, growing constraints on the building of new lines are appearing as a consequence of increasing focus on environmental aspects as well as of growing scarcity of land available for the purpose. This invokes a more efficient use of the existing infrastructure rather than building new ones while the need for power transmission capacity increases, making the power transmission capacity more cost effective in a deregulated market. Flexible alternating current transmission systems (FACTS) is an enabling technology available to use the existing lines more effectively (Hingorani and Gyugyi, 1999).

The ever-increasing demand for power, and in the long run the integration of electric vehicles, and the need of reducing CO_2 emissions at the same time, requires the integration of more renewable power and more distributed energy supply into the system without compromising the reliability of the supply. A future electric system is needed that handles those challenges in a sustainable, reliable and economic way. The resulting system will be based on advanced infrastructure and tuned to facilitate the integration of all involved. The forces now driving the development of smart grids are as varied as they are influential. Environmental concerns are increasing around the

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globe, driving the development of renewable energy on a larger scale than ever before. The widespread addition of wind, solar and other renewables give rise to additional operational challenges due to their intermittent nature. A system that can handle a generation mix with a high percentage of renewables will become a necessity for those technologies to realize their full potential.

For intermittent power sources like wind and solar, the challenge is to connect and integrate them without compromising the required reliability at a low reserve capacity level. This requires viable solutions of electrical energy storage both for distributed and bulk power applications. This paper presents a dynamic energy storage system which is based on the Static VAr Compensator (SVC) Light® (Grünbaum *et al.*, 2001a, b), for utility-scale energy storage. This storage system utilizes Li-ion batteries. This development started around 2000 as a technology-driven project. After benchmarking of battery technologies Li-ion has been chosen in 2007. This followed by a system development in close cooperation with the battery manufacturer Saft and the market launch was early 2010. This paper will give first an introduction to smart grids after which the battery energy storage system will be explained. The first pilot installation at EDF Energy Networks in the UK will be presented followed by the electrical storage applications.

2. Smart grids

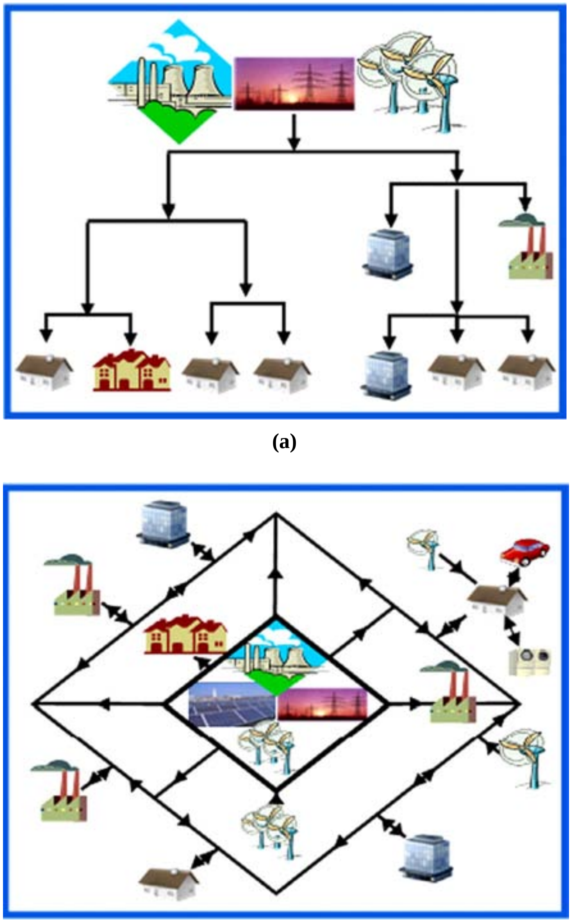
Traditional grids as shown in Figure 1(a) are characterized by centralized power generation and uni-directional power flow. Future grids as shown in Figure 1(b) are characterized by centralized and distributed generation, intermittent renewable power generation, and multi-directional power flow where consumers become also producers. The ever increasing demand for power, and the need of reducing CO_2 emissions at the same time, requires the integration of more renewable power and more distributed energy supply into the system without compromising the reliability of the supply. A future electric system is needed that handles those challenges in a sustainable, reliable and economic way. The resulting system will be based on advanced infrastructure and tuned to facilitate the integration of all involved.

For intermittent power sources like wind and solar, the challenge is to connect and integrate them without compromising the required reliability at a low reserve capacity level. This requires viable solutions of electrical energy storage both for distributed and bulk power applications. Dynamic energy storage will play a vital role in this field.

3. Battery energy storage

The battery energy storage is an add-on to the existing SVC Light, ABBs voltage source converter (VSC)-based FACTS device (Hingorani and Gyugyi, 1999), designed for high-power applications and using series-connected insulated gate bipolar transistors (IGBTs) to adapt to high voltage levels. Figure 2 shows a valve of a typical SVC Light installation with several series-connected IGBT devices.

Therefore, a number of batteries must be connected in series to build up the required voltage level. Figure 3 shows a schematic layout of the dynamic energy storage device consisting of an SVC Light together with a number of series-connected batteries on the DC-side and an artist's view of the dynamic energy storage, DynaPeaQ®. Thus, the device can both inject and absorb reactive power, as an ordinary SVC Light, and active power due to the batteries.



(a)

(b)

Figure 1.
(a) Traditional grid and (b) smart grid

The grid voltage and the VSC current set the apparent power S_{VSC} of the VSC. Note that the peak of the active power of the battery does not have to be equal to the apparent power of the VSC. For instance, the apparent power of the SVC Light can be 50 MVA and the active power of the batteries can be equal to 10 MW.

The core range for DynaPeaQ is 5-50 MW and 5-60 min.

A number of plants for considerably high power and voltage, based on the VSC technology have been built for both industrial (Grünbaum *et al.*, 2001a, b, 2003; Larsson and Ratering-Schnitzler, 2000) and power system applications (Grünbaum *et al.*, 2001a,b; Larsson *et al.*, 2001). Some of the applications that SVC Light performs are:

- reactive power compensation;
- power factor correction;
- dynamic voltage control;

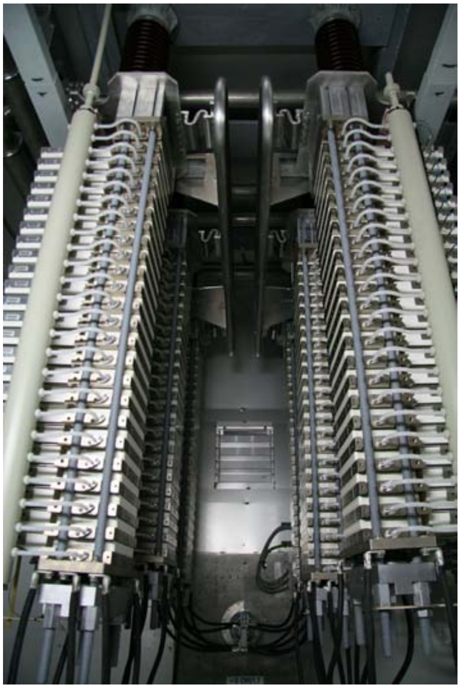


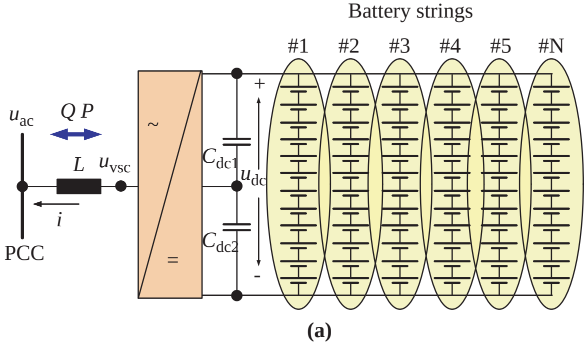
Figure 2.
SVC Light semiconductor switching valves with series-connected IGBTs

- dynamic voltage balancing when the loads are unsymmetrical and rapidly fluctuating;
- active filtering of low-order current harmonics; and
- flicker mitigation of electric arc furnaces

The size of the battery energy storage depends on the application. However, a simple reasoning is to assume that a certain active power P_l is injected into the grid during the load time T_l, thus discharging the battery (Figure 4). The total energy E_l injected into the grid becomes equal to P_l times T_l. To recharge the battery, approximately the same amount of energy must be absorbed from the grid by the battery. When charging the battery with the power P_c, the charging time becomes equal to T_c so that $E_l = E_c$. During a certain time, the battery is in an idle state before the cycle is repeated again.

4. Pilot system

ABB and Saft have developed a pilot of a new high-voltage dynamic energy storage based on high-voltage Saft Li-ion batteries and ABB:s SVC Light to combine dynamic energy storage with reactive power compensation and dynamic voltage control. After tests at ABB laboratories, where its performance to specification was confirmed (Hermansson *et al.*, 2009), a first pilot will be installed in the field in EDF Energy Networks' distribution network in the UK during 2010 to demonstrate its capability under a variety of network conditions, including operation with nearby wind generation. The reactive power rating of this pilot station is 600 kVAr inductive and



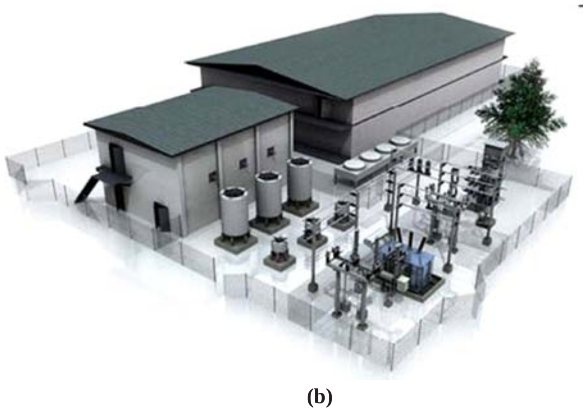
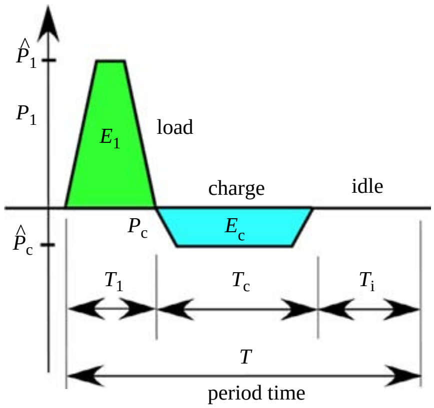


Figure 3.
(a) Single line diagram of DynaPeaQ, the dynamic storage device consisting of SVC Light with series and parallel-connected batteries on the DC side and (b) artist's view of DynaPeaQ



Notes: During the total cycle time T, the battery is discharged to the grid with power P_l during time T_l and charged with power P_c during time T_c; remaining time T_i is idle time

Figure 4.
Battery load cycle

capacitive, the active power rating is 200 kW-1 h and 600 kW-10 min, the nominal line voltage is 11 kV. Some details of the Li-ion battery system are shown in Figure 5.

Table I shows some basic data of the pilot system.

Figure 6 shows a photo of the pilot installation in EDF Energy Networks' distribution network in the UK. It is made to demonstrate the concept.

5. Experimental results

Some tests were made at ABB's laboratories to verify the performance of the system.

Figure 7 shows graphs of a discharge of 200 kW for 1 h and Figure 8 shows an example of 600 kW discharge for 4 min.

In these tests, the system controller is set to keep the power constant, which results in a steadily increasing discharge current when the battery voltage decreases during the discharge.

Figure 9 shows an example of battery charging from a state-of-charge (SOC) = approx. 50 percent, up to fully charged at 100 percent. The charging follows a special procedure in order to avoid overvoltage and overcharging of the battery cells and allow cell balancing to achieve a good homogeneity among the cells. At the start, the charging is

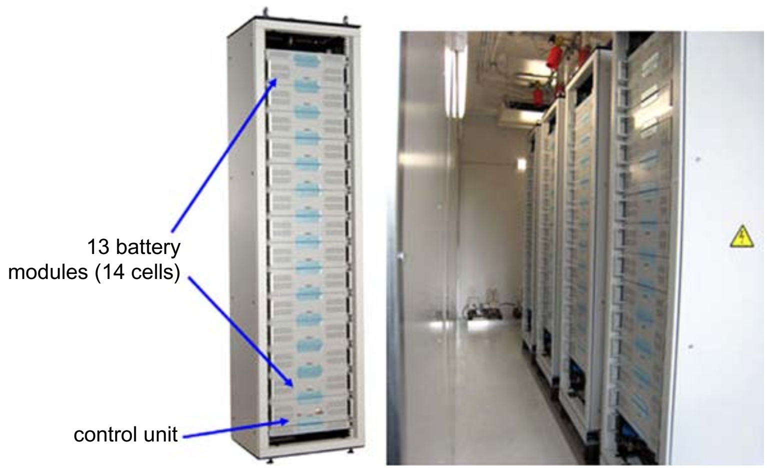


Figure 5.
Battery unit with 13 modules and one control unit (BMM) (left) and battery units inside a container (right)

Nominal line voltage	11 kV
Nominal voltage u_{ac}	2.22 kV
Nominal DC voltage	±2.18 kVdc
Nominal reactive power S_{vsc}	0.6 MVAr cont
Active power	0.2 MW, 1 h
Max. active power	0.6 MW, 10 min
Nominal current I	250 A
Nominal frequency f	50 Hz
Pulse number p	27
Switching frequency f_{sw}	1,350 Hz
Phase reactor L	4.18 mH
DC capacitors C_{dc1}, C_{dc2}	1,253 μF

Table I.
Basic system data of pilot system

Figure 6.
Photo of the pilot installation in EDF Energy Networks' distribution network in the UK

made with a maximum current of 40 A (set by the battery management modules (BMMs)), and at a level of SOC > approx. 80 percent the maximum charging current is reduced down to 20 A (determined by the limit value as received from the BMMs) and finally when the total battery voltage reaches 5,840 V, corresponding to 4.01 V/cell, the control shifts and keeps the battery voltage constant at this level until a full charge at 100 percent is reached. During this period also the BMMs automatically take care of the cell balancing.

6. Storage applications

Many applications with energy storage could be identified (Eyer and Corey, 2009), which are independent of the grid location such as load shifting, spinning reserve or primary frequency regulation. Examples of storage applications that are location dependent are T&D facility deferral, grid angular stability, grid voltage stability, renewable energy management, customer energy management and distribution power quality (Figure 10). Some applications will now be described in more detail.

6.1 Grid stabilization

First, the grid angular stability: this is the mitigation of power oscillations by injection and absorption of real power at periods of 1-2 s. The difference between the phase angle on the generation and the load side cannot be too large. If the utility cannot quickly (within a few cycles) damp the oscillation the power system can collapse. Energy storage systems can assist the utilities to maintain synchronous operation by discharging to provide power and charging to absorb power as the system load conditions change (Johansson *et al.*, 2004).

Second, there is the grid voltage stability: this is the mitigation of a degraded voltage by additional reactive power plus the injection of real power for durations up to 2 s. The need for a short response time is high. Figure 11 shows the voltage at the end of two parallel transmission lines, having a VSC with and without storage. To damp the oscillation with active power a nearly constant voltage can be achieved after 0.5 s where the VSC without storage lasts nearly 2 s.

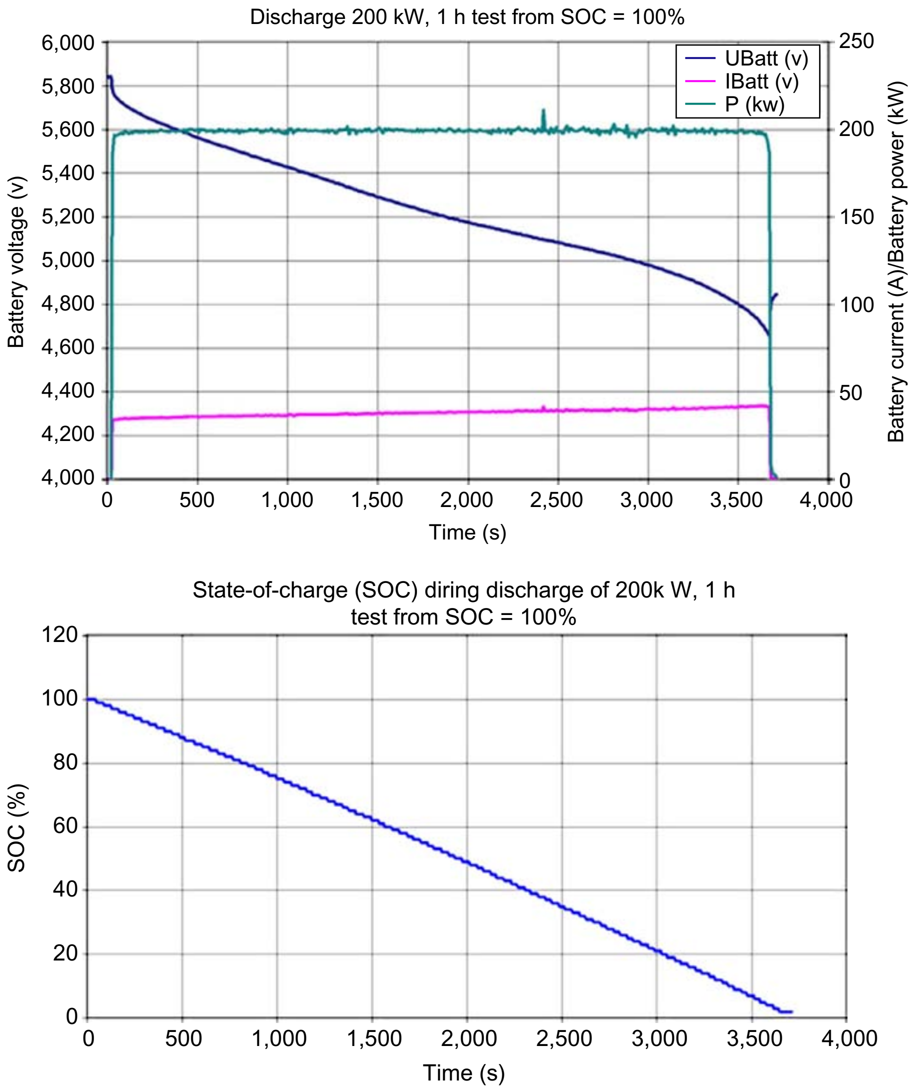
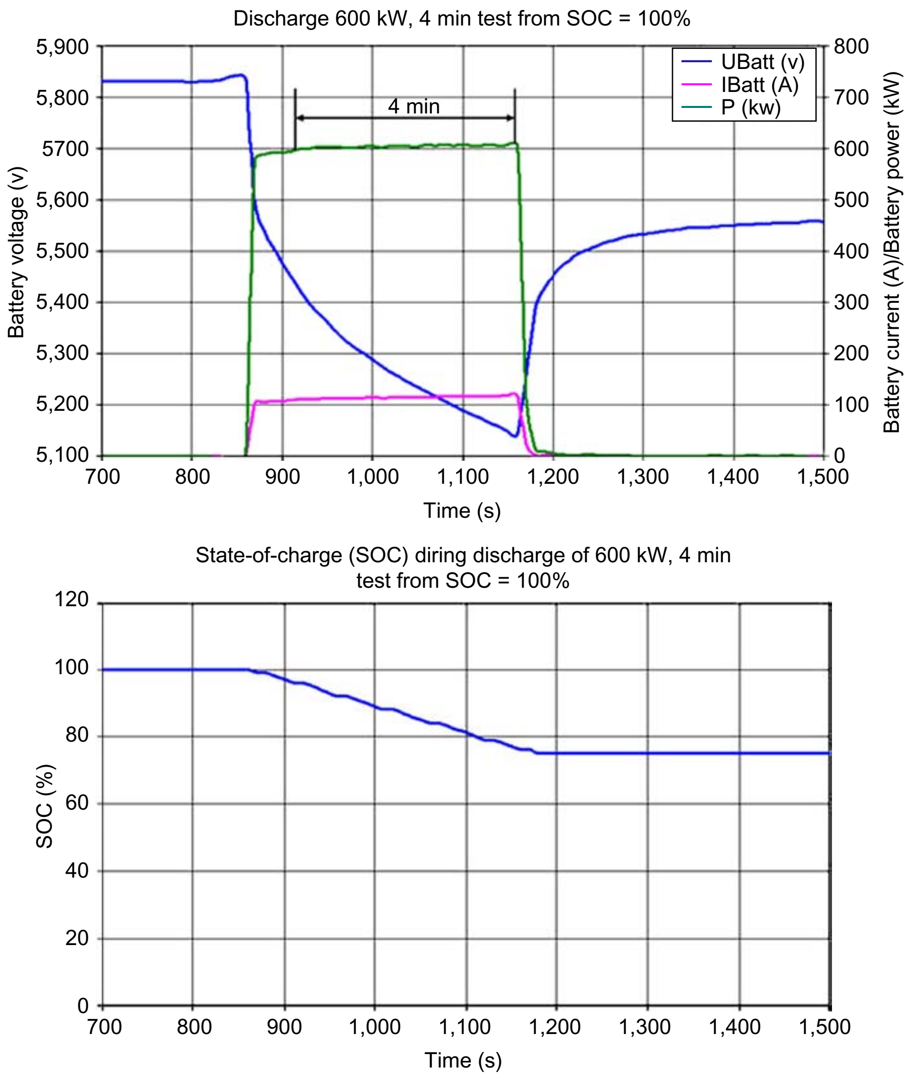


Figure 7.
Discharge of 200 kW, 1 h from SOC = 100 percent

Note: Upper curves: battery voltage, current and power during the discharge and lower curve: SOC

Third, there is the active damping of power oscillations: in the case of power oscillations the reactive power production/consumption capacity of SVC Light may be utilized to damp oscillations. In addition, the active power discharge of the energy storage may be varied such as to damp the power oscillations. Figure 12(a) shows a system voltage variation when the VSC with storage is not active and in Figure 12(b) the oscillations are removed by the injected current (inner waveform) from the VSC with storage.



Notes: Upper curves: battery voltage, current and power during the discharge and lower curve: SOC

Figure 8. Discharge of 600 kW, 4 min from SOC = 100 percent

6.2 Frequency regulation

First, the primary frequency regulation: this implies the mitigation of load-generation imbalance requiring an instant-spinning reserve (or load) to discharge real power for durations of say 30 min under contingency operations. Such a storage system has to absorb or deliver power as it fluctuates. Figure 13 shows the principle of primary control.

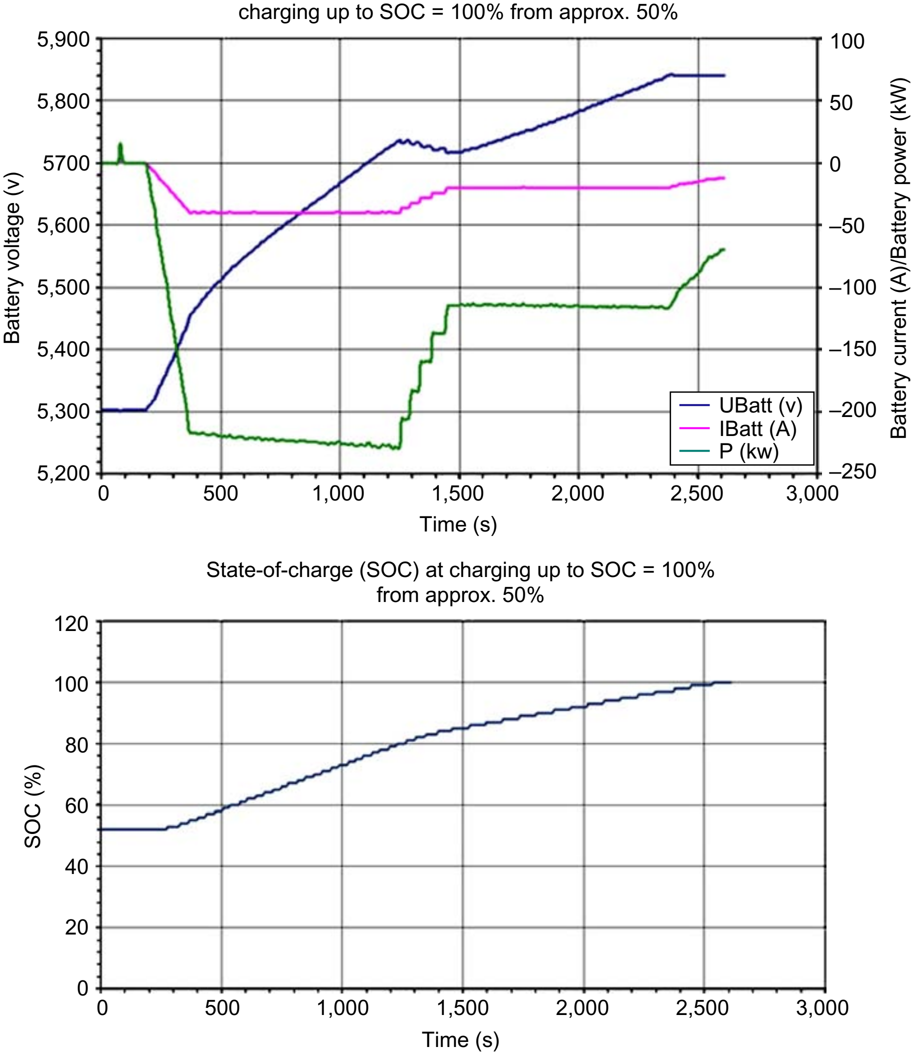


Figure 9.
Charging from SOC = approx. 50-100 percent

Notes: Upper curves: battery voltage, current and power during the discharge and lower curve: SOC

Large changes in the load affect the speed of generators at power plants. This deviation is picked up by the primary controllers of all generators to respond in a few seconds. The controllers alter the power delivered until a new balance has been found. As the balance is reached the system frequency stabilizes and remains at a quasi-steady state but differs from the set point due to the droop. To regulate the frequency the utilities can install storage systems that discharge during rising load or charge when loads fall off. In this way, the storage systems protect the generator from the fluctuation in the load and prevent subsequent frequency variations (Kirby, 2004).

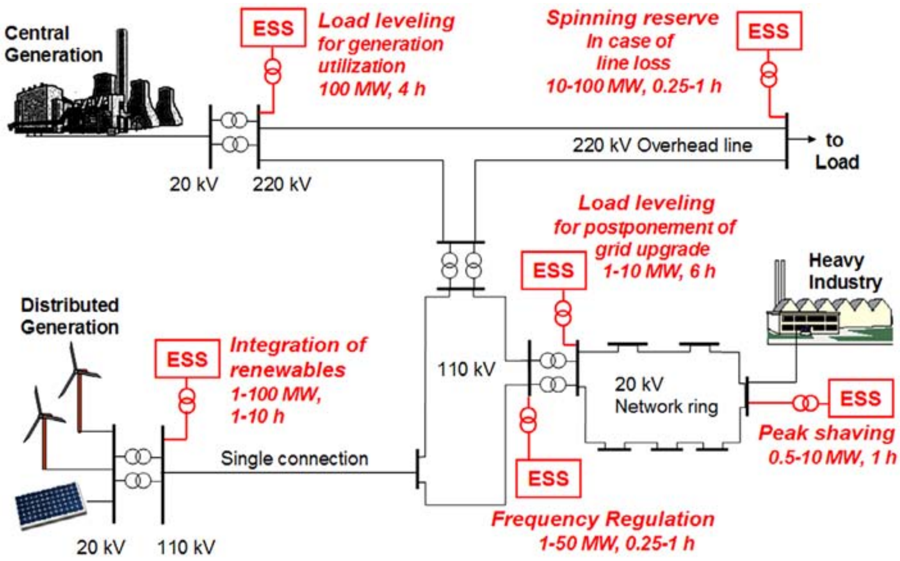
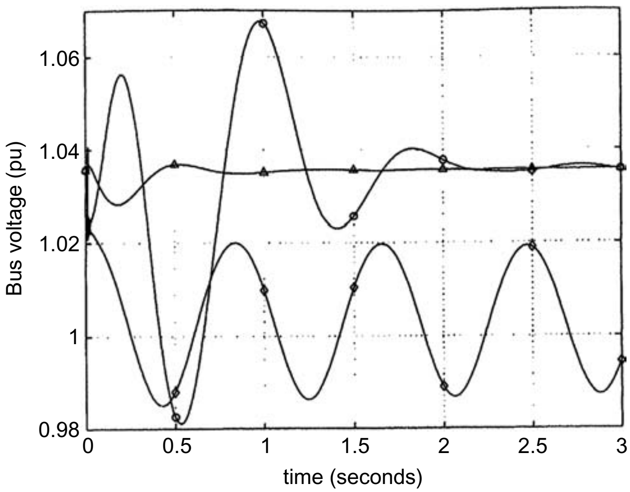


Figure 10.
Utility storage application examples

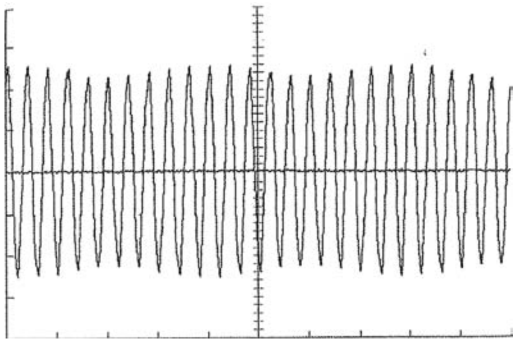


Notes: ◊ – no control; o – voltage-sourced converter;
Δ – voltage-sourced converter + battery energy storage facility

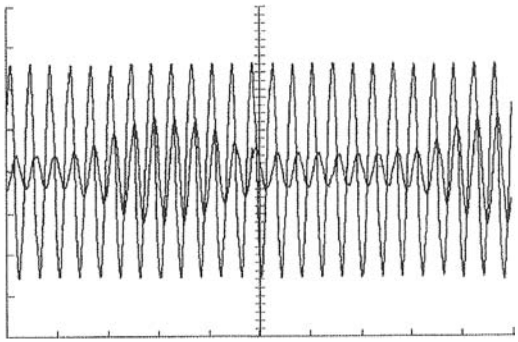
Figure 11.
Voltage at the end of parallel transmission lines

Then there is the secondary frequency regulation: the secondary control holds the mitigation of load-generation imbalance under contingency operations, where the function of the secondary control is to restore the frequency to its set point 50/60 Hz and the power interchange with adjacent control areas to their programmed scheduled values. Thus, to ensure that the full reserve of primary control power is available again.

Third, there is the tertiary frequency regulation which is reserves that are not automatically delivered when required, but are instead instructed.



(a)



(b)

Notes: (a) Without voltage-sourced converter + battery energy storage facility; (b) with voltage-sourced converter + battery energy storage facility

Figure 12.
Power-oscillation damping

6.3 Grid operational support

Regulation control: this service implies the continuously balance of the generation and load under normal conditions. This control regime is a minute-by-minute generation-load balance within a control area. It uses online generation, storage, or load that is equipped with automatic generation control and that can change the output quickly (MW/min) to track the moment-to-moment fluctuations in generation.

Conventional spinning reserve: this yields reserve power for up to 2 h with 10 min notice. To start-up cold power plants require hours and combustion engines a half-hour to get generators ready to accept the load. Energy storage can help utilities maintain rapid reserve, reduce or eliminate the need for supplemental power and bridge the gap.

6.4 Renewable generation support

For example, power transmission and distribution systems are facing an increased amount of wind generation where the power generated varies depending on the location just as well as on the available wind resources. This creates new challenges for the stable and reliable operation of the power system, requiring, in many instances, network reinforcement to maintain network reliability. Energy storage will increasingly play a

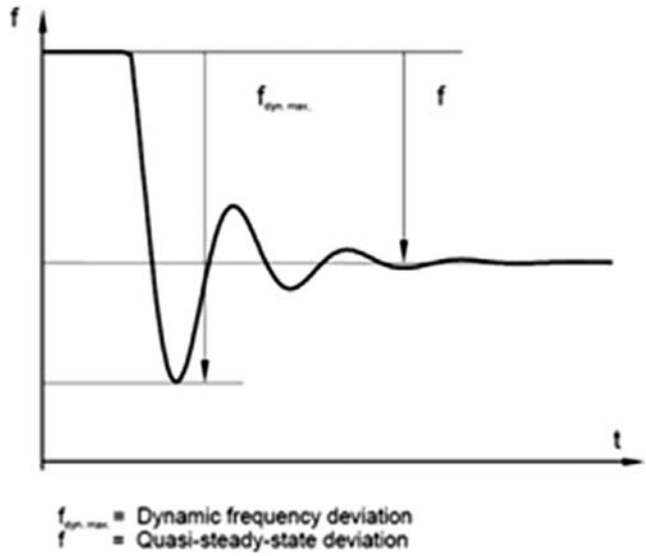


Figure 13.
Principle of primary frequency regulation

role in economically managing power networks to meet demand and maintain supply reliability during these generation and demand fluctuations. Solar power from photo-voltaic plants is another coming area in the renewable power field. Here, too, dynamic energy storage will offer benefits and widen the usability of the concept as a source of clean, environmentally attractive energy. This includes time shifting (store and release of wind energy), renewable capacity firming (store during low demands and release during high demands) and the like.

6.5 Vehicle grid integration
An electric vehicle needs to be connected to the grid every time its battery is depleted (Figure 14). Therefore, an infrastructure is needed in the form of charging poles and or possibly battery exchange stations. Moreover, it is technically feasible to adapt the dynamic energy storage concept to a future battery exchange station. Charging can occur during off-peak hours or peak hours. Particularly, during peak hours most of the power system is demanded as a fast ramp-up of power and a higher peak load. Battery energy storage could advance the integration particularly in areas with a high number of electrical vehicles.

Figure 14.
Electric vehicle integration

7. Conclusion

The smart grid is open for all types and sizes of generation and takes care of the demand side and operation in an efficient and reliable way. To balance production sources or support the integrity of the power system itself energy storage is a vital aspect to guarantee power quality and bridging power applications. A dynamic storage device based on batteries, for utility scale, has been outlined, as well as some of its applications. It is an add-on to the existing, proven high-performance SVC Light, which results in increased functionality with minimum design modifications. It is able to control both active and reactive power with fast response and independently of each other, making it suitable for a number of applications in today's and future transmission and distribution systems.

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Frans Dijkhuizen received his Electrical Engineering degree in 1995 and the PhD degree in Electrical Engineering in 2003, both from the Eindhoven University of Technology TU/e, the Netherlands. He joined ABB Corporate Research in Västerås in 2001 working in the field of high voltage power electronics for HVDC and FACTS applications. His interest includes the whole area of power electronics. Frans Dijkhuizen is the corresponding author and can be contacted at: Frans.dijkhuizen@se.abb.com

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Konstantinos Papastergiou (SM'98,M'06) obtained a BEng from the Technology Institute of Crete in Greece and a PhD degree from the University of Edinburgh under industrial sponsorship by BAE Systems. He worked on the More-Electric Aircrafts (MOET) EU project as a PostDoctoral Research Fellow with PEMC group at the University of Nottingham. In 2006 and 2007 Konstantinos was the co-founder of two technology start-ups in the UK. His research interests are focused on contact-less transfer of energy, magnetics design and optimisation, and multilevel power electronic converters. Konstantinos Papastergiou has received a IEEE/IES student award as well as grants from Marie Curie, the UK Royal Society and the Greek State foundation for Scholarships.

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Rolf Grünbaum received his MSc degree in Electrical Engineering from Chalmers University of Technology in Gothenburg, Sweden. He is currently working for ABB AB within its FACTS Division, where he is Senior Marketing Manager of FACTS and Reactive Power Compensation Systems. Mr Grünbaum has been active in ABB and previously in Asea for a number of years. Before that, he was employed by DISA Elektronik in Skovlunde, Denmark, where he was involved in the marketing of scientific equipment for fluid flow research. He has also held positions as Scientific Counsellor in the Swedish Foreign Service. Mr Grünbaum is a member of Cigré and IEEE and the author of numerous FACTS.