

Superconducting Magnetic Energy Storage (SMES) for Energy Cache Control in Modular Distributed Hydrogen-Electric Energy Systems

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Abstract—The proposed energy cache control enables fast compensation of stochastic power fluctuations through the use of Superconducting Magnetic Energy Storage (SMES) connected to the DC bus of Distributed Generation (DG). The term energy cache control is chosen to reflect its analogy to the utilization of the data cache in computers. The SMES provides an energy cache for other types of storage with a higher capacity of energy but also longer response times. Together, the two types of storage provide high controllability over diverse time scales. The SMES so enables the creation of modular DG building blocks which can be readily connected to the network in a plug-and-supply mode. In the developed case study, the SMES is part of a DG unit of a model commercial facility that includes renewable-based electric power generation and a hydrogen-electric conversion and storage plant composed of an electrolyser, a fuel cell, and tanks. It is shown how the cache energy control deals with fast fluctuations of power generation and load that are caused by changing wind and sudden power demands of an elevator, respectively. Through its shock-absorbing role, the energy cache control of the SMES prevents the involved disturbances from propagating over the network interface and makes the DG unit behave as a good citizen in terms of network integration.

Index Terms—Distributed generation (DG), fuel cell, hydrogen economy, renewable energy, superconducting magnetic energy storage (SMES).

I. INTRODUCTION

THE US Department of Energy estimates that the energy market penetration of distributed generation (DG) could be as high as 30% by 2030 [1]. In addition, DG has the potential of playing a synergistic role with regards to the development of a hydrogen economy by providing the capability of distributed hydrogen-electric co-generation [2], [3]. The use of DG to meet future energy demands represents a paradigm shift from the traditional use of a smaller number of large power plants with much higher power ratings [4], [5]. As the number of DG units grows, it will be increasingly challenging to manage the tasks of power system design and operation. Here, it is proposed to modularize these tasks in the same way they are modularized in computer system design and operation in order to facilitate successful system integration. In this context, the SMES plays the proposed important role of an energy cache that finds its analogy in the data cache of the computer system [6].

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The modularization of the tasks of design and operation implies that a DG unit becomes a modular building block by itself. As such, the DG unit is to obtain a well-defined interface that enables controlled exchange of power with the connected network over diverse time scales. The SMES as part of the building block can provide important fast controllability over short time scales that ensures rapid response behavior to stochastic changes of renewable power input and load. The SMES so makes the DG unit behave as a good citizen as part of the overall power system. It is the focus of this work to introduce the modular DG building block, to describe the role of the SMES in the design and operation of the building block, and to validate the operation of the SMES through modeling and simulation. The work thus establishes a novel role for the SMES in the growing field of DG and complements its use in other power system applications [7]–[9].

The paper is arranged as follows. In Section II, the building block concept with the SMES as a key component is presented. A case study illustrating the use of the SMES as an energy cache and the effectiveness of the building block paradigm on a hydrogen-electric DG unit is discussed in Section III. Conclusions from this work are drawn in Section IV.

II. MODULAR DISTRIBUTED GENERATION

The integration of diverse DG units into a low-voltage (LV) distribution network requires the utility to consider the operating characteristic of each type of DG and their aggregate effect on the well-being of the network in terms of issues that include coordination of active power, coordination of reactive power, power quality, and reliability [4]. Particularly challenging is the integration of DG units that make use of renewable power conversion with intermittent power output. The mentioned issue may require the utility to upgrade the distribution network. An example of an upgrade is a centrally controlled mitigating device, such as energy storage.

The described scenario illustrates the additional coordinating work that is required when connecting DG units. The integration is complicated by the fact that different DG units can have diverse behavior. It would be better to integrate units with standardized and well-defined behavior. Ideally, the units would be plugged in having them readily supply power, a plug-and-supply concept similar to its plug-and-play counterpart for devices connected to computers. In Section II-A, the concept is described in more detail. The important role of the SMES technology is elaborated in Section II-B. The control of the SMES is explained in Section II-C.

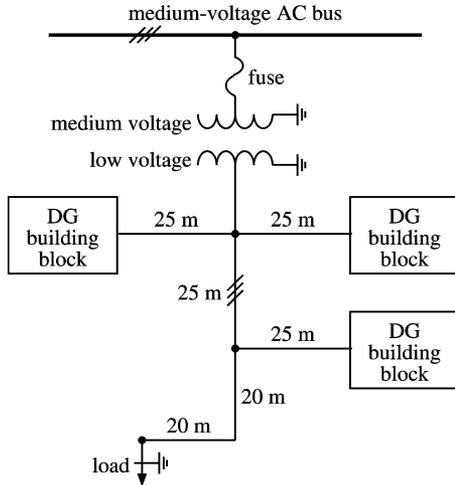


Fig. 1. LV distribution network with modular DG building blocks.

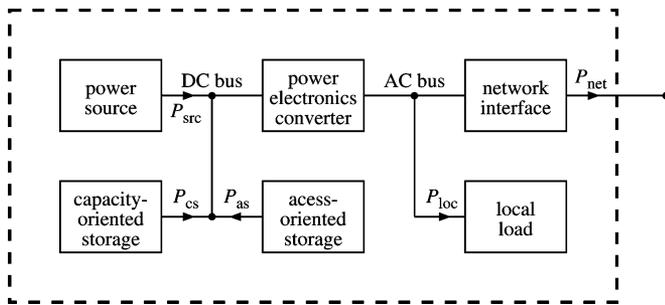


Fig. 2. Functional components of the DG building block.

A. Functional Components of DG Building Block

In Fig. 1, an LV distribution network is shown with the diverse DG units and loads replaced by DG building blocks with well-defined behavior. A central mitigating device is not necessary. The term building block is used to highlight modularity in the same way it is used for the power electronics building block (PEBB) [10]. The functional components of each DG building block are shown in Fig. 2. The power source is representative of the original DG unit and is based, for example, on wind or solar power conversion. It is assumed here that the power source delivers its power via a DC bus and that the local load is connected to an AC bus. Alternative arrangements are possible.

The building block contains two complementary types of energy storage that are connected to the DC bus with the aim to provide the well-defined behavior: access-oriented and capacity-oriented storage. Access-oriented storage is a generic term for those technologies that can provide access to power quickly at a high round trip efficiency and a high cycle life of charge and discharge operations. SMES technology fits into this category. Capacity-oriented storage is a generic term for those energy storage technologies that can contain large amounts of energy at a relatively low cost per unit of energy stored. Examples of this type include batteries or hydrogen storage plants. Together, access- and capacity-oriented storage form a multilevel storage that is controllable over a wide range of time scales [2].

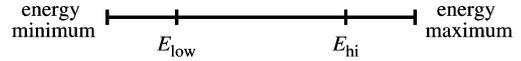


Fig. 3. Boundary levels within the SMES energy level continuum.

B. Contribution of SMES

The primary function of the SMES is to insulate the network from high-frequency power fluctuations thereby acting as a shock absorber. Assuming lossless conditions and using the directional power flow conventions in Fig. 2, the power exchanged with the network, P_{net} , can be determined by solving the power balance equation:

$$P_{net} = P_{src} - P_{loc} + P_{cs} + P_{as}. \quad (1)$$

High-frequency power fluctuations can originate from the stochastic renewable power source and the local load, expressed in (1) by P_{src} and P_{loc} , respectively. The power from the capacity-oriented storage, P_{cs} , may be unable to respond quickly enough to compensate for fast fluctuations. However, the response time of the SMES, typically on the order of milliseconds [11], enables it to compensate for fluctuations in P_{src} and P_{loc} . Therefore, the contribution of the SMES is increasingly important in DG applications with a stochastic power source component, or if the local load is characterized by intermittent usage of large motors. The peak power fluctuations of these sources and loads are used to determine the power rating of the SMES. The energy rating of the SMES should be sufficient enough to provide compensation until the capacity-oriented storage can respond.

C. Cache Control

In order to have a well-defined interface with the network, the DG building block must be capable of tracking a scheduled power exchange, P_{sch}^* , which is the setpoint value for P_{net} . The value of P_{sch}^* at a particular time is dependent on the projected power from the power source, the forecasted local load and the energy levels of the storage. The value of P_{sch}^* is then communicated to the utility. Communicating and adhering to the scheduled power exchange is beneficial to the utility as it assists in the coordination of real and reactive power. The utility can then model the DG unit as a building block with a well-defined interface.

The output of the DG building block tracks P_{sch}^* by allocating power to the storage devices through cache control [2]. Like the use of RAM and a hard drive in a computer, cache control employs the fast responding SMES to increase the overall performance of the building block, whereas the capacity-oriented storage is used to expand the overall energy storage capability. The cache control premise relies on the ability of the SMES to exchange power at all times. It is therefore critical that the SMES not reach a full or empty state. Cache control manages the energy level of the SMES by adjusting the power to the capacity-oriented storage so that the SMES remains within specified boundary levels. The boundary levels, E_{hi} and E_{low} , indicate the upper and lower limits and are shown in Fig. 3.

For energy levels above E_{hi} , the portion of power allocated to the capacity-oriented storage decreases, leading to an increase

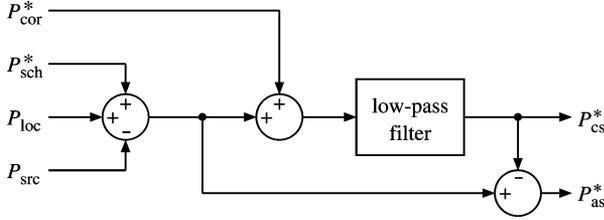


Fig. 4. Cache control power allocation and SMES energy management process.

in the power out of the SMES. For energy levels below E_{low} , the power allocated to the capacity-oriented storage increases. Power allocation adjustments are sent to the capacity-oriented storage through a corrective signal, P_{cor}^* . The value of the signal is found through proportional integral control of the difference between the current energy level and the violated boundary level. When the energy level is between E_{hi} and E_{low} , the corrective signal is zero and the power allocation is solely based on tracking P_{sch}^* .

Cache control uses a filtering process that allocates different spectrums of power to each storage component in order to track P_{sch}^* . Filtering schemes for SMES devices have been previously employed, but each is application specific, dependent on the spectrum of the signals and the response times of the components [12], [13].

The filtering process proposed for use in DG applications is shown in Fig. 4. Here, P_{src} and P_{loc} are measured signals from the corresponding functional components, whereas P_{as}^* and P_{cs}^* are the power level request signals sent to the storage components. The process begins with the calculation of a difference signal equal to $P_{sch}^* + P_{loc} - P_{src}$. This signal represents the power to be compensated by the SMES and capacity-oriented storage due to power fluctuation. Next, the corrective signal is added to manage the SMES energy level. The signal is then passed through a low-pass filter that has a cut-off frequency commensurate with the capacity-oriented storage used. The filtered signal is sent to the capacity-oriented storage as a control signal. The capacity-oriented control signal is then subtracted from the difference signal and is used as a control signal for the SMES. Through this process, the cache control allocates a spectrum of power that is suited for the response time and energy capacity of each storage device.

III. APPLICATION

The following is a case study of a commercial facility with an integrated modular DG unit containing a hydrogen production and storage plant. Highlighted in the study are the contribution of the SMES to the DG building block and its operation as dictated by cache control.

A. Study Specifications

The schematic in Fig. 5 details the functional components and the management and control signals used by the facility [2]. Here, the power source is a 50 kW wind turbine. The access-oriented storage block is realized by a 3 MJ SMES with a response time of 5 ms. The capacity-oriented storage is a 23 kg hydrogen

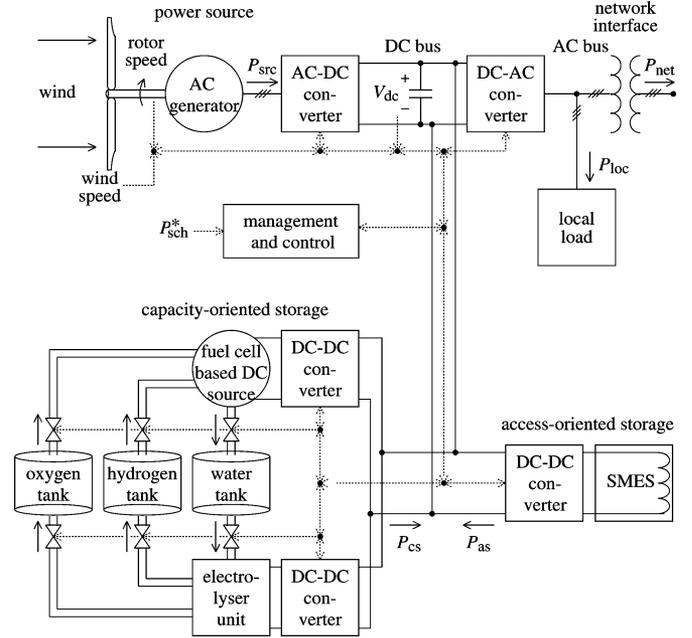


Fig. 5. Hydrogen-electric distributed generation unit with cache control of energy storage.

tank, large enough to absorb the continuous rated wind turbine power output for 24 hours. Both storage devices are initialized at one half of their maximum energy storage levels. Associated with the storage are an electrolyser and a fuel cell, both rated at 50 kW. Operational considerations seeking to maximize the lifetime and efficiency of the electrolyser and fuel cell dictate that their output should be smooth. With this as motivation, the low-pass filter is used to limit the response time of the capacity-oriented storage to approximately 250 seconds. The models of the electrolyser and fuel cell are based on descriptions in [14].

The simulation is performed with MATLAB and has a ten minute duration. The SMES has a round trip efficiency of 95%, the efficiencies of the electrolyser and fuel cell are assumed to be 75% and 50%, respectively; the rest of the system is considered lossless. The DC-DC converter connected to the SMES is represented by its average model and is duty ratio controlled [15].

Nominal local load consumption is 90 kW, which is also the scheduled power exchange from the network to the facility. The load rapidly changes when the elevator is in use. The elevator power demand is representative of a 720 kg car with a 1440 kg counterweight traveling up and down ten stories [16]. The peak load of the elevator is approximately 30 kW. Also varying is the power from the wind turbine. The wind speed is from actual data taken at a height of 60 m on 7 January 1993 beginning at 11:53 AM in Tjæreborg, Denmark [17].

B. Results

The sources of fluctuating power, P_{src} and P_{loc} , are shown in the first and second plots in Fig. 6, respectively. Note the erratic nature of the elevator load beginning at 300 seconds. In order for the building block to track P_{sch}^* at its value of -90 kW, the cache

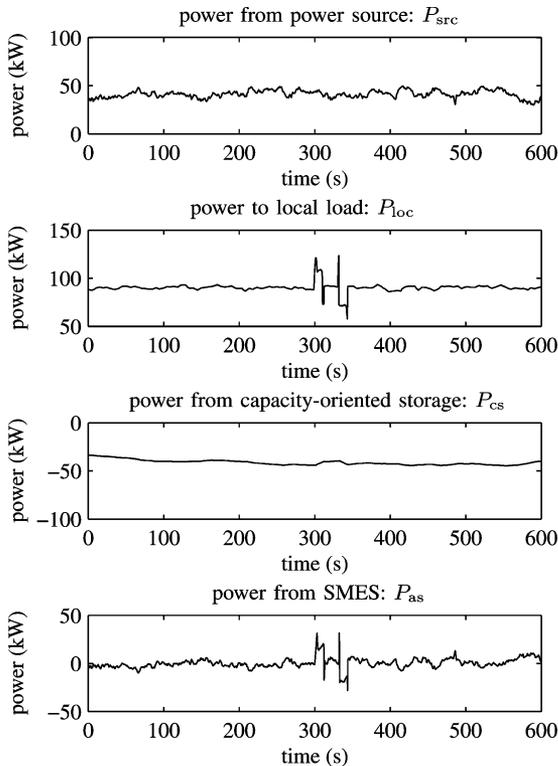


Fig. 6. Resulting functional component power flows from simulation.

control must allocate power corresponding to the variation in wind turbine power production and in local load.

The electrolyser is allocated the low-frequency portion of the power to be compensated, as shown in the third plot of Fig. 6. This power tends to follow the mean of the wind turbine power production; the rapid changes in wind turbine power production and local load are removed by the low-pass filter. The remaining high-frequency power is allocated to the SMES and is shown in the final plot in Fig. 6. The contribution of the SMES in compensating for the fluctuation in power production from the wind turbine and the local load is evident through the comparison of the final plot with the first and second plots.

The presence of the SMES allows the hydrogen-electric DG facility to be modeled as a building block by the utility. The power exchanged with the network is well-defined, even under rapid power changes with diverse time scales in accordance with the plug-and-supply concept.

IV. CONCLUSIONS

The SMES provides critical fast controllability in the described plug-and-supply concept for DG in order to support the integration of the latter into the power electric network. In the same way that a computer makes use of cache memory to boost performance, the SMES with fast access to power provides an energy cache for storage types with slower response but lower cost per unit energy and therefore higher energy capacity. Together the complementary access-oriented and

capacity-oriented storage form a multilevel storage, which in the discussed case study consists of the SMES and hydrogen storage connected to the DC bus of a DG unit at a commercial facility.

In the case study, it was shown through modeling and simulation that the energy cache control enables the SMES to compensate for fast fluctuations while slower change is accommodated by the hydrogen storage. Neither disturbances caused by changing wind turbine power nor by the load of an elevator propagated over the network interface. The SMES so acts like a shock absorber to isolate network and DG unit disturbances. From the network point-of-view the DG unit was shown to act as a modular building block with controlled power source or sink, easing DG integration.

REFERENCES

- [1] E. Boedecker, J. Cymbalsky, and S. Wade, "Modeling distributed electricity generation in the NEMS buildings models," *Issues in Midterm Analysis and Forecasting 2000*, U.S. Energy Information Administration.
- [2] K. Strunz and E. K. Brock, "Stochastic energy source management: Infrastructure-integrative modular plant for sustainable hydrogen-electric co-generation," *International Journal of Hydrogen Energy*, vol. 31, no. 9, pp. 1129–1141, Aug. 2006.
- [3] H. Aki *et al.*, "Fuel cells and energy networks of electricity, heat and hydrogen in residential areas," *International Journal of Hydrogen Energy*, vol. 31, no. 8, pp. 967–980, 2006.
- [4] H. B. Puttgen, P. R. MacGregor, and F. C. Lambert, "Distributed generation: Semantic hype or dawn of a new era," *IEEE Power Energy Mag.*, vol. 1, no. 1, pp. 22–29, Jan. 2003.
- [5] F. Farret and M. Simões, *Integration of Alternate Sources of Energy*. Chichester, England: Wiley-IEEE Press, 2006.
- [6] K. Strunz, "Computer system design analogies for synthesis of sustainable distributed generation systems," in *Proc. CIGRE Symposium: Power Systems with Dispersed Generation*, Athens, Greece, Apr. 2005.
- [7] W. V. Hassenzehl *et al.*, "Electric power applications of superconductivity," *IEEE Trans. Appl. Superconduct.*, vol. 92, no. 10, pp. 1655–1674, Oct. 2004.
- [8] B. K. Johnson, R. H. Lasseter, and F. L. Alvarado, "Incorporation of a SMES coil into a superconducting LVdc transmission system," *IEEE Trans. Appl. Superconduct.*, vol. 7, no. 2, pp. 419–422, June 1997.
- [9] M. V. Aware and D. Sutanto, "SMES for protection of distributed critical loads," *IEEE Trans. Power Delivery*, vol. 19, no. 3, pp. 1267–1275, July 1997.
- [10] T. Ericson, Y. Khersonsky, and P. K. Steimer, "PEBB concept applications in high power electronics converters," in *Proc. IEEE Power Electronics Specialists*, Recife, Brazil, Sept. 2005, pp. 2284–2289.
- [11] H. Hayashi *et al.*, "Test results of power system control by experimental SMES," *IEEE Trans. Appl. Superconduct.*, vol. 16, no. 2, pp. 598–601, June 2006.
- [12] T. Ise, M. Kita, and A. Taguchi, "A hybrid energy storage with a SMES and secondary battery," *IEEE Trans. Appl. Superconduct.*, vol. 15, no. 2, pp. 1915–1918, June 2005.
- [13] S. Suzuki, J. Baba, K. Shutoh, and E. Masada, "Effective application of superconducting magnetic energy storage (SMES) to load leveling for high speed transportation system," *IEEE Trans. Appl. Superconduct.*, vol. 14, no. 2, pp. 713–716, June 2004.
- [14] J. Larminie and A. Dicks, *Fuel Cell Systems Explained*, 2nd ed. Chichester, England: J Wiley & Sons Ltd, 2003.
- [15] L. Chen *et al.*, "Detailed modeling of superconducting magnetic energy storage (SMES) system," *IEEE Trans. Power Delivery*, vol. 21, no. 2, pp. 699–710, Apr. 2006.
- [16] A. Rufer and P. Barrade, "A supercapacitor-based energy-storage system for elevators with soft commutated interface," *IEEE Trans. Ind. Applicat.*, vol. 38, no. 5, pp. 1151–1159, Sept. 2002.
- [17] 2006 [Online]. Available: www.winddata.com