Cache Energy Control for Storage: Power System Integration and Education Based on Analogies Derived From Computer Engineering

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***Abstract*—Energy storage is an enabling technology for power system integration of renewable sources, while data storage enables computer system integration. In this paper, a functional analogy relating energy and data storage is derived. Battery or hydrogen storage can provide large energy capacity similar to a hard disk providing large data capacity. Supercapacitors or flywheels provide fast and frequent access to cache energy similar to the computer's RAM providing fast and frequent access to data. In analogy to computer engineering, a cache control that coordinates the operation of a multilevel storage consisting of such complementary capacity and access-oriented storage technologies is designed. It is illustrated how for an industrial distributed energy system with renewable generation, local load, fueling station, and connections to the electricity and gas distribution networks, the cache control provides energy management to support a modular plug-and-play-like system integration. The benefit of the analogy in education is evaluated on a representative sample of electrical engineering students at the University of Washington. While familiar with computing, students do not typically have the same level of exposure to power engineering. The understanding of distributed energy systems concepts is shown to improve thanks to this bridging analogy between computer and power engineering.**

***Index Terms*—Battery storage, cache control, cache energy, distributed generation, flywheel, fuel cell, hydrogen storage, multilevel energy storage, plug-and-play, power engineering education, renewable energy, solar energy, supercapacitor, system integration, virtual power plant, wind energy.**

I. Introduction

CONSERVATIVE estimates by the U.S. Department of Energy place the worldwide growth of the capacity of distributed energy resources (DER) at 20 GW per year over the next decade [1]. A significant part of the DER units to be installed will be based on renewable wind and solar power conversion with intermittent availability. As the penetration of DER grows, it will be increasingly challenging to integrate these units in the power system, whose operation has largely been dominated by few but large power plants with controllable output. Energy storage [2]–[7] is widely seen as an important enabling technology for solving the challenge of integrating DER. It so also becomes a topic of interest in the area of power system education [8]–[10]. Among the commercially available energy storage technologies, significant differences exist in terms of the key features and applications. For example, supercapacitors, superconducting magnetic energy storage (SMES), and flywheels have high cycle life periods of charge and discharge operations and provide fast access to power. Standard batteries, in turn, have a lower cost per maximum amount of stored energy.

Diverse technologies are also available for storing data in computers. When designing a modern personal computer (PC), computer engineers complement two types of data storage technologies. Firstly, a hard disk is installed to provide low-cost data storage at large capacities typically ranging from tens to hundreds of gigabytes. Secondly, the latter is complemented by up to a few gigabytes of random access memory (RAM) whose major virtue lies in enabling fast access to data. The advantage of fast access comes at the expense of a much higher cost per bit of stored data. The role of the RAM as the access-oriented storage is to serve as a cache for the hard disk, which acts as the capacity-oriented storage. This type of computer system integration yields high performance at competitive cost [11]. It has contributed to the transition from a computing infrastructure where only relatively few supercomputers existed to an infrastructure where personal computing is ubiquitous. An analogous transition from a power infrastructure with only few but large power plants to a scenario with many integrated distributed energy resources is desirable.

The research that lead to the results presented in this paper was inspired by the consideration of an analogous transition. Three major contributions are discussed. Firstly, an analogy of data and energy storage is developed and related to system integration in the areas of computer and power engineering [12]. Secondly, the educational value of the analogy is studied through a sequence of pretest, presentation of materials, and posttest on a group of 30 university students registered for the Bachelor of Science (B.S.) degree in electrical engineering at the University of Washington. The results point to the importance of the methodology as an instructional aid in that it is effective in improving the understanding of diverse types of energy storage among students and among the audience of power system presentations in general. Thirdly, based on the analogy a control for cache energy is developed. It is shown how analogous to the plug-and-play concept of computer engineering, the modular network integration of the renewable generation is obtained.

In Sections II and III, data and energy storage technologies are surveyed, respectively. In Section IV, data and energy storage technologies are classified. Based on this classification, the analogy is introduced and illustrated. In Sections V and VI, it is shown how the analogy provides value in education and

Manuscript received January 10, 2008; revised May 13, 2008. First published December 09, 2008; current version published January 21, 2009. Paper no. TPWRS-01008-2007.

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Digital Object Identifier 10.1109/TPWRS.2008.2005713

presentation, respectively. Section VII deals with the application in the design of distributed energy systems. Conclusions are drawn in Section VIII.

II. Data Storage

A wide variety of data storage technologies is available. A selection is introduced in the following, while a detailed description is given in the Appendix.

Hard disk and digital versatile disk (DVD) are cost efficient for a high capacity of stored data, as the cost per bit of stored data is very low. Capacity levels of hard disks in modern mainstream PCs are of the order of hundreds of gigabytes, and the DVD stores multiple gigabytes. Access to data on hard disks takes about 5 to 10 ms. It is slower for DVDs at about 100 ms.

Static random access memory (SRAM) and dynamic random access memory (DRAM) are installed for fast access to data that are frequently used in the central processing unit (CPU). Access times are of the order of up to 10 ns and 100 ns for SRAM and DRAM, respectively. Implementation is in the form of solid-state integrated circuitry. The cost per bit stored is high and particularly high for SRAM. Therefore, implementations in mainstream PCs are for comparatively low capacities of up to a few megabytes.

III. Energy Storage

As with data storage, the characteristics of energy storage vary significantly as a function of the underlying technology [13]. A selection is introduced hereafter, details are discussed in the Appendix.

Flywheel and supercapacitor technologies can provide fast and frequent access to stored energy at high roundtrip efficiencies of the order of 90%. Response times are of the order of milliseconds, and both also have a very high cycle life of charge and discharge operations [2]. Whereas the flywheel stores kinetic energy within a rapidly spinning wheel-like rotor, electrochemical supercapacitors store energy in electric fields created between electrodes and electrolytic ions that are very close to one another. The cost per maximum amount of stored energy is relatively high.

Hydrogen and battery storage technologies allow for storing at a low cost per maximum amount of stored energy in environments that do not impose space constraints. They are therefore suitable for the storage of large amounts of energy if the required space is readily available. Hydrogen can be made available in pure form through electrolysis where water is split into its component parts of hydrogen and oxygen or through reforming from gas. The amount of energy that is stored depends only on the rating of the hydrogen tanks. Electric power is generated in fuel cell stacks with the hydrogen as input. Thus, energy and power ratings are decoupled. The same is true for the so-called flow batteries [2]. Roundtrip efficiencies of the latter are of the order of 80%. Research programs are underway with the objective to attain roundtrip efficiencies for hydrogen storage closer to 50% within the next years. However, these roundtrip efficiencies are lower than for the flywheel and supercapacitor. The latter also feature shorter response times and higher cycle life of charge and discharge operations.

TABLE I
Classification of Data Storage

class	term	cost per unit data	access speed
access orientation	SRAM	high	high
	DRAM	high	high
capacity orientation	hard disk	low	moderate
	DVD	low	low

TABLE II
Classification of Energy Storage

class	term	cost of capacity	access speed
access orientation	supercapacitor	high	high
	flywheel	high	high
capacity orientation	battery	low	moderate
	hydrogen storage	low	low

TABLE III
Analogies of Data and Energy Storage

analogy	data storage	energy storage
access orientation	SRAM DRAM	supercapacitor flywheel
capacity orientation	hard disk DVD	hydrogen storage battery

IV. Identification and Illustration of Analogy

The prior Sections II and III were dedicated to individual discussions of data and energy storage, respectively. In what follows, analogies are first identified and then illustrated.

A. Identification

In Table I, a classification of the data storage technologies discussed in Section II is introduced [12]. SRAM and DRAM provide fast access to stored data and are therefore classified as access oriented. The strengths of hard disk and DVD storage are the low cost per bit stored. Therefore, they are classified as capacity oriented.

As discussed in Section III, cost per maximum amount of energy stored and access speed are two of the key characteristics that make supercapacitor and flywheel on the one hand and hydrogen and battery storage on the other hand differ significantly. This also justifies the classification into the categories access and capacity orientation as summarized in Table II.

Tables I and II readily reveal commonalities in the classifications made for data and energy storage. This is highlighted in the new Table III that introduces the analogies of data and energy storage.

B. Illustration

For the purpose of illustration, let it be assumed that the specifications of a computer are such that it is to store 40 GB of data with an access time of the order of 10 ns. One approach of implementation may be to only use RAM as a fast accessible data storage technology. Further assuming a cost of 0.1 U.S. Dollars per megabyte, the computer's storage cost would amount to a

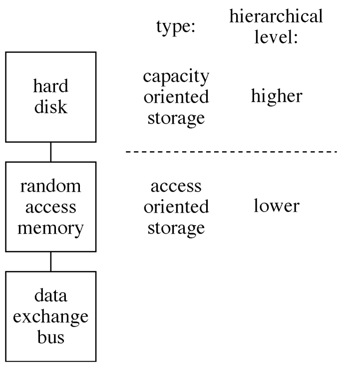

Fig. 1. Hierarchy of cache control in computer systems.

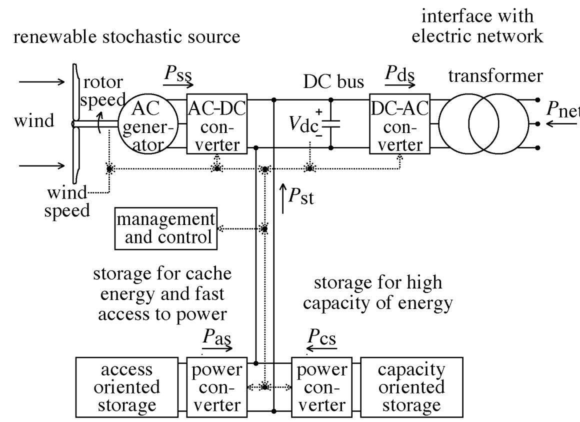

Fig. 2. Multilevel energy storage for virtual power plant.

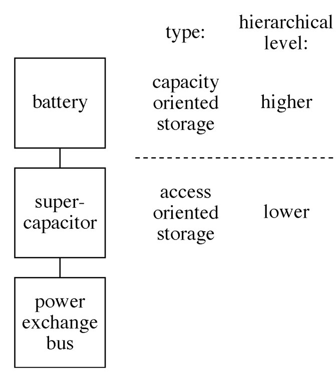

Fig. 3. Hierarchy of proposed cache control in power systems.

staggering 4000 U.S. Dollars. The use of cache, however, allows the achievement of a high speed of access to data at a lower cost. The cache is a small amount of access-oriented storage on which the data most frequently used is stored [11]. Thus, only a fraction of the overall storage is implemented as RAM. The hard disk stores the bulk of the data and is accessed comparatively rarely. The process of selecting data storage locations is known as cache control.

The design of a cache control amounts to a hierarchization as depicted in Fig. 1. The CPU retrieves the majority of its data via a bus from the lowest level in the hierarchy: the cache, which is implemented in RAM technology. At the top of the hierarchy is the hard disk, which, as said previously, is accessed comparatively infrequently. This hierarchy of access and capacity orientation contributes to the very good performance at a given cost as known from today's PCs. This balance of access and capacity orientation is exploited in every off-the-shelf PC to create effective overall storage that can provide fast access as well as high capacity. Using one type of storage technology alone would result in an unsatisfactory compromise. Given the observed analogies, it appears sensible to exploit this complementary nature in a similar way when designing energy storage systems.

Synergies of access and capacity orientation in energy systems can for example be obtained by interconnecting an access-oriented and a capacity-oriented storage as shown in Fig. 2. In the shown virtual power plant, referred to as stochastic energy source access management in [14], multilevel energy storage is connected to a dc bus to create an infrastructure-integrative wind energy conversion system that mimics the behavior of a power plant with deterministic power output P_{ds}. The access-oriented storage serves to improve power quality in that it can react to fast stochastic fluctuations of the stochastic power P_{ss} of the wind energy converter. The capacity-oriented storage serves the purpose of making the overall plant dispatchable. This is further detailed in Section VII and Fig. 3 for the example of a multilevel storage composed of battery and supercapacitor, which stores cache energy. A hierarchization can be synthesized in analogy to the computational counterpart depicted in Fig. 1. The resulting plant behaves as a good citizen in that the power flow P_{ds} over its interface with the electricity infrastructure is well controllable over diverse time scales. This supports system integration, as the original power electric network was designed for the integration of deterministic power plants.

The use of the capacitor for storing cache energy is also popular in transportation power systems, where it is coupled with batteries in hybrid and fuel cell cars to help meet peak power demands [15], [16]. In [17]–[19], the SMES was used for this purpose as part of a multilevel energy storage in a stationary power system. In the example of Section VII, a flywheel is employed.

V. Value in Higher Education

In the preceding sections, it has been demonstrated that there is an analogy between data storage and energy storage in the context of system integration. It is sought to ascertain the level in which this analogy can be used to leverage an individual's existing knowledge of data storage to increase the understanding of DER in general and energy storage concepts in particular. The familiarity of university students with data storage concepts from their daily interactions with computers makes them ideal candidates for applying the analogy as an educational tool. Specifically, the value of the analogy for aiding in comprehension and retention of energy storage concepts was examined. A sample of electrical engineering students at the University of Washington in Seattle was used for this study.

A. Methodology

The evaluation of the analogy as an educational tool consisted of three sections: pretest, educational material, and posttest. This format is based on standard methodology used in educational research [20], [21]. The purpose of the pretest is to measure the students' baseline knowledge of energy storage. During the educational material portion, the students are divided into a Control Group, who were not exposed to the analogy, and an Experimental Group, who were exposed to the analogy through printed material. Aside from the difference in exposure to the analogy, the groups were given identical printed material on energy storage. The posttest was then administered to both groups in order to compare the efficacy of the two material sets in terms of the students' comprehension and retention of energy storage concepts. Each section is described in greater detail in the following.

1) Pretest: In order to ensure a consistent use of terminology, the pretest began with a brief physical description of the following energy storage devices: battery, hydrogen storage, flywheel, and supercapacitor. A description of the electrolyzer and fuel cell was included as part of the hydrogen storage. The pretest then required the students to rank each energy storage device, relative to one another, in terms of response time, cost per maximum amount of energy stored and roundtrip efficiency. These tasks are important since effective energy storage utilization is related to the relative characteristics of the storage devices. The pretest also establishes a baseline of the students' knowledge of energy storage devices.

2) Educational Material: After grading the pretest, the students were partitioned into a Control Group and an Experimental Group. The performance of the Control Group on the posttest would serve as a baseline for evaluation and comparison against the Experimental Group. The two groups were comprised of students such that the average grade on the pretest of both groups were similar. Each group was then presented with printed educational material that described each energy storage device in terms of approximate magnitude of response time, cost per maximum amount of energy stored and roundtrip efficiency. In addition to this material, the Experimental Group was provided with the analogy given in Section IV. Except for this analogy, the educational material provided to both groups was identical. The students' time with the material was monitored to be 20 min. This time was consistent with the length of the educational material. While reading the educational material, the students in each group were kept isolated and asked not to exchange information with the members of the other group so that the students in the Control Group did not have access to the analogy from the students in the Experimental Group.

3) Posttest: After one week, the students were given a posttest to determine if they could apply their new knowledge of energy storage. The posttest had two principal questions, each of which described a facility with differing constraints and requirements that was in need of energy storage. The students were required to recommend an energy storage for each facility from the discussed technologies: hydrogen storage, battery, flywheel, and supercapacitor. Multiple device recommendations were allowed. The purpose of these questions was to determine if the students were able to identify the relative merits of each energy storage device when used as part of DER designs. The questions, along with the correct responses, are given in Fig. 4.

Question 1: Which energy storage device or devices would you recommend for a facility that requires energy storage with a fast response time and high efficiency?

Solution: This facility requires either of the access oriented storage types such as flywheel or supercapacitor.

Question 2: Which energy storage device or devices would you recommend for a facility that requires energy storage with a large energy capacity at a relatively inexpensive cost?

Solution: This facility requires either of the capacity oriented storage types such as battery or hydrogen storage.

Fig. 4. Synopsis of posttest questions and solutions.

B. Results

The results of the pretest were analyzed to determine the students' baseline knowledge of energy storage. Table IV shows the students' average ranking of the devices for each characteristic on the pretest.

TABLE IV
AVERAGE RELATIVE DEVICE RANKINGS BY STUDENTS ON PRETEST

energy storage device	response time [a]	cost of capacity [b]	roundtrip efficiency [c]
hydrogen storage	3	2	2
battery	2	4	3
flywheel	4	3	4
supercapacitor	1	1	1

[a] 1: fastest, 4: slowest
[b] 1: most expensive, 4: least expensive
[c] 1: most efficient, 4: least efficient

From Table IV, it is seen that the device with the greatest misconception is the flywheel. The majority of students considered it to have the slowest response time, a relatively inexpensive cost of capacity and the lowest roundtrip efficiency. The answers for the magnitude of the response time for the flywheel varied widely from microseconds to hundreds of seconds. Follow-up interviews with the students indicated that the misconceptions about the flywheel were rooted in its mechanical nature. Several students assumed a mechanical device would naturally have a slow response time.

In addition to the flywheel, the average rankings for the hydrogen storage were incorrect. The students tended to overestimate the cost per maximum amount of energy stored and the roundtrip efficiency. The energy storage types ranked most appropriately by the students were the battery and the supercapacitor.

From the results of the pretest, it can be deduced that there was no initial expertise in the subject of energy storage characteristics. This result is not surprising, given that most of the students have had little or no formal exposure to these devices at this point in their collegiate education. The majority of their technical knowledge of energy storage would come from the educational material. The posttest is then a good indication of the efficacy of the material in educating these students.

The results of the posttest for each group are given in Table V. The numbers shown in the second and third columns are the percentage of students in each group that answered the question correctly. The largest improvement was seen in the comprehension of access-oriented energy storage, which increased from 47% to 87%. In this category, the students in the Experimental Group were almost twice as likely to answer the question correctly.

TABLE V
PERCENTAGE OF CORRECT ANSWERS BY STUDENTS ON POSTTEST

question number	control group (% correct)	experimental group (% correct)
1	47	87
2	87	100

The fact that the question with the larger improvement involved the flywheel, the characteristics of which were subject to significant misconception in the pretest, indicates that the analogy is memorable. This was confirmed in follow-up discussion with the students. The underlying premise that enabled the analogy to be effective was the fact that the students tested were familiar with data storage concepts from their day-to-day interactions with computers. The analogy acted to extend these specific concepts of storage to the unfamiliar field of energy storage, thereby bridging a knowledge gap, allowing for increased understanding and retention.

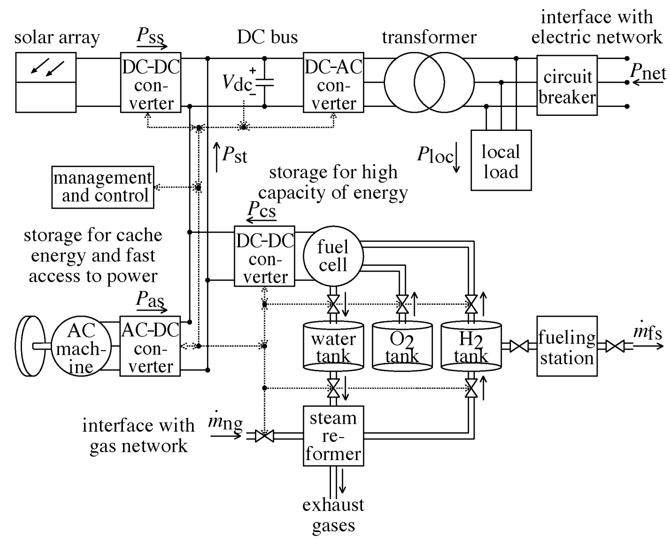

Fig. 5. Industrial distributed energy resource designed in analogy to concepts known from computer system integration.

VI. VALUE IN PRESENTATION

A large part of the general public is familiar with computers and the role of data storage. This makes the analogy a suitable tool for presentations that are aimed at explaining the role of energy storage in power systems to managers and engineers. Experience with numerous presentations given has indeed shown that the analogy is effective in explaining the function of the flywheel in power systems in analogy to the function of the RAM in computer systems [22]. The analogy has shown to impact the audience of presentations in the same way as students in lectures as described in Section V [22].

VII. VALUE IN CONCEPTUAL DESIGN

The conceptual DER design can be synthesized from the insight provided by the translation of data storage design techniques as used in modern computers. By doing so, a multilevel storage as discussed in Section IV can be considered for responding to changes in power over diverse time scales, such as intermittent power from renewable sources, the starting of large motors, the delivery of back-up services, the fueling of vehicles, or the moderation of the power exchanged with the network such that it is devoid of rapid changes. While the capacity-oriented storage provides the energy to balance the long-term trends of fluctuations, the access-oriented storage for cache energy provides a shock absorbing capability to shield other devices from fast fluctuations. As shown in the following study, this promotes modularity since it allows the overall DER design to be connected to the network in a plug-and-supply fashion similar to the plug-and-play concept used in computers [19].

A. Adoption in DER Systems With Multiple Energy Carriers

In the DER illustrated as an example in Fig. 5, a 25-kW roof-mounted solar array generates electric power during daylight hours. Since the photovoltaics alone cannot supply the local industrial load of 90 kW, the DER is connected to the energy infrastructure to obtain both electricity P_{net} and natural gas $\dot{m}_{\mathrm{ng}}$ as energy carriers. While the gas may be employed for industrial processes, it is also used here to reform hydrogen. The hydrogen is stored in a 50-kg hydrogen storage tank that serves as the capacity-oriented storage. The hydrogen flow $\dot{m}_{\mathrm{fs}}$ may be directed to a dispenser to fuel continuous-duty vehicles such as fork lifts with around-the-clock operation and requirement of short refueling times [23]. The hydrogen can also be delivered to the 100-kW fuel cell, whose efficiency is assumed to be 50%. Operational considerations seeking to maximize the efficiency and lifetime of the fuel cell dictate that the fuel cell output should be void of erratic changes in power output. With this impetus, the fuel cell is controlled such that the response time is limited to 250 s. The cache energy used to bridge the response time of the capacity-oriented storage is a 50-MJ flywheel rated at 100 kW with a roundtrip efficiency of 90% and a response time of 5 ms. The access-oriented storage therefore absorbs or supplies any high frequency fluctuations, exploiting the fast response time, high roundtrip efficiency and high cycle life of charge and discharge operations.

The design used to realize the cache control that coordinates the operation of the two storage types relies on filtering to separate the high frequency power fluctuations from the rest of the spectrum as detailed in [19]. Note that the configuration largely corresponds in structure to the stochastic energy source access management plant shown in Fig. 2. It differs in that now connections to both the electric and natural gas networks are present. The supercapacitor is an alternative candidate for storing the cache energy.

B. Scenario of Events

The scenario emulated in Fig. 6 shows the operation of the DER during a loss of connection to the electric distribution network by way of circuit breaker operation and relies on models implemented in the Matlab software similar to those used in [12]. Since the focus here is on energy management, the electromagnetic transients resulting from the operations of the circuit breaker and from power electronic switching are not modeled.

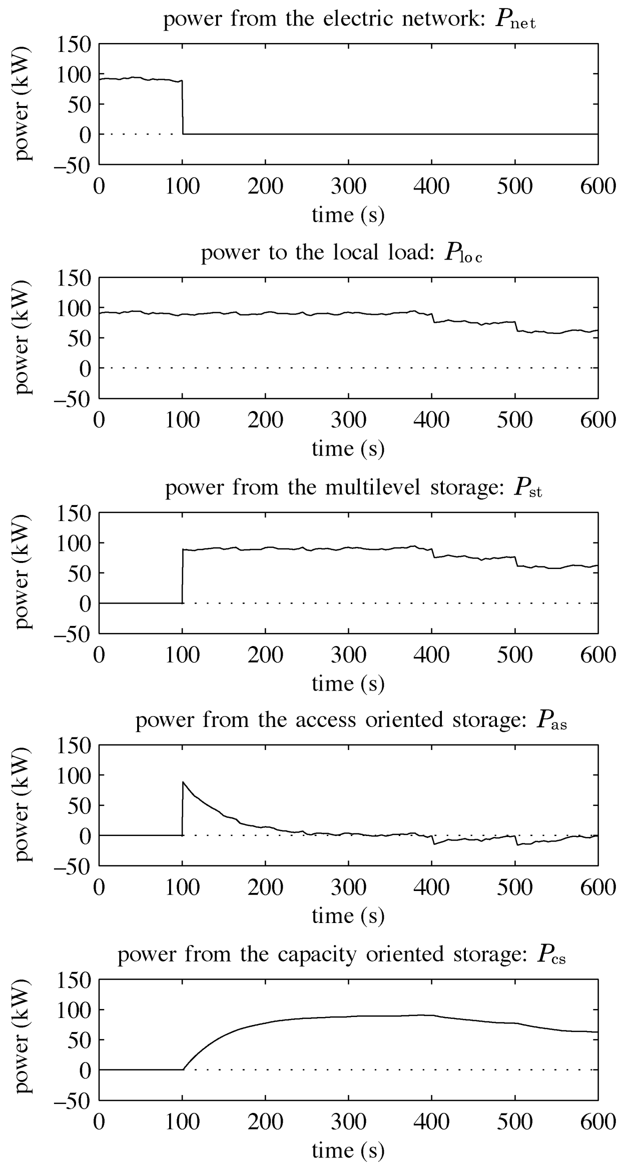

Fig. 6. Simulation results of the cache operation of the multilevel energy storage.

All power electronic converters are represented using their average models.

The simulation covers a 10-min interval showing the transition from electric distribution network power to local back-up power. At 100 s, a loss of power from the electric distribution network resulting from a fault upstream of the DER causes the network connection to be interrupted by the opening of the circuit breaker as the DER transitions to back-up power. The first three plots in Fig. 6, respectively, show the resulting power flows from the electric distribution network, to the local load of the DER, and from the multilevel energy storage. The fourth and fifth plots show the allocation of power from the multilevel energy storage, from the flywheel and hydrogen storage, respectively. In order to highlight the back-up power application of the multilevel energy storage, it is assumed that the simulation occurs after dusk—hence there is no power from the solar array. Extension of cache control in the presence of a renewable resource is trivial as the power from this source conceptually acts to reduce the load and therefore the results shown can be generally applied.

The local load initially fluctuates around its nominal value of 90 kW by about 5 kW. The system is designed to shed nonessential load at specified time intervals in the case of a continuing interruption of the connection to the distribution network. This is manifested as the step shedding of 15 kW of load 300 s after the interruption of the network connection, and another 15 kW of load 100 s thereafter. The multilevel energy storage responds to the loss of power from the electric distribution network at 100 s by supplying power to satisfy the local load. The access-oriented storage, with its fast response time, supplies power to the majority of the local load until the capacity-oriented storage has enough time to increase its output within the specified operating constraints. In accordance with the cache energy concept, the flywheel absorbs or supplies the rapid fluctuations in load, whereas the fuel cell responds to the longer term load changes. The result is a smooth transition to back-up power, without loss of the local load. As 15 kW of load is shed at 400 s, and again at 500 s, the cache effect can be seen as the flywheel balances the rapid changes in power. Note that once the connection to the electric distribution network is restored, the flywheel will need to absorb energy, and the hydrogen plant will require additional natural gas supplied to the reformer in order to compensate for the energy supplied during the interruption. Overall, the simulation results confirm that the multilevel storage makes the DER to behave like a good citizen that can bridge the power fluctuations. It so supports plug-and-supply network integration of the DER.

VIII. Conclusions

The introduction, illustration, and design of the cache energy control for energy storage makes use of three contributions that were described in this paper. First, the creation of the analogy between data and energy storage stimulated the exploration for the transfer of concepts of system integration from computer to power engineering. In particular this concerns the cache energy concept. Second, the value of the analogy was evidenced in that it was shown that university students were able to better understand and retain energy storage concepts via the knowledge bridge to data storage. Third, the analogy can stimulate interest in the early adoption of certain technologies of distributed energy systems. This was illustrated for the case study where multilevel energy storage comprising complementary access and capacity storage emulated the plug-and-play as known from computer system integration.

Key to the creation of the analogy between computer and power engineering principles was the proposed classification into access and capacity-oriented storage types. Access-oriented data storage types such as RAM on the one hand and energy storage types such as flywheel and supercapacitor on the other hand all share the capability of providing fast access to the stored medium at a high cycle life of charge and discharge operations. Capacity-oriented storage types such as hard disk, battery, or hydrogen storage can be designed for a very low cost per maximum amount of medium that can be stored and are so suitable for large capacities.

Coupled together, the two access and capacity storage types of complementary characteristics form a multilevel storage that unites the advantages. As in computers, the access-oriented storage provides a cache for the capacity-oriented storage. Using the example of an industrial distributed energy system that is connected to electric and gas distribution networks, it was shown how the cache energy control contributes to the integration of distributed energy systems. The hydrogen plant provides storage to prevent longer outages and can serve as a fueling station. For the hydrogen plant to provide electric power to prevent outages, its fuel cell units need to be started. The time that is needed for the start-up can be bridged by the flywheel that can compensate disturbances quickly and improve power quality at a high roundtrip efficiency. From the point of common coupling with the electric distribution network, the plant appears as a good citizen whose exchange of power with the network can be controlled over diverse time scales. The cache energy concept was also shown to be implemented by a capacitor coupled with a battery. Cache energy control enhances modularity in that a plug-and-supply capability in analogy to the plug-and-play of computers is attained.

A well-known method consisting of pretesting of knowledge, presentation of educational material, and posttesting of knowledge was employed to verify the value of the analogy in power system education. The results showed that electrical engineering students at the University of Washington better understood the contributions of the diverse energy storage technologies to power system integration by relating them to the well-known computational counterparts. Similar observations were made when presenting the analogy to other audiences. In this sense, the presented analogy stimulates the thinking across traditional subject boundaries and highlights the value of using diverse storage technologies in system integration.

Appendix

A. Selected Data Storage Technologies

Four common data storage technologies are discussed in the following. Special attention is given to each device in terms of data access time and cost per megabyte stored.

1) Static Random Access Memory: SRAM is implemented as a solid-state integrated circuit and contains addressable static memory cells. The notion static refers to the fact that the memory cells retain their statuses without refreshing. This is made possible by implementing the memory cells with a form of latched storage using flip-flops. Access to the stored information can be as fast as 10 ns when designed for high-speed application. However, SRAM has a high cost per bit stored due to the relatively expensive realization of the memory cells. The price per megabyte can be of the order of tens of U. S. Dollars.

2) Dynamic Random Access Memory: DRAM is implemented as a solid-state integrated circuit and contains addressable dynamic memory cells. Each memory cell is composed of one transistor-capacitor pair. The transistor allows access to the capacitor and can change the electric field. Access to the data is fast and of the order of 100 ns. Prices per 1000 megabytes are of the order of tens of U. S. Dollars.

3) Hard Disk: Hard disks are round hard platters on which a magnetic medium is coated. The latter is capable of storing magnetic flux patterns through which information is encoded. Read-write heads are mounted on arms and allow access to data. The access time includes the time for the read-write head to move to the location of interest and is about 5 to 10 ms. Prices per 1000 megabytes are only of the order of tens of U. S. Cents.

4) Phase-Change Digital Versatile Disk: On a DVD with phase-change technology, the so-called phase-change medium can be brought into different states of reflectance through the heat generated by the laser beam of the DVD drive. The information can be read by optically identifying the different states along a spiral track. The access time is of the order of 100 ms. Each disk can store multiple gigabytes of data and the manufacturing of the disks is cheap. This results in low cost of storage of the order of tens of U. S. Cents per 1000 megabytes.

B. Selected Energy Storage Technologies

In what follows, five energy storage technologies are considered. This list is not exhaustive and can be extended with further descriptions [2].

1) Supercapacitor: Capacitors allow for the storage of cache energy in an electrostatic field, which is due to the separation of electric charges. The highest level of performance is obtained with supercapacitors, which are commonly designed as electrochemical capacitors. A direct voltage is applied between the electrodes that are separated by an electrolyte. A polarized layer is formed to provide charge separation over very small distances between each of the electrodes and the electrolyte ions. This will result in the storage of energy in the formed electrostatic field. Access to power of several tens of kilowatts can be provided rapidly within milliseconds. Important features are the long cycle life, which allows for several tens of thousands of charge and discharge processes, and efficiencies of the order of 90%. Capital cost per maximum unit of stored energy can be several thousand U. S. Dollars per kilowatthour for high power capacitors.

2) Flywheel: Flywheels store cache energy in kinetic form within a rapidly spinning wheel-like rotor or disk. For utility applications, access to power can be provided rapidly within milliseconds. A flywheel's long cycle life, which allows for several tens of thousands of charge and discharge processes, and efficiencies of the order of 90% and higher are key advantages. Capital cost per maximum amount of stored energy can be several thousand U. S. Dollars per kilowatthour for flywheels with high power ratings.

3) Superconducting Magnetic Energy Storage (SMES): SMES devices store cache energy in magnetic form in a field created by a direct current circulating through a superconducting coil. For utility applications, access to power can be provided rapidly within milliseconds. An advantage is that the lifetime of the SMES does not depend on the number of charge and discharge operations. Efficiencies of the order of 90% and higher are achieved. Capital cost per maximum amount of stored energy can be several thousand U. S. Dollars per kilowatthour for SMES systems with high power ratings.

4) Battery: Battery technology provides one of the oldest means of storing energy. Applying a voltage between the electrodes causes an internal chemical reaction inside the battery, and energy can be stored. When this process is reversed, the stored energy can be accessed. For utility applications, access to power can be provided rapidly within milliseconds. Efficiencies are of the order of 80%. A disadvantage is the relatively short cycle life of charge and discharge processes of common battery technologies. Capital cost per maximum amount of stored energy is of the order of several hundred U. S. Dollars per kilowatthour.

The cycle life is improved when only a fraction of the battery capacity is used for charge and discharge processes as done in hybrid cars. In such an arrangement, the battery also serves to provide cache energy.

5) Hydrogen Storage: With strong interest in the development of the hydrogen economy, hydrogen is frequently seen as a key energy carrier of the future. While hydrogen is the most widely available element, it is found in the form of compounds. It can be extracted through electrolysis where water is split into its component parts of hydrogen and oxygen. In order to run the electrolysis, electric power is necessary. The generated hydrogen and oxygen can then be stored in tanks. From there, it can be delivered to fuel cell units for electric power generation. Access times depend on the fuel cell type and can be of the order of seconds for utility applications. Strong research programs are underway to improve the efficiency of fuel cell and electrolyzer systems with the goal to eventually reach storage efficiencies closer to 50%. An advantage is that energy and power ratings can be specified independently. The capital cost per maximum amount of stored energy depends on the hydrogen tank and is of the order of tens of U. S. Dollars per kilowatthour if no space constraints are present.

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