Experimental Evaluation of Energy Transfers by an Energy Packet Switch in a Digital Microgrid

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***Abstract*—In this paper, we experimentally demonstrate the performance of the recently proposed Energy Packet Switch (EPS) for energy distribution. The $N \times M$ EPS aggregates the energy from N sources and dispatches energy to M outputs, each of which feeds one or many loads. Energy is distributed from a source to a load in the form of energy packets. The operation of the EPS is an enabler device to realize a digital microgrid. We carry out exhaustive experiments to show that the EPS grants energy to keep demand satisfied and even in cases when the demand overwhelms the EPS capacity. Results of the experiments show that the EPS ably grants all energy requests that fall within its capacity, and it controls the distribution of energy under extenuating conditions by approaching a level of fairness. The experiments also show the average time that a request waits for the corresponding grant**.

Keywords-Digital Grid , Energy Packet Switch, Controlled-Delivery Power Grid, EPS Testbed

I. INTRODUCTION

During the past decades, the North American power infrastructure has evolved into what many experts consider to be the largest and most complex system of the technological age. However, the vulnerability and potential problems of the power grid have placed the challenges of energy transmission and distribution into the limelight. Recently, several works are proposing the concept of a digital grid (DG) [1]-[3]. In such a paradigm, the grid transmits energy as the Internet does with data. Elements of the grid (e.g., generators, distributors, buses, and loads) play active roles in the estimating and configuring the path that electrical energy follows, from energy generators to consuming loads. In particular, our approach to the digital grid is the controlled-delivery power grid (CDG) [3]. The CDG aims to perform finer and more efficient management of energy distribution, which in turn sets up front the balance between the generation of electrical power and the demand of it rather than in a reactive approach [3]-[5].

The DG, which is much inspired by the operation of the Internet [1], is expected to share many of the properties of a data network and with that, provide the level of service of today's power grid plus additional features needed to overcome its weaknesses. The improvements are a higher level of resiliency and direct integration of alternative energy sources. In the digital grid, energy is analogous to what data is to the Internet. Therefore, the digitization of energy is needed to complete the analogy. However, digitization of energy is a concept complex to realize. A reason for that is the existing long tradition of using the grid passively, where energy is considered a flow whose behavior adheres to Kirkhoff's laws. Nevertheless, one can consider digital energy bits as discrete amounts of energy, which are also transmitted as a flow but in controllable amounts. The time of transmission and the amount of transmitted energy define the amount of supplied energy.

The DG offers an alternative for performing precise control on energy delivery. In a DG as in the CDG, users may issue requests for energy, and the provider may entirely or partially grant them within a time period. Such an approach facilitates the estimation of total demand and gives the provider the ability to determine how and when to satisfy the requests. This management model also favors the adoption of a highly controlled supply.

The concept of controlling the distribution of energy through micro-grids is under consideration as the next generation electrical grid [4]-[14]. Approaches to verify user identification before the start of energy transmission in point-to-point communications is a common feature of a more advanced grid in such proposals [2, 13]. However, the ability to scale up point-to-point distribution systems challenges its scalability and uncontrolled delivery (and consumption) remains along with its associated risks to abusing the grid balance, and then expose it to failures. Elastic loads have been proposed to balance the grid [15]. However, such an approach requires scheduling of user loads by the provider and not by the user. This approach is unsuitable for paying customers.

In summary, recent efforts to define a power or energy switch seek direct or alternating current controllers where Internet addresses enable distribution paths. The properties of having a permanently energized grid and discretionary loads remain in existing designs, realizing but partial digitization of the grid. These facts raise the following question: Is it possible to control the energy delivered in discrete amounts to a load on a network-controlled power grid as a more robust approach to a digital grid?

To address this question, we propose an *energy packet switch* (EPS) that receives and supplies energy in discrete and addressable amounts. The switch receives energy by the ingress ports and issues energy by the egress ports. The combination of transmitting energy on finite and discrete amounts with associated network addresses gives place to what we call an energy packet. The switch issues an energy packet after the execution of a request-grant protocol. The design of our energy packet ensures that the amount of energy the load receives is defined. We use supercapacitors as energy containers to achieve this operation. The supercapacitors shape the energy packets, enable receiving energy from multiple and diverse sources, and supply energy to one or multiple diverse loads.

In this paper, we introduce the design of the EPS, discuss its properties, and experimentally show the operation on critical tests. Within these experiments, we show how the EPS transmits energy from inputs to outputs. The combination of controlled energy supply through energy packets and the use of the request-grant protocol increase reliability and reliance of the grid under challenging environments.

We organize the remainder of this paper as follows. Section II introduces the concept of the digital grid. Section III introduces the proposed energy packet switch. Section IV introduces the EPS testbed. Section V shows evaluations on experiments transferring energy from the EPS. Section VI presents our conclusions.

II. A Digital Microgrid

A major advantage of a digital microgrid (DMG) is the supply of discrete and finite amounts of energy, on demand, to loads. In the DMG, energy delivery follows a request-grant protocol performed between energy sources and users to avoid exposing the power grid to discretionary consumption. After being requested by the user(s), the source or an EPS supplies an energy packet to the requesting user, who is the only one allowed to access the transmitted energy. The energy packet carries the granted amount of energy. An energy packet can also be sent to multiple requesting users and carry aggregated energy.

Addresses considered for each entity in the grid are expected to adopt those from the Internet Protocol (IP). The assigned addresses of the users enable the concept of energy ownership. In the CDG, the power line may carry the destination addresses of energy recipients or also a parallel data network, as considered in this paper. Both options require the synchronization of energy and data. In the CDG, energy sources and users exchange control data via the data network. Based on the exchanged data, the central controller determines the supply of energy through the power network. Here, we adopt this operation mode.

In this paper, we consider that time is slotted, and that energy is transmitted every time slot. The time it takes to supply the granted energy from the EPS to the user determines the duration of a time slot. This time is the interval a user is allowed to access energy from the grid per each received grant [5]. In this paper, we set a fixed amount of energy in one energy packet by adjusting the voltage of each supercapacitor, as energy os proportional to the voltage. We use supercapacitors as energy containers with limited capacity.

III. Energy Packet Switch

The EPS is a network- and data-controlled switch that has M inputs and N. The inputs connect energy sources (or another EPS) to the EPS and the outputs connect the EPS to receiving loads (or another receiving EPS), to supply the energy to energy-demanding users. Figure 1 shows an $M \times N$ EPS.

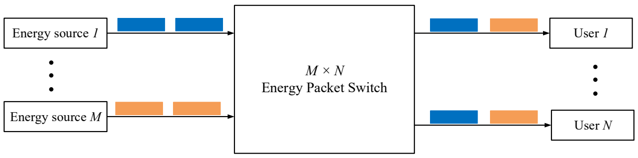

Figure 1 Energy packet switch with *M* inputs and *N* outputs and an example of multiple energy sources sending energy packets to multiple uses through the switch.

This figure shows how multiple energy transmit energy packets to multiple users. The EPS integrates the energy supplied by multiple energy sources and deliver it to a heavily demanding user.

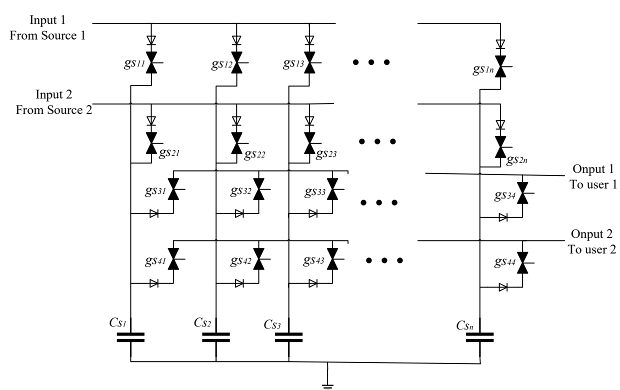

Figure 2 Schematic of a 2x2 energy packet switch.

Similarly, the EPS also supplies the energy requested by multiple users from a single energy source. In both scenarios, each source-EPS or EPS-user energy transfer carries a finite amount of energy; this is what we call an energy packet.

The EPS uses multiple supercapacitors, each of which is a unit of shared energy storage. The EPS works with direct current (DC) although it can be accommodated to work with AC.

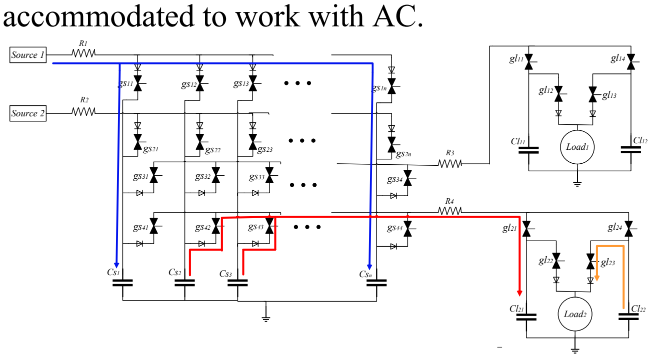

Figure 3 Schematic EPS testbed with two energy sources and two users.

Figure 2 shows the schematic diagram of a 2×2 EPS with *n* supercapacitors. The energy sources connected to the inputs of the EPS may supply energy to one or multiple supercapacitors each, and one or multiple supercapacitors may store energy for short-term storage and supply that energy to users at fast rates as well. Therefore, in our design, the EPS plays the role of a user when it receives energy from sources and the role of a source when it transfers energy to users. As the figure shows, combinations of solid-state relays (SSRs) perform the function of switching elements in the EPS. The EPS controller sets the state of the switching elements as closed or open, according to the amount of requested energy and the amount of available energy. The switch elements interconnect one input, or incoming energy, to one or multiple supercapacitors to receive energy, and interconnect one or multiple supercapacitors to an out to transfer their energy to a load. Here, we use supercapacitors as energy containers that have a defined capacity, such that energy that is transferred is bound.

To be able to interface the EPS with loads for a proper energy transfer, we consider that users, and loads in turn, also use supercapacitor as energy storage. Figure 3 shows the structure of a user with two supercapacitors working as energy containers and four switching elements, or SSRs, for routing energy to each supercapacitor. In the user infrastructure, each of the supercapacitors exchanges the role of energy provider to the load at different time intervals such that the load can perform work continuously. In short, while one supercapacitor receives energy from the EPS, the other supplies energy to the load, and vice versa. Therefore, two SSRs are needed for each supercapacitor as one controls the receiving of energy from the EPS and the other controls providing energy to the load.

The operation of the EPS aims at handling the charging/discharging process of the supercapacitors with configurable capacitance. Supercapacitors have the property of charging and discharging at a fast rate as long as large the circuit rescinds from large resistances. Furthermore, the energy density of supercapacitors keeps increasing with new developments to such a point that the amount of energy stored in today's supercapacitors is becoming applicable to higher-power loads.

This testbed has two energy sources and two users connected to the EPS. As the figure shows, gs_{ij}, implemented by the SSR, is a network-controlled switch that connects an input (or output) port with supercapacitor Cs_j. Similarly, gl_{ij} is a network-controlled switch that connects the EPS

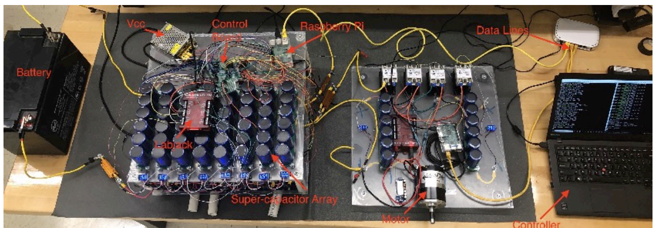

Figure 4 Implementation of the EPS testbed.

with the user supercapacitor (Cl). We call these SSRs network-controlled switches as their status depends on the request/grant data exchanged through the data network. A power access point (PAP) interprets the data exchanged through the network and decides the status of the SSRs. A PAP is CDG components at the user premises, and it works as an interface to access the data and power networks. It communicates with an EPS and enables receiving energy and designating a receiving supercapacitor(s). A controller in an EPS controls the passing energy from sources to loads; this is, from the supercapacitors in the EPS to the supercapacitors connected to requesting users. The PAP controls the status (open or close) of the SSRs for setting the final connection for establishing energy distribution routes. For example, as the figure shows, the blue lines are the routes where Cs_l and Cs_n receive energy from energy source 1 and the red lines are the routes where Cs_2 and Cs_3 provide energy to Cl_{21}. At the same time, the orange line shows the route to supply energy from Cl_{22} to load 2.

We tested the CDG concept through simulations, and results show that high current transmitted between an energy source and a supercapacitor enables the fast-paced energy transfer [16]. Moreover, the experiments show that an energy source with high current capacity may act as a fast-charging supply to rapidly charge the supercapacitors in the EPS. In turn, the EPS and a user may act as fast-charging and discharging devices, via *Cs* and *Cl*, respectively.

IV. Implementatin of the EPS Testbed

Figure 4 shows the implementation of the 2×2 EPS testbed with eight supercapacitors. Each capacitor is 83.3 Farads. Here, we use one energy source, a 12-V battery, and one user for the experimental testing of the EPS testbed. As the figure shows, a laptop works as the central console to remotely configure/activate the EPS controller. Both EPS and user have a Raspberry Pi that works are the controller and PAP, respectively. By following a request-grant protocol, the EPS communicates with the user via PAPs. After the execution of the request-grant protocol, the EPS issues energy packets to the demanding users whose addresses match that in the requests sent through data packets.

In the testbed, energy packets are formed and transmitted by adjusting the voltage of a supercapacitor. For example, when k supercapacitors are getting energy from the energy source, the payload of the energy packets are written as:

$$Ess = \frac{1}{2} kCs(V_{so}^2 - V_s^2) \qquad (1)$$

where Cs is the capacitance of each supercapacitor and V_{s0} and V_s are the voltages after and before the supercapacitors are charged, respectively. Similarly, if energy packets are transmitted between the EPS and a user, the energy in the system is:

$$kCs\,(V_{so} - V_s) = Cl\,(V_l - V_{l0}) \qquad (2)$$

$$E_{sl} = \frac{1}{2}\, Cl\,(V_l^2 - V_{l0}^2) \qquad (3)$$

where (2) describes charge conservation when k supercapacitors in the EPS charge the load supercapacitor, and (3) is the amount of energy contained in the energy packets transmitted to the user.

The EPS testbed works as follows: At first, the energy source initializes the voltages of all the supercapacitors in the EPS to V_{s0}. When the voltage(s) of the supercapacitors of the user(s) is below a threshold V_{l0}, the user sends a request for energy to the EPS. The request message contains the IP address and the target voltage V_l of the requesting user. After receiving the request, the EPS calculates the number of supercapacitors, k, that are required to charge the user's supercapacitor to the requested voltage according to (2). If there are more than k supercapacitors available in the EPS, the demanding users receive all the requested energy. An energy packet carries the amount of energy as in (3). The energy source recharges the k capacitors in the EPS to the maximum voltage level after they transmit energy to the user, where (1) describes the amount of energy a source transmits to the EPS.

In this paper, we adopt a two-state modulated Markov process to describe the energy requests of a user's load. The state of the load changes from ON to OFF with probability p, or remains ON with a probability *1-p.* Similarly, a load changes state from ON to OFF with probability q and it remains in the OFF state with probability *1-q*. The model is programmed in the PAPs and describes a burst-idle pattern. The total length of the time T, or a cycle, for a time ON and OFF is $T=n\ (T_{ON} + T_{OFF})$, where $T_{ON} = 1/p$ and $T_{OFF} = (1-q)/q$. Here T_{ON} represents the average burst ON time and T_{OFF} is the average idle (OFF) time.

V. Experiments and Results

A. Parameters of the experiments

We carry experiments on the EPS testbed. Table I lists some of the parameters used in the experiments.

Table I: Parameters used in the experiments

Parameters of the EPS testbed		
EPS	Number of supercapacitors	8
	Initial voltage of supercapacitors	7.5V
User	Number of supercapacitors	2
	Threshold (V_{l0})	2.8V
	Target voltage (V_l)	4.2V
	Load	A DC Motor
ON-OFF	Total test time	1 hour
	Cycle time	20s
	Probabilities: p, q	vary
	Time slot	2s
Others	Resistors	0.5, 1 or 2Ω
	Limiting current	15, 7.5, or 3.75A
	Energy source (Battery)	12V
	Current	DC

B. Test with Maximum Limiting Current

We measure the satisfaction ratio and the amount of energy transmitted to the load as functions of the average burst time ratio is $r = T_{ON}/(T_{ON} + T_{OFF})$. It is clear that as the average burst time increases, the energy demand of the load increases.

We first test these two metrics for the maximum limiting current in this paper to show that the EPS can achieve 100% satisfaction ratio. The satisfaction ratio is the number of granted energy requests over the sum of granted and ungranted. requests. Figure 5 shows the ratio of satisfied time slots of the load and the total transmitted energy from the EPS to the user with different ratios of average burst time for the maximum limiting current of 15 Amps. In the figure, the orange line shows that the satisfaction ratio remains at 100%. The blue bars in the figure show the total amount of transmitted energy in the one-hour test. When the ratio of average burst ratio is 90%, the maximum tested, the total transmitted energy is about 20 kJ.

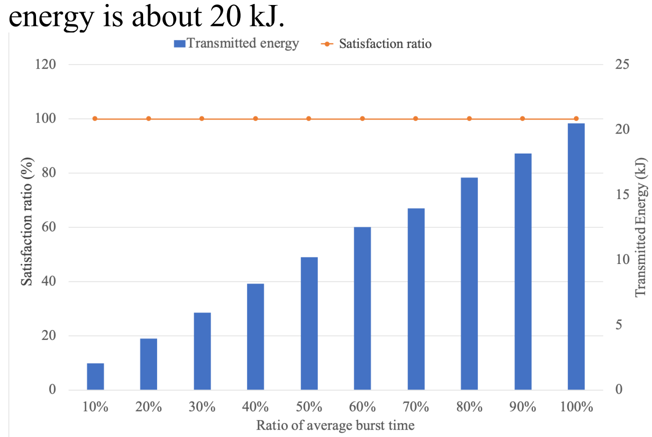

Figure 5 Satisfaction ratio and total transmitted energy of different average burst time.

C. Experiments with Small Limiting Currents

The speed in what the EPS transfers energy to a load largely depends on the maximum limiting current used to charge the supercapacitors. In a time slot, the total amount of energy that can flow from the EPS to a load is also affected by the limiting current. Here, we consider the cases for 3.75 and 7.5 Amp. Figure 6 shows the performance of the EPS under these two limiting currents. The blue line shows the ratio of satisfied time slots when the maximum limiting current is

3.75 Amp. As the figure shows, as the ratio of the average burst time increases, the ratio of satisfied time slots decreases from 100 to about 75% for the largest burst ratio. However, as the orange line in the figure shows, the satisfaction ratio is about 85% for the 7.5-Amp current. In this figure, the blue bars show the total transmitted energy for a limiting current of 7.5 Amp. The maximum transmitted energy or 13 kJ is reached when the average burst ratio is about 70%.

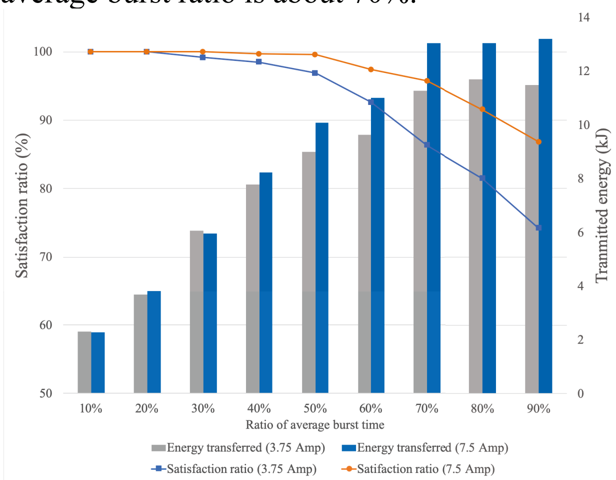

Figure 6 Satisfaction ratio and total transmitted energy.

The maximum transmitted energy, in gray bars, show similar behavior but at 11 kJ for the 3.75-Amp current. This scenario shows that under a heavy demand, the satisfaction ratio remains high.

VI. Conclusions

In this paper, we introduced the implementation of an energy packet switch (EPS) based on supercapacitors as energy containers. The EPS connects multiple energy sources and multiple users and to distribute energy between them. Every element of the microgrid, including the EPS, uses supercapacitors to achieve high flexibility on the timing and rates of energy transfers. In this digital approach, energy includes an address and supply follows a request-grant protocol, as in a digital grid. We control the amount of energy transmitted by adjusting the voltages of transmitting and receiving supercapacitors. We show, through actual experiments on our tested, the controllability of the EPS and that it achieves high satisfaction ratios.

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