Management of a Smart Grid with Controlled-Delivery of Discrete Levels of Energy

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Abstract—**At time of energy shortage electrical grids may be exposed to consumption uncertainties, overloads and ultimately power failures. The main reason is that, at present, the response of the power provider to increasing demand is lagging after requests for power are made. In this paper, we examine a different request-supply approach where the amount of delivered power must be requested beforehand. The power is then supplied in compliance with the physical, economical, and management limits of the distribution loop (DT), and in accordance with scenarios, such as a sudden demand surge or supply shortage.**

As proposed recently, in the controllable-delivery power grid, delivery of electrical power is made through discrete power levels directly to customers. The customer's addresses are embedded in the electrical signal, and smart loads associated to customers curve the consumed power and provide reactive stability to the DTs. We analyze an approach for distributing electrical power, where the capacity of the DT is capped by the average of the requested power (and therefore introduces a very stringent requirement). In cases of power shortage, the DT is scheduled by using a round-robin model. We show that a DT can satisfy about 98% of power requests in scenarios of energy scarcity and beyond 99% by adding small safety margins. Further advantages are seen when unused energy is stored in local distributed storage elements (cloud storage) during supply surges and used in time of demand peaks. This grid proposal is advantageous for green power distribution because it enables a direct exchange of energy between customers and local suppliers at the discretion of the grid manager.

I. Introduction

A major operation task for the present power grid is keeping it stable while maintaining the difference between power production and demand to a minimum. Recently, a controllable-delivery power grid concept, called the digital grid, has been proposed [1]; here energy is delivered in discrete (digital) levels. By contrast, present grids distribute energy in analog fashion. In analog grids, generators might be adapted to re-balance the grid at times of overproduction and safety margins are imposed to avoid under production.

Everyday experience shows us that the power grid is fairly robust; yet, the response of power providers (and generators) to increasing demand may still lag due to demand and production fluctuations beyond forecast estimations. Luckily, these fluctuations are mitigated by the large number of customers served, leading to a statistically robust averaged behavior.

The stability of the grid also relies on careful data analysis and use of sophisticated predictive models. Such approach helps maintaining relatively small safety margins [2]. On the other hand, if we to compare worst case scenarios during peak hours to average consumption, this difference may reach 60% or more, leading to energy waste. Power failures are relatively rare but their overall impact is devastating. Thus, quick adjustment of power production to temporal demand is key to power grids stability and minimal power waste.

The search for a smarter stable grid, where demand is most closely followed by the supply, is very desirable. The present grids allow customers to access and consume large amounts of electricity at any time. Grid overloads have to be carefully monitored and in case of an extraordinary event, DTs ought to be taken out of the grid. Decisions like that are made on a broad scale and cannot pin-point specific customers. Close monitoring of the grid's performance may be achieved by deploying parallel (auxiliary) sensing networks [3]–[12]. Concerns about ensuring working paths which carry energy all the time translate into additional management complexity [10], [13]. The adoption of a controlled distribution of power, which is seamlessly coupled with grid monitoring, becomes an important part of the grid management.

In our proposed model, customers issue requests for power and the provider may fully, or partially grant these requests. This enables the provider to determine how to satisfy the requests ahead of time. Our model also implies the adoption of a controlled supply. In this grid, management of supply with limited capacity can be made on a customer-by-customer and fair bases. It allows the service provider supplying part of the energy needed and even a negotiation where part of the provided energy is supplied.

The amount of delivered power is controlled with the designation of ownership to specific power amounts. Here ownership means that the delivered power may only be used by the destined customer(s) [1]. Thus, the electrical signal carries the customer grid address (which can be considered to be similar to an Internet address). Power is delivered upon matching the customer address at an access point near the customer's premises. The address is carried by the electrical signal or by an auxiliary data network.

The concept of controlling the distribution of energy through micro-grids has been recently discussed [14]. Approaches to verify customers identification before the start of energy transmission have been also considered [10]. These approaches, however, require one-to-one connection and therefore, are un-scalable to large number of customers. Some of these works were motivated by alternative-energy applications, where sources and appliances are connected through separate direct current (DC) lines, [15]. However, uncontrolled delivery (and consumption) remains an undesirable factor in these approaches, as well.

Our approach is asynchronous, meaning that we can satisfy customer requests issued at any time. The request starts when an appliance is turned on and a hand-shake protocol with the energy provider is established. Smart power switches ensure the time and level of power delivered during any given cycle. Demand fluctuations, if present, are known in real time and the energy provider has the option to meet these sporadic demands in full, or negotiate a partial supply. Therefore, one may think of prioritizing the power delivery to specific customers upon need and urgency. Our inter-grid approach is scalable and deployable to intra-grid models. The approach is very attractive when the overall available energy is limited. In this case, a fair way of controlled power delivery is proposed the round robin schedule ensures that the customer served in the last cycle is ranked the lowest in the preference list for the following cycle. Finally, the concept of distributed energy storage (cloud storage) is introduced. Such concept helps mitigating power delivery fluctuations and points to the importance of short-term local energy storage, on the scale of ms to a few hours.

Here, we set to show that a fair management of controlled-delivery grid also achieves high satisfaction ratio of customer energy requests, especially when energy of the distribution loop is scarce. For this, we modeled and studied a controlled-delivery power grid, using a round-robin schedule for selecting customer requests, with a moderate number of customers (namely 1000 customers), and show that we can accommodate over 98% of power requests when we cap the maximum power supply to the average of overall demands, and 99% of requests with small safety margins. This approach differs from the prevailing analog approach, where the capacity is capped at the maximum expected demand (or capped at the worst case scenario level plus a safety margin). We consider the use of energy storage and show that the ratio of satisfied energy requests reaches over the level of 99% without the need for safety margins. In this paper, we refer to power and electrical energy indistinctly.

The remainder of this paper is organized as follows. Section II presents a list of general features of currently deployed power grids. Section III introduces the controlled-delivery power grid. Section IV analyses the achievable satisfaction of energy requests for a power loop. Section V describes our conclusions.

II. Efficiency Factors of a Power Grid

In general, there are several factors [11], [12] determining the efficiency of power grids:

i **Customer energy expenditure**. Presently, the recording and accounting of customer power consumption is based on cumulative data of energy used, generally in watt-hour units, through electricity meters. Power provider companies typically collect metered values on a monthly basis [16].

ii **Forecasted power demand**. Power providers estimate the expected power requirements on the basis of past data. The amount of electricity produced may be set by the maximum recorded such that customers have energy available all the time.

iii **Ability to re-route surplus energy to other grids**. A grid or segments of it must be able to route surplus energy to other grids with energy deficits. Although very desirable, this function is not simple to achieve as losses and phase synchronization maybe required, in addition to providing a transmission route to the demanding grid.

iv **Conversion efficiency**. Conversion of voltage, from alternating current (AC) scheme to high-voltage DC and back to AC at various points of the grid is part of the system operation, and it incurs energy loss. Although the efficiency of several electrical subsystems is high (e.g., transformers) and transmission lines have a moderate loss, these loses need to be considered in the production of energy.

v **Energy storage**. Energy storage is considered in this paper as a means to save energy surplus. In cases where the power production level is given and cannot be further reduced (e.g., in the case of a nuclear generator), energy storing may be sought. Yet, storage of electrical energy is an inefficient process. In the case of an elaborate power grid, energy storage may require major endeavors. For example, a viable possibility is to store solar energy in melted salt towers [17] but this may not practical for the grid of the entire Manhattan Island, for example. Hydro- and thermal storage modes are interesting solutions, however, on relatively small scales. Yet, if instead, local energy-storage devices, or even large capacitors momentarily store the relatively small electrical power consumed by a single appliance, the overall effect is that of a giant storage media. Such a *cloud storage medium* would help minimizing the power overproduction, and as we shall see below, it may increase the processing gain of the individual appliances, as well.

vi **Loss**. In the current grid, electrical energy that is not used, not re-routed, and not stored decreases generators' load, and nevertheless, it is ultimately dissipated. In a power grid using a request-supply protocol, loss is monitored at the consumer level. Furthermore, the use of various levels of energy storage may minimize this loss (i.e., ultra-short term storage in a form of super capacitors, medium term storage such as batteries and ultra-long storage such as thermoelectric wells).

vi **Security**. Here, we consider two levels of security: secured service and user profile information. The present grid has limited protection against unregistered consump-

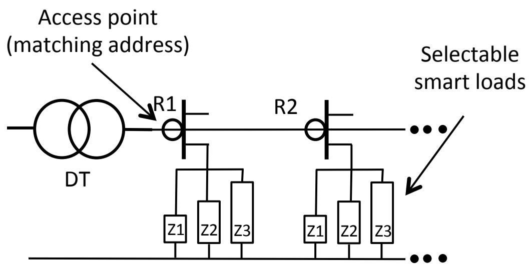


Fig. 1. Smart load selected for each customer.

tion of power, and customer information is only provided by the periodic meter readings. While a smarter grid, based on the request-supply mechanism, may expose the expenditure habits of the customer, something that some customers may be wary to disclose.

III. Controlled-delivery Power Grid

The power grid with controlled delivery aims at supplying discrete and finite amounts of energy to customers. The approach minimizes the difference between energy generation and demand, facilitates power distribution amongst several grids, and increases grid stability through local and instantaneous traffic monitoring.

The controlled-delivery power grid carries energy in discrete units, or energy quanta. Each quantum unit of power may be controlled by time, current, or a combination of both. To overcome having the grid with energy all the time, the electrical signal carries the destination address(es) of specific (or multiple) customer(s) who are the only one(s) allowed to get access to the transmitted energy. Because energy may need to be simultaneously distributed to a single or a number of customers, addressing through code division multiple access (CDMA) [18] can be used, where customers have their own address [1]. Using a modulated signal may be another alternative. The amount of energy per slot may be scaled up in two dimensions: 1) by using several time slots together and form a train of granted requests, and 2) by setting the amount of energy transmitted within a time slot by adjusting the amount of current. In this power grid model, the amount of current may be set to discrete levels. The selected level of power destined for a customer may be set by using selective current limiters, called smart loads, at the customer premises, as Figure 1 shows. The energy supplier performs the selection of a smart load by also embedding the amount of current granted per customer in the electrical signal.

Herein, generation plants are assumed to have a time response much slower than to the second-by-second demand fluctuations, such that only the distribution points are able to show the real-time demand. Therefore, distribution loops may have limited energy capacity and this energy may need to be carefully and fairly distributed. In this power grid model, the forwarding and aggregation of customer demands are performed by gateways that process both information and electrical power.

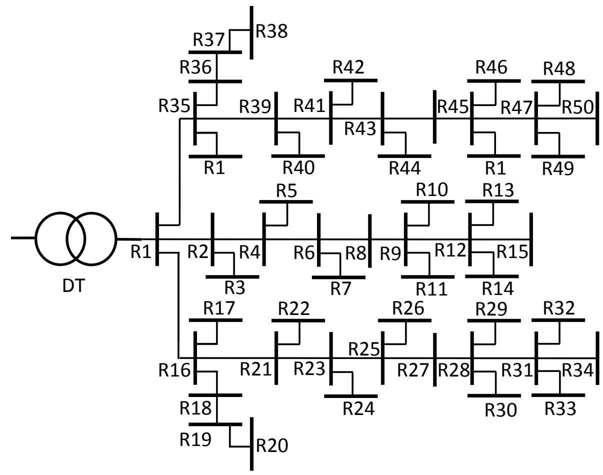


Fig. 2. Distribution network.

The distribution loop (Figure 2) has a large number of customers. Each of them is able to receive addressed energy and paired with the controlled smart loads. Nodes of the controlled-delivery grid (labeled as DT in the figure) adjust the voltage levels, perform signal conversion, and forward the embedded addresses to the signal forwarded to the end customers (labeled as R1 to R50 in the figure).

Unlike the present grid, the protocol for the controlled-delivery grid anticipates some delays in supplying the energy requested by customers. These delays can be listed as: a) A delay may occur when decoding the address, or deciding the granted distribution line before energy is transmitted. b) Routing capacity must be considered to avoid delays, or energy loss could occur. Overbooked distribution points may require efficient energy storage; otherwise, a routing scheme with a guaranteed clear path needs to be secured. c) Delay in the processing of power requests.

The path of data, coupled to the power grid: a) finds the requested energy levels as issued by customers (or local distribution points) and assigns the power coming from the generation plants to supply those requests, b) finds routing information about where to forward the energy, and c) attaches the destination address and the amount of current for the supplied power for secure and guaranteed delivery. Because energy quanta can be used by any destination (in terms of a single unit), the supply of energy does not need to differentiate the incoming energy (from the generator) but the outgoing one, in a destination (or customer) basis.

A. Distribution Points

Distribution points transfer energy in two possible directions: 1) from the generator to the customer, and 2) from the distribution loop towards other grids (energy re-route). These distribution points also perform energy conversions, including voltage step-up and -down, as they may also be used to interconnect different distribution segments, from generators to costumer supply. The forwarding of energy to other grids is out of the scope of this paper.

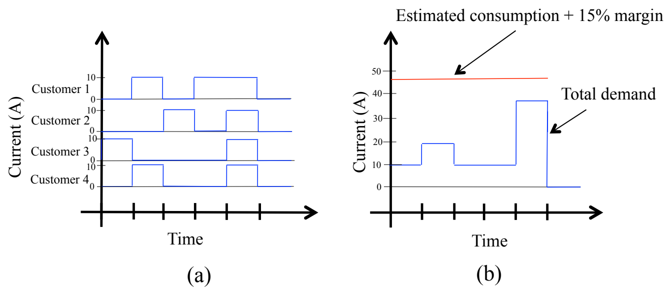


Fig. 3. Example of current demand (a) individual demand of four customers, and (b) total demand.

Because the objective is on supplying energy in discrete levels, a distribution point may have different set of transformers that support different levels of current rather than having a single transformer supporting a maximum amount of current. These transformers may be coupled with the smart loads. In this way, the aggregated amount of current can satisfy the different discrete levels of energy requested by customers and as granted by the distribution point.

Figure 3 shows an example of delivery of discrete energy to customers, considering 1-level requests. We compare it with the a present power grid whose capacity is capped at the worst case scenario level plus a safety margin to maintain grid stability. In this example, there are four customers, each issues a random request for an amount of current. The grid can only provide discrete levels of current, which are 1, 2, 4, or 8 Amps. Figure 3(a) shows the individual requests and Figure 3(b) shows the total current supplied, in discrete levels, within the loop capacity.

B. *Round-robin Management for Discrete-amount Requests*

As the distribution loop has limited capacity, the aggregated customers' requests may exceed it. The distribution point selects requesting customers in a round-robin schedule for satisfying the discrete-amount requests. The selection performed by the distribution point is described as follows:

Phase 1. Each customer issues an energy request, if any, to the distribution point in an allowable discrete amount.

Phase 2. The distribution point grants a request if the amount of energy remaining is larger than the requested level (full supply), or if the remaining energy is equal to smaller level or energy (partial supply). Once the remaining amount of energy is zero or smaller than the smallest level, no more customer requests are granted, and the distribution point waits until the next cycle starts. Energy is supplied in the following time slot after a request is granted.

IV. Evaluation of Energy Distribution

We evaluated the efficiency of the management mechanisms for the controlled-delivery power grid. For this, we modeled a distribution loop and the management mechanisms in Matlab for computer simulation. The energy requests of a customer were modeled as a two-state (ON-OFF) modulated Markov process. The energy request that is currently OFF becomes ON with probability q, or remains OFF with a probability $1 - q$ for one hour, which is a characteristic time window. The request change its state to OFF with a probability p, or continued its ON state with probability $1 - p$. The ratio of satisfied customers, defined as customers whose energy request is fully satisfied was then assessed. In addressing a request the program first fulfilled the lower power needs of all customers and moved on to fulfill the next level using the round-robin rule. Specifically, the distribution node keeps track of the customers served and in the order in which they are served. We considered 1000 customers in each loop. The demand from all customers in the loop was averaged for 1 year (365 days) and the value obtained served as the average capacity of the loop. Each day was split into three 8-hour intervals, with each interval having a different average request-burst size, with values of 4, 6, and 3 hours. This approach is very similar to the way power grid providers estimate production levels [19].

A. *Power Line Supply with Margin and Energy Storage Support*

Table I shows the 15 different scenarios (enumerated from 1 to 15) considered in our study. The scenarios differ in the number possible levels of energy and amount of energy per level that a customer may request. The controlled-delivery power grid then attempts to satisfy the energy requested. However, if the power grid cannot fully provide for an energy request (e.g., because of limited energy capacity), it attempts to provide the next lower energy level instead. For example, Scenario 2 calls for two energy levels: 3 and 6 units. If a request is made for 6 units and the limited capacity grid is not able to fulfill such request, it may provide 3 units instead. Note that this scenario cannot be accommodated in the present power grid as energy is not addressable and all customers connected would consume whatever is available from the distribution line, leaving most customers unsatisfied.

TABLE I
Test scenarios

Scenario	No. of levels	Levels	Prob. per level
1	1	3	1
2	2	3, 6	0.7, 0.3
3	2	3, 6	0.5, 0.5
4	4	3, 6, 9, 12	0.25, 0.25, 0.25, 0.25
5	4	3, 6, 9,12	0.1, 0.2, 0.3, 0.4
6	4	3, 6, 9,12	0.4, 0.3, 0.2, 0.1
7	4	1, 2, 4, 8	0.25, 0.25, 0.25, 0.25
8	4	1, 2, 4, 8	0.1, 0.2, 0.3, 0.4
9	4	1, 2, 4, 8	0.4, 0.3, 0.2, 0.1
10	8	3, 6, 9, 12, 15, 18, 21, 24	0.125,0.125,0.125,0.125
11	8	3, 6, 9, 12, 15, 18, 21, 24	0.025,0.05,0.075,0.1,0.125,0.15,0.175,0.3
12	8	3, 6, 9, 12, 15, 18, 21, 24	0.3,0.175,0.15,0.125,0.1,0.075,0.05,0.025
13	8	1, 2, 4, 8, 16, 32, 64, 124	0.125,0.125,0.125,0.125
14	8	1, 2, 4, 8, 16, 32, 64, 124	0.025, 0.05,0.075,0.1,0.125,0.15,0.175, 0.3
15	8	1, 2, 4, 8, 16, 32, 64, 124	0.3, 0.175,0.15,0.125,0.1,0.075,0.05,0.025

Furthermore, an energy request is modeled by providing a probability that a level is requested by the customer. The table then shows the probabilities for each possible energy level in each scenario, in the third column. We explore the cases when the probabilities for each level request are either the same or different.

TABLE II
RATIO OF SATISFIED REQUEST FOR THE DIFFERENT TEST SCENARIOS

Scenario	Sat. req. by PL only (%)	Sat. req. PL +2% (%)	Sat. req. PL +5% (%)	Sat. req. PL +10%	Sat. req. PL+ storage (%)
1	98.92	99.54	99.87	99.98	99.61
2	98.66	99.37	99.81	99.98	99.54
3	98.69	99.39	99.80	99.98	99.57
4	98.52	99.27	99.78	99.96	99.51
5	98.69	99.41	99.81	99.98	99.57
6	98.47	99.21	99.75	99.96	99.48
7	98.19	98.98	99.61	99.93	99.40
8	98.41	99.20	99.73	99.95	99.47
9	97.99	98.85	99.52	99.89	99.36
10	98.20	99.11	99.69	99.94	99.28
11	98.47	99.31	99.78	99.96	99.38
12	97.86	98.80	99.55	99.92	99.17
13	96.43	97.51	98.63	99.55	98.35
14	97.73	98.66	99.42	99.87	99.10
15	93.29	94.57	96.20	98.04	96.11

Table II shows the ratio of satisfied customer requests for all cases, collected in 1000 days. In this table, the energy provided only by the power line is labeled as PL. The ratio of satisfied request by the power line with an average capacity, $\bar{C}_l$, is presented in the second column. The ratio of satisfied requests by the power line (as in the previous case) but with an additional 2% more energy, PL+ 2%, follows. The ratios for PL+5% and PL+10% follow. We also include the case where a energy-storage unit is considered. In this last case, the power line is provided with capacity $\bar{C}_l$. In the cases where the requested amount of energy is smaller than the supplied energy, the energy storage device is charged with the remaining energy. $\bar{C}_l$ equals the average amount of requested energy, $\bar{R}$, or $\bar{C}_l = \bar{R}$. We considered storage with unlimited capacity and high efficiency. Stored energy is then used when the total amount of requested energy is larger than loop capacity. We summarize the results as follows. When using the power line with a limited capacity, such that $\bar{C} = \bar{R}$, most scenarios achieve about 98% requests satisfaction, with the largest satisfaction ratio for Scenario 1 (98.92%), and the lowest ratio for Scenario 15 (93.29%). The addition of the power line capacity increases the satisfaction ratio, as shown by PL+2% and PL+5%, reaching 99% or more for most scenarios (except for Scenarios 13 and 15, which are 98% and 96%). However, an additional 10% on the power line capacity leaves Scenario 15 with 98% satisfaction (while Scenario 13 now also reaches 99%). In this case, Scenario 15 achieves only 98.04%. On the other hand, the satisfaction ratio of using a energy storage unit on a power line with capacity $\bar{C}_l$, and labeled as PL+storage in the table, is the same as for grids with an additional 5% capacity. Therefore, an energy storage unit would save about 5% or energy if only the residual energy is stored. The number of satisfied request can be increased if the energy storage receives energy from alternative sources.

These results also show that the significant efficiency of the studied framework. Take for example Scenario 4, where the average amount of energy requested by a customer is 7.5 units. Rather than providing the maximum possible of energy request, say 12 units, the average suffices to satisfy about 99% of the average request, which is about 60% of the maximum. The energy needed in the controlled-delivery grid

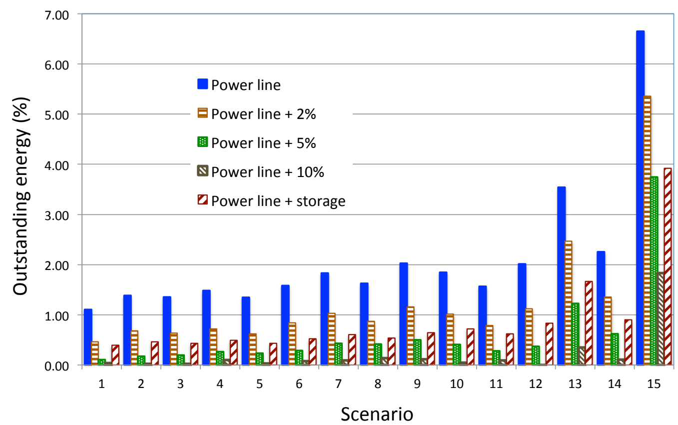


Fig. 4. Energy difference between requested energy, $\bar{R}$ and the energy in a) power line with $\bar{C}_l = \bar{R}$, b) power line +2% the capacity in a), c) power line + 5% the capacity in a), d) power line +10% capacity, and e) power line with a energy storage charged by residual power-line energy.

can be compared to the energy provided by the present power grid, which equals the peak. And for an average demand, a large portion of power may be unused for a period of time.

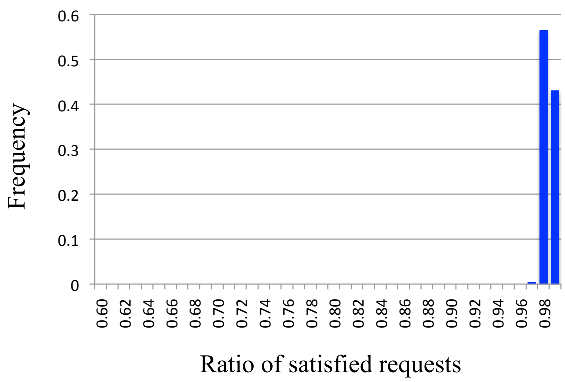
Figure 4 shows the percentage of outstanding energy for fully satisfying customers requests. As the figure shows, PL+10% approaches to 100% of satisfied requests. This level of satisfaction is followed by PL+5% and PL+storage, which achieve similar ratio of satisfied requests.

Energy request fluctuations may be the reason why even when a large capacity margin is introduced; the rate of customer satisfaction does not reach 100%. In the case of large power fluctuations, energy storage units may be a more practical solution.

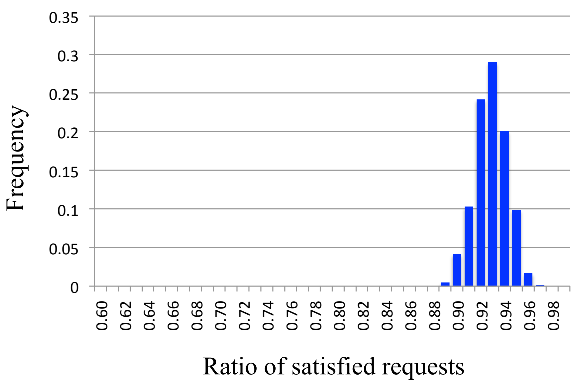
Figures 5(a) and 5(b) show the quality of the satisfaction, shown as concentrated satisfied request around the mean the histograms for two scenarios using supply by PL. Here, the distribution of satisfied requests is highly concentrated around the mean value indicating that the service is fair and even for most requests.

V. CONCLUSIONS

In meeting the challenges of the modern power grid where many providers and customers share the same transmission line, we study a grid control model where energy is supplied in discrete amounts. This power grid differs from the present one, which carries energy all the time and performs consumption monitoring thereafter. At the core of our power grid proposal is the energy bit (quantum) which carries a discrete amount of energy and carries data, which includes the addresses of the customers granted to be supplied and the amounts of current that each customer is granted to consume at a given time. In addition, since the power demand is dynamic and requires using the same shared grid lines, the energy delivery is not synchronized among all customers; instead, this grid model enables the transfer of energy to all needing customers at the same time and as bound by the grid line capacity.



(a) Distribution of Scenario 1



(b) Distribution of Scenario 15

Fig. 5. Ratio of satisfied requests (those requests that have been fully satisfied). (a) Scenario 1 and (b) Scenario 15. In both cases, the values are highly concentrated around the mean.

Herein, we evaluated a round-robin scheme for selecting the customer(s) for supplying energy in a distribution loop where energy is limited. We evaluated the efficiency of the management scheme by assessing the ratio of satisfied energy requests. We simulated customer needs over 1000 days. We demonstrated that an efficient power delivery system is possible with a limited capacity grid. The system requires a very small energy safety margins, of approximately 2% of the average energy demand, and satisfy 98% of customer energy requests. Furthermore, we showed that the storage of energy surplus could be used to satisfy sporadic surges of energy demand and minimize the safety margins even further. Energy storage is a natural extension to the controlled-delivery grid because every energy bit is accounted for.

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