Reducing Frequency of Request Communications with Pro-active and Aggregated Power Management for the Controlled Delivery Power Grid

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***Abstract*—We present a feasibility analysis of the controlled delivery power grid (CDG) that uses aggregated power request by users to reduce communications overhead. The CDG, as an approach to the power grid, uses a data network to communicate requests and grants of power in the distribution of electrical power. These requests and grants allow the energy supplier know the power demand in advance and to designate the loads and the time when power is supplied to them. Each load is assigned a power-network address that is used for communication of requests and grants with the energy supplier. With addressed loads, power is only delivered to selected loads. However, issuing a request for power before delivery takes place requires knowing the demand of power the load consumes during the operation interval. However, it is a general concern that having issuing requests in a time-slot basis may risk request losses and therefore, generate intermittent supply. Therefore, we propose request aggregation to minimize the number of requests issued. We show by simulation that the CDG with request aggregation attains high performance, in terms of satisfaction ratio and waiting time for power supply.**

I. Introduction

A power grid is a complex system connecting electric power suppliers and customers through transmission and distribution networks across a large area. Reliability and stability of the power grid are two critical features of the grid as failures can incur into great losses and costs. For example, the U.S.-Canadian 2003 blackout affected approximately 50 million people in eight U.S. states and two Canadian provinces. In this event, about 63 GW of load was interrupted, equating to approximately 11% of the load served in the Eastern Interconnection of the North American system, which spans from the central states of the United States to the East Coast and from the eastern Canadian provinces to Florida. During this event, over 400 transmission lines and 531 generating units at 261 power plants tripped, with an estimated total costs ranging between \$4 and \$10 billion U.S. dollars in the United States and \$2.3 billion Canadian dollars in Canada [1].

H. Shah and M. Petrula are NSF REU student participants at NJIT.
This work was supported in part by National Science Foundation under Award 1641033.

During the past decades, the North American power infrastructure has evolved into what many experts consider the largest and most complex system of the technological age. However, the vulnerability and potential problems of the power grid has put the challenges of energy transmission and distribution into the limelight. Recently, the concept of a controlled-delivery power grid (CDG) has been proposed to achieve a finer and more efficient balance between generation of electrical power and the demand of it [2]–[5]. In the CDG, electric energy is delivered in discrete (digital) levels. Herein, we refer to energy and power indistinctly but with the understanding that power is the energy consumed in a period of time. By contrast, the present power grids distribute energy in an analog fashion, in which customers are allowed to consume discretionary amounts of power at arbitrary times. In the analog power grids, this uncontrolled accessibility requires generators to adapt the generation of power to re-balance the grid at times of overproduction or surging demands.

Peak Plants for such surges - very expensive

Although everyday experience shows us that the power grid is fairly robust, the response of electricity providers (and generators) to increasing power demand may still lag due to demand and production fluctuations beyond forecast estimations [6]. In real time, suppliers may monitor the amount of power supplied and consumed only on a large-scale basis (namely, for feeders containing a large number of loads). An underlying assumption on presently used systems is that fluctuations of local consumption, especially local power surges, are rapidly averaged out when the number and variety of loads is large.

Therefore, there is a search for a smarter grid where demand is most closely followed by the supply. A tighter grid stability increases the efficiency of the grid by lowering the amount of generated power, and in turn, extend the life of non-renewable energy resources. The CDG may attain a high degree of stability. In the CDG, energy is supplied in discrete amounts to specific customer(s) and the delivered amounts are assigned and controlled. However, two properties of the present grid; perpetually energized lines and allowance of discretionary access, make it a challenge to follow. The perpetually energized property allows customers to access and consume electricity at any time and demand from providers to generate forecasted amounts of power at all times. The discretionary access property allows customer to demand discretionary amounts of power, where power capacity may be limited and challenged. Grid overload must be carefully monitored and in case of an extraordinary event, distribution loops ought to be taken out of the grid. This broad-scale monitoring cannot pinpoint specific users nor failures. Close monitoring of the grid's performance may be achieved by deploying (auxiliary) sensing data networks [7]–[16]. Concerns about ensuring working paths, which are perpetually energized translate into additional management complexity [14], [17]. These works show the adoption of a controlled distribution of power that can be seamlessly coupled with grid monitoring as an objective.

The CDG offers an alternative while performing precise control on energy delivery. In a CDG customers issue requests for power and the provider may fully or partially grant these requests. This is what it is called a power distribution by a request-grant protocol, where customers issue requests and the energy supplier issues grants. Such protocol facilitates the estimation of total customer demand and gives the provider the ability to determine in advance how to satisfy the requests. The CDG model also implies the adoption of a controlled supply and a limited capacity. The discretionary access property of the current grid challenges the deployment of a controlled-supply model. Customers expect limitless power from the present grid and this expectation encourages customers to indiscriminately connect large loads. However, such availability of power also puts the grid at risk for line overloads and disables the grid from distributing electrical power under cases of shortage.

The concept of controlling the distribution of energy through micro-grids as the next generation electrical grid has been discussed before [18]. Approaches to verify users identification before the start of energy transmission in point-to-point communications have been also considered [14]. However, these approaches require one-to-one connection and therefore, are unscalable to a large number of users. Some of these works are motivated by the consideration of alternative-energy sources, where sources and appliances can be matched through dedicated lines, using direct current (DC) multiplexors [19]. However, uncontrolled delivery (and consumption) may remain. Elastic loads have been proposed to balance the grid; but through load scheduling by the provider [20].

In a CDG, the amount of delivered power can be controlled with the designation of ownership and limited to specific power levels. Here, ownership means that the supplied power is delivered to addressed customer(s). To realize delivery, the customer's address is carried together with electrical signal or through an auxiliary data network, and a power access point (PAP) at the customer's premises checks if the address carried in the signal matches the customer's address. This address is an Internet Protocol (IP) address.

The request-grant protocol used by CDG to supply energy is executed in a time-slot basis, where a grant of energy enables supplying a load during a time slot. As an example, time slots may have a of 300 ms.

In the current approach of the request-grant protocol used by the CDG, a load issues a request per every time slot of needed power. Loads that require a continuos supply of power may be not temporarily disconnected from receiving power. It is then expected that a large number of requests is issued. With this large load on the network, there is a concern that packet loss would occur and, in turn, trigger power loss for a load. Therefore, we propose an approach that could potentially reduce the number of packets issue for requests and, in turn, decrease the possibilities of supply power loss. Our request scheme aggregate the amount of requested power such that a single request may be made by a user. Although this approach may effectively achieve our objectives, it may also impact the performance of the CDG. Therefore, we investigate the impact of our proposed request-grant protocol on the performance of the CDG.

The remainder of this paper is organized as follows. Section II introduces the concept of the controlled-delivery power grid. Section III introduces the proposed request-grant protocol analyzed in this paper. Section IV shows the performance on distribution of power of our proposed request-grant protocol, in terms of satisfied request and amounts of power. We also analyze the time it takes for a load to start receiving energy after issuing a request. Section V presents our conclusions.

II. Controlled-Delivery Power Grid

The objective of a power grid with controlled delivery is to supply discrete amounts of energy that are actually on demand. This objective may overcome what may be weaknesses of the underlying concept of the present power grid: to be permanently energized (this feature demands to produce more energy than that needed) and availing discretionary amounts of power anywhere and anytime (this feature demands to generate beyond a maximum that would never be reached). In addition, allowing "discretionary access" to the amount of power on the distribution feeder opens the possibility of a load to consume large portions of the energy available, leaving then other users with little or no power. Furthermore, a failing transmission line, acting as a load with extremely high consumption can bring down the feeder and all other customers connected to it. Delivering power as per the CDG objective can be realized by using a data network, where data packets are used as time mark indicating the initial and end times when a user is permitted to receive energy from the power grid. This time interval is called time slot. In addition to the timing feature a packet provide, it also carries the amount of power requested or granted and addresses of users or even loads (e.g., appliances). The embedded data enables monitors to track the power supply and compare it agains the one granted. The addresses allows to finely determine which user or which load may receive the For the energy supplier to grant an amount of power, loads issue requests for needed amounts, through a request-grant protocol. The adoption of the CDG may minimize the difference between energy generation and demand, facilitates

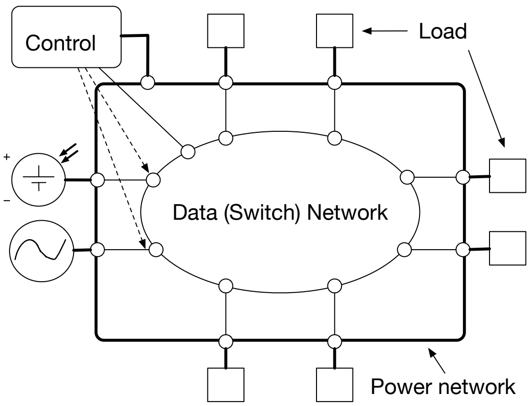

Figure 1. CDG using a parallel data network.

the power distribution amongst several grids, and increases the stability of a power grid through local and instantaneous traffic monitoring.

One can think of many different methods to manage requests and specially to address power. The destination address(es) may be embedded into the electrical signal(s) or sent through a parallel data network. Figure 1 shows an example of the CDG using a parallel data network. In the remainder of this paper, we adopt a data network for communicating the loads and the energy supplier.

The distribution of power is addressed to a single or multiple users, simultaneously. Each data packet may indicate one or multiple user addresses. The amount of energy per slot may be determined 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 and adjusting the amount of current for a fixed voltage. The network may use broadcast packets to address multiple users. In the CDG, the amount of power may be set to discrete levels, with the resolution per level be depending on the ability of actual equipment to manage it. The CDG is then based on a request-grant protocol: a user request power and the service provider decides the grantee, the amount and time of supply.

After the power is requested by the customer(s), it is then supplied in compliance with the physical, economical, and management limits of the feeder which may have a large number of customers connected to it. Each of them can receive addressed energy and be paired with controlled smart loads (Figure 2), which may ensure delivery of the largest amount of granted energy. The energy supplier performs the selection of a smart load at the customer premises by embedding the amount of current granted per user in the electrical signal.

In the CDG, data is coupled to the power lines. A control node, such as a distributor or a substation of the grid: a) finds the requested energy levels as issued by users (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.

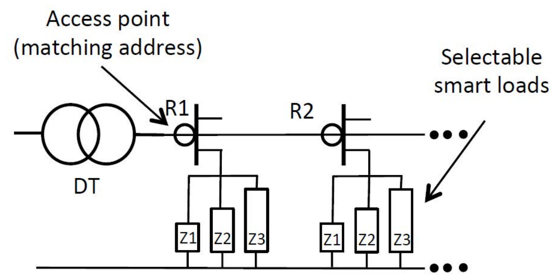

Figure 2. Smart load selected for each customer.

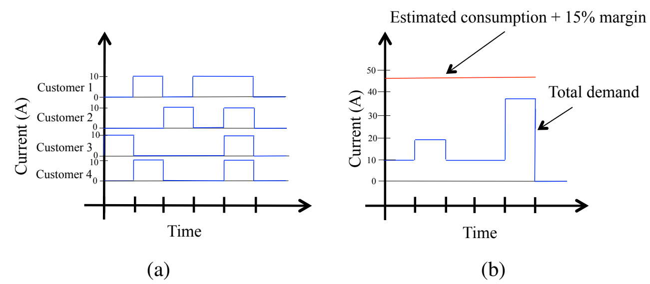

Figure 3. Example of power demand (a) individual demand of four customers, and (b) total demand. This example assumes resistive loads.

Figure 3 shows an example of how the power is supplied to demanding loads (or customers), considering requests and a safety margin needed to maintain a grid stable. There are four customers, each of them can issue a random request for an amount of current. Figure 3(a) shows the individual requests and Figure 3(b) shows the total current supplied, which is within the maximum loop capacity. Recently, we have shown that the CDG with Per-Time-Slot power Request (PTSR), with a power feeder capped to the average user demand can satisfy up to 99% of energy demand [4]. Furthermore, we have experimentally tested the satisfaction level of energy request through a testbed with resistive loads [5]. These results show that the CDG may achieve a fine granularity in the control of energy distribution. However, reactive loads offer a more complex pattern demand for power and we address this issue in this paper.

III. Request-Grant Protocol

In the CDG, providing a means to control the amount of power delivered to a user is needed to avoid excessive loads. With controlled delivery, a demand-supply mechanism is used to manage not only the power supply, but also to manage the grid more efficiently. In this case, a request is made by a customer to the energy supplier for a precise power demand at the time a switch of an electrical device is turned ON. A hand-shake protocol is established between the consumer and supplier, and power is delivered to the consumer. We refer to this demand-supply model as *request-grant* protocol.

The request-grant protocol can take the shape of different schemes. What is common in any method is that users (or loads) issue requests for the amount of needed power before being supplied (or taken from the grid). In this way, if there is excessive demand, the grid can determine to who and where the power is supplied. It is then up to the granting policy to make a fair distribution of power.

In a previous approach to the request-grant protocol, a user may issue one request of power per time slot that power is needed, as the PTSR scheme. This means that if a user needs 100 units of power in a feeder that can grant up to one unit of power in each time slot (per user), the user would need to issue 100 requests, one per time slot. The user would then need to keep track on how much energy is needed and whether a request is granted or not. The service provider would then need to only select which user gets power.

Here, what we propose is to decrease the number of issued requests to a) decrease traffic on the data network, and b) more importantly, to minimize the number of possible lost requests. We consider that users need to continuously power supplied to make loads work correctly.We don't consider batteries or other forms of energy storage in this paper. Therefore, our proposed requests carry the total amount of continuous requested power. We call this approach Aggregated Single Time-slot Request (ASTR) scheme. However, a user may have the freedom to issue a second (or third, etc.) separate request for power if more energy is eventually needed beyond that already requested. We treat these requests are separate ones. Although we keep the grant frequency, one per time slot. As an example, if we have the same conditions as before, where one unit of power can be granted per time slot, a user may need to issue a single request for 100 units rather than 100 as before. Therefore, this approach would achieve the target objectives.

However, embracing this approach raises the question on whether the performance of the CDG would remain high. In this paper, we aim to answer this question.

A. *Policy for Selection of Requests*

1) Each user issues an energy request, if any, to the energy supplier in an allowable discrete amount. 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 user requests are granted. Energy is supplied in the following time slot during which the request is granted.

We adopt the first come first serve (FCFS) selection policy to determine which of the users is granted. In this way, the service provider implements a queue, with FCFS service, where each user may receive up to one power unit.

Most of today's electrical appliances require this form of supply. In such cases, energy packets must be provided continuously (for the time the load is on) in the CDG as long as energy is needed. To emulate this scenario in a testbed, the light bulbs and the electrical motor require energy packets continuously. For example, Customer 1 would request 0, 40, 60, or 100 W and Customer 2 would request 0, 165, or 370 W at any given time.

IV. Performance Evaluation

We modeled the CDG and the request-grant protocol for computer simulation in C language. One of the mains concerns about the achievable performance of the CDG was to determine the average waiting time for a user to start receiving energy considering that the power grid has limited capacity. Other used metrics are the ratio in which the CDG with the proposed request-grant model satisfies the number of requests, named *request satisfaction ratio*, and the ratio in which the actual amount of power is satisfied, named *power satisfaction ratio*. A request is considered satisfied if the whole amount of power is provided. On the other hand, the power satisfaction ratio accounts for the amount of power provided over that requested.

A. *Experiment Setup*

In order to evaluate the CDG model, we considered a feeder with 100 users, where each could request and be granted power. The feeder has a limited capacity, in number of power units (e.g., Watts). In this way, the feeder may have enough energy to supply all requests every time slot, or else, the service provider would have to schedule the time when a user is supplied with power. Figure 4 shows a scaled down example of CDG where there are different small loads (light bulbs, a motor, and a fridge). Each light bulb is a *resistive load*, and the third load (Customer 2) is an electric motor, used as a *reactive load*. All of these loads require continuous power to perform their correct operation.

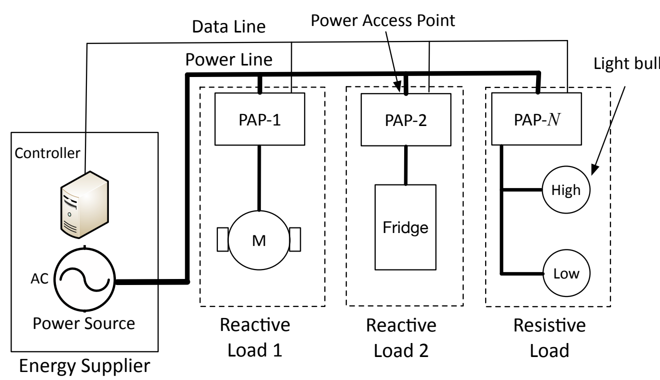

Figure 4. Diagram of an example of the several loads that may need continuos supply of electrical power.

In our experiment, each user has an independent and identical probability of issuing a request, labeled as *request probability* in our simulations. This probability can also be considered as the load to the feeder. Each time a user issues a request, this request may be found between one and 20 units of power (or time slots of power), where the probability is uniformly distributed. The simulation time used is 10,000 time

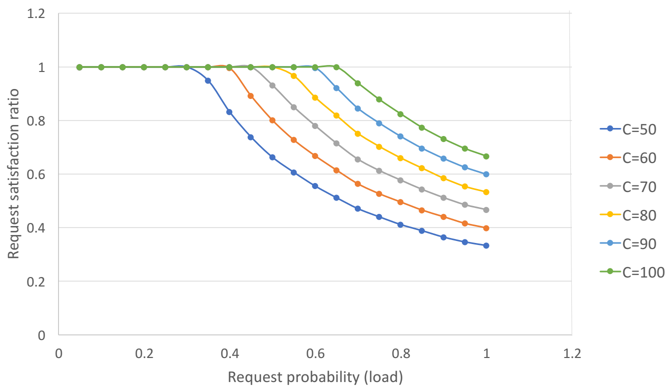

Figure 5. Request satisfaction-ratio of different grid loads.

slots. The capacity of the feeder, C, indicates how many power units can be supplied in a time slot. We vary this capacity as C= $\{50, \dots, 100\}$.

B. Results

We tested the CDG using the proposed request-grant protocol and measured the number of fulfilled requests. Figure 5 shows our obtained results on terms of the request satisfaction ratio. As the figure shows, the satisfaction ratio is 1.0 for small request probabilities. As these probabilities increase, the demand grows and the feeder capacity becomes insufficient to satisfy all requests. We also measured the power satisfaction ratio. Figure 6 shows our results. This graph shows quite similar curves to those of the request satisfaction ratio but the ratio is however, a bit higher as this metric accounts all supplied units of power vs those requested. As expected, the satisfaction ratio is higher for larger feeder capacities. We

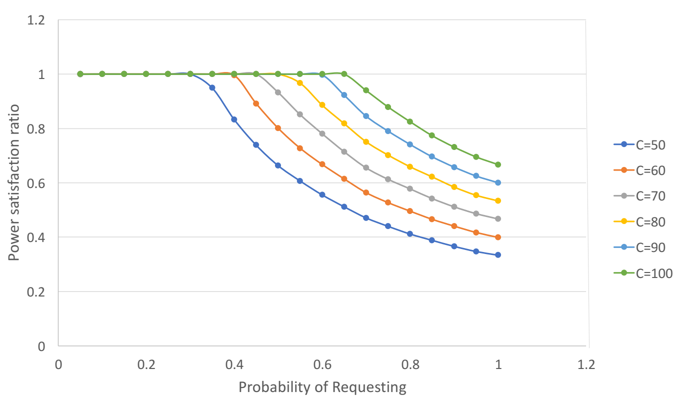

Figure 6. Power satisfaction ratio of different grid loads.

tested the CDG with ARP for the Average Waiting Time. Figure 7 shows the average waiting time for a CDG feeder with different capacities. The graphs shows that when C=50, which is the lowest capacity, the waiting time is the longer. Yet, when the load approaches 1.0, the waiting time is about 340 times lots. We see that even with reduced power, users receive power in a finite and rather small number of time slots.

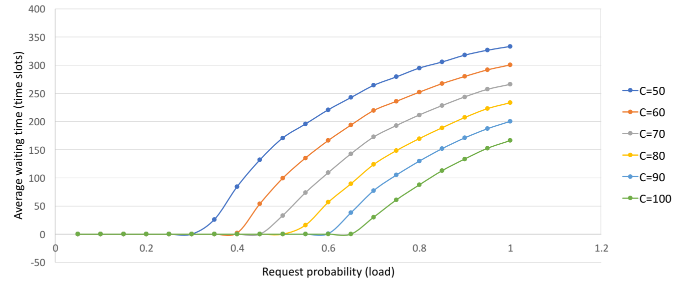

Figure 7. Average waiting time of different grid loads.

V. Conclusions

We showed the performance of a request-grant protocol used in the concept of the CDG, where energy is addressable and finely controlled by a data network, to distribute power among loads that require power continuously. This CDG uses a data plane, which transmits information about the power requested and granted through a parallel data network to the power network. This data plane is used to realize the management the distribution of energy on the power line, or power plane. Our proposed request-grant protocol aggregates requests of power into a single one, called ASTR scheme, to decrease the number of issued requests and the possibility that there could be interrupted power supply. The performance was analyzed in terms of the request satisfaction ratio, power satisfaction ratio, and average waiting time (to start supplying power as requested). Our results show that the CDG using the proposed request-grant protocol that carries aggregated amounts of power in each request is effective and can achieve a high satisfaction ratio, in terms of number of request and units of power. In addition, our results show that the CDG is able to grant power in short times.

As a future work, we plan on comparing the presented results with a CDG using one request per time slot (PTSR scheme), and determine if there is any effect on the performance of the grid using our proposed ASTR scheme. We also plan on doing an evaluation of the increased reliability of our proposed scheme.

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