The Digital Power Networks: Energy Dissemination Through a Micro-Grid

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Abstract— **The Digital Power Network (DPN) is an energy-on-demand approach. In terms of Internet of Things (IoT), it treats the energy itself as a 'thing' to be manipulated (in contrast to energy as the 'thing's enabler'). The approach is mostly appropriate for energy starving micro-grids with limited capacity, such as a generator for the home while the power grid is down. The process starts with a request of a user (such as, appliance) for energy. Each appliance, energy source or energy storage has an address which is able to communicate its status. A network server, collects all requests and optimizes the energy dissemination based on priority and availability. Energy is then routed in discrete units to each particular address (say air-condition, or, A/C unit). Contrary to packets of data over a computer network whose data bits are characterized by well-behaved voltage and current values at high frequencies, here we deal with energy demands at high-voltage, low-frequency and fluctuating current. For example, turning a motor ON requires 8 times more power than the level needed to maintain a steady states operation. Our approach is seamlessly integrating all energy resources (including alternative sources), energy storage units and the loads since they are but addresses in the network. Optimization of energy requests and the analysis of satisfying these requests is the topic of this paper. Under energy constraints and unlike the current power grid, for example, some energy requests are queued and granted later. While the ultimate goal is to fuse information and energy together through energy digitization, in its simplest form, this micro-grid can be realized by overlaying an auxiliary (communication) network of controllers on top of an energy delivery network and coupling the two through an array of addressable digital power switches.**

Keywords-digital micro-grids, energy dissemination, digital energy, packetized energy

I. INTRODUCTION

Micro-grids [1-2] – group of interconnected loads and distributed energy resources (DERs) with defined electrical boundaries – attracted large attention recently due to a relative increase in power outages. Micro-grids can be integrated with larger power networks, or may be considered an autonomous entities. After a grid blackout, micro-grids in an island-mode play an important role for both emergency situations (such as a disaster centers) and during grid re-activation. The stability of the grid is of utmost concern and should be accomplished with minimal energy loss.

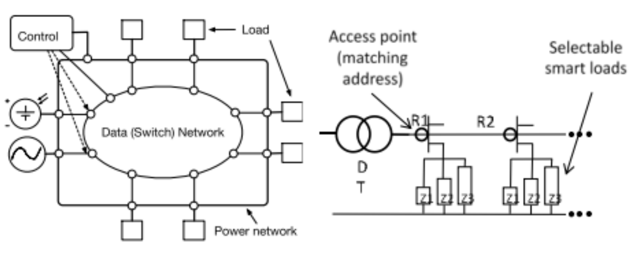
The DPN aims at optimizing the electrical power that is flowing through the grid. While emphasis in the Internet of Things (IoT) [3-4], is typically on the communication and cooperation between physical objects, here, in addition to information about the total energy available, grid status, the energy requests and satisfactory delivery, it carries also the energy itself – the message is energy. Specifically, the designation of a power storage as a source or as a consumer depends upon energy needs; the designation of a node as an active or pass-through user depends upon system status [5].

The original design of the power grid was to transport power in a single direction, from a generator to the loads. This means that the loads dictate the energy flow in an analog way: adding more loads means an increase in current demand. Since energy demands are unknown a *priory*, the grid must react to varying situations. Such approach increases uncertainty and compromises the grid stability. This is equally true for a micro-grid made of a home generator and several appliances. Specifically, there is no guarantee that the heating, ventilation and air-condition units (HVAC units) will not turn ON at the same time as the refrigerator, thus challenging the maximum power available in the grid at every moment.

We offer a different approach that attempts to gain knowledge of the energy demands ahead of time. That knowledge would then be used to optimize energy delivery throughout the entire micro-grid, and before enabling the energy flow. The DPN is an energy on demand protocol where energy is first requested and then delivered to a particular address. Obvious digital examples are information networks or computer networks. These high-speed networks transfer information (which can be considered as energy) in a digital format. The digital format increases the robustness of the system by decreasing noise. These networks allow bi-directional communication upon information request. However, a direct mapping of protocols that are handling information to power networks is too simplistic. Information networks rely on memory devices, system addresses and a network of nodes (smart routers and switches). Information networks are governed by established protocols while the current power grid is a simple distributive network available to all loads – any load may tap to the energy at any time. In information network terms, the power grid is but the physical layer of the network and our vision is to add management and control plane to it [6-8]. The control is achieved by a dynamic feedback from the node (a hand-shake protocol) and not by just monitoring of signals from arrays of sensors while, or after energy is consumed. At its core, information networks differ from digital power networks: it is the difference between the well-defined voltage, current and time characteristics of the information bit and the not so well behaved energy bit. While one may define a specific time slot and voltage requirement for the energy bit, the fluctuating current demands pose a problem. Making the current levels discrete necessitates an energy storage that will pick up the difference between the required and the instantaneous dissipated energy at the load because the latter is typically an analog entity. In the digital approach to the micro-grids, the loads are micro-managed by the system.

In this paper we study a digital optimization scheme whereby a set of loads (DC motors) are randomly turning ON or OFF. The generator (a fuel cell) can handle merely two motors at the time due to the large surge of current required for turning the motor ON from an OFF state. We show, that if the motors are interfaced with an addressable super-capacitor which picks up the initial current surge, then the generator can handle many more motors. After initial discharge, the super-capacitor is slowly charged by the surplus of energy available in the system. The super-capacitor serves two purposes: (1) as a starter, and (2) as a small back-up energy source. The former is much more important than the latter. One would think that as large as possible capacitors are preferred but then, their charge time is increased too and diminishes their effectiveness. Overall, the system takes full advantage of addressable elements (either the generator, the super-capacitor or each of the motors). For one, the super-capacitor plays the role of a consumer or a generator. In case of an over demand, the controller delays the supply of energy until available. All of these applications are not available within the framework of the current analog power grid.

A general purpose DPN network is schematically diagramed in Fig. 1a. The physical layer enables the energy flow through an array of smart switches (Fig. 1b). The physical layer is integrated with a data control plane that transmits the energy requests and open and close the switch array.



(a) (b)

Fig. 1. (a) Schematics of a general purpose DPN composed of two energy sources and a data control plane. (b) Smart switch array enable energy flow to the load.

In the following we study a micro-grid made of 8 DC motors. The DC generator is a fuel cell (FC). The generator is interfaced with a super-capacitor aimed at starting the motor but rarely serves as a backup energy source for steady states use. The energy requests are random. Unsatisfied requests are sent to a queue and are considered later when energy is available. The parameters of operation have been chosen such that hardly two motors can start without the super-capacitor (SC). In the following we present a comparative study on the effect of the micro-grid with and without the super-capacitor booster.

II. Characteristics of The Power Network

A. The System

We studied a micro-grid made of 8 addressable DC motors. Each motor has a steady state power requirement of 660 W. The power requirement is typically eight times larger if the motor needs to turn ON from an OFF state. Since the generator (Fuel Cell, FC, see Fig. 2) can deliver between 10 KW to 12 KW of power, hardly two motors can be turned ON and keep working by use of the FC alone. We added a super-capacitor [9] to aid the ignition of the motors, similar to a starter in a car. The super-capacitor (SC) is charged by the FC when power is available and is discharged for a fraction of a second during motors' ignition. The SC is addressable too. The simulations run on a MATLAB platform (Simulink).

Fuel cell nominal parameters:
Stack Power:
-Nominal = 10287.5 W
-Maximal = 12544 W
Fuel Cell Resistance = 0.024535 ohms
Nerst voltage of one cell [En] = 1.205 V
Nominal Utilization:
-Hydrogen (H2)= 39.59 %
-Oxidant (O2)= 42.88 %
Nominal Consumption:
-Fuel = 113.2 slpm
-Air = 269.5 slpm
Exchange current [i0] = 0.98372 A
Exchange coefficient [alpha] = 0.94554

Fuel cell signal variation parameters:
Fuel composition [x_H2] = 99.95 %
Oxidant composition [y_O2] = 21 %
Fuel flow rate [FuelFr] at nominal Hydrogen utilization:
-Nominal = 287.2 lpm
-Maximum = 367.7 lpm
Air flow rate [AirFr] at nominal Oxidant utilization:
-Nominal = 732 lpm
-Maximum = 937 lpm
System Temperature [T] = 318 Kelvin
Fuel supply pressure [Pfuel] = 1.16 bar
Air supply pressure [PAir] = 1 bar

Fig. 2. Fuel Cell (FC) characteristics.

B. The Protocol

A flow chart of the process is shown in Fig. 3. The process starts with an energy request from a specific load (the motor). The request sends a trigger pulse to a server. The server collects all requests and assigns priority on a first come first served basis. The code estimates the power available for motor ignition (via the SC, or the FC) and the steady-states level needed for continuous operation. Energy requests that cannot be accommodated are sent to the queue; they are prioritized in the order of request. Energy requests are made for a time segments of 5 seconds (also called cycles). Extra energy is directed towards the SC until fully charged or until it is able to aid in the motor ignition process.

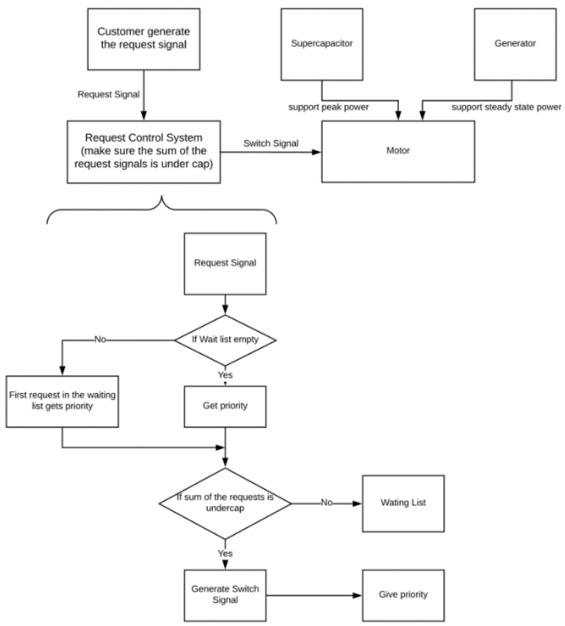


Fig. 3. A flow chart of the energy management protocol

The request for energy by each motor is random. A random number is generated with a probability p to ignite the motor ON. If $p<p_0$, then, the motor is turned ON. If the motor is already ON, another random number is generated, q. If $q<q_0$, then the motor continues to run without the necessity to turn it ON again and, thus avoiding the need for the SC. Otherwise the motor is turned OFF. Without the queue (equivalent to a memory in information systems) the process constitutes a 2-state Markovian chain. With queue in place, the process is not Markovian. The program runs for 200 seconds for each of the probabilities and SC capacity value and the data are collected. Energy is requested for an operational duration of 5 seconds segments.

C. Energy Request Pattern

An example for the request signal process is shown in Fig. 4. Here, the probability to ignite the motor is p=0.4 and the probability for a running motor to stay ON is q=0.2. Take for example, the request starting at 60 seconds in Fig. 4. There are 3 consecutive energy requests which could be made from the same motor or three different motors. If the requests from a single motor are consecutive, then there will be only one ignition signal from the SC and the motor will run continuously for 3 cycles. In this particular case, the SC provided three boosting energy pulses for the 3 motors involved.

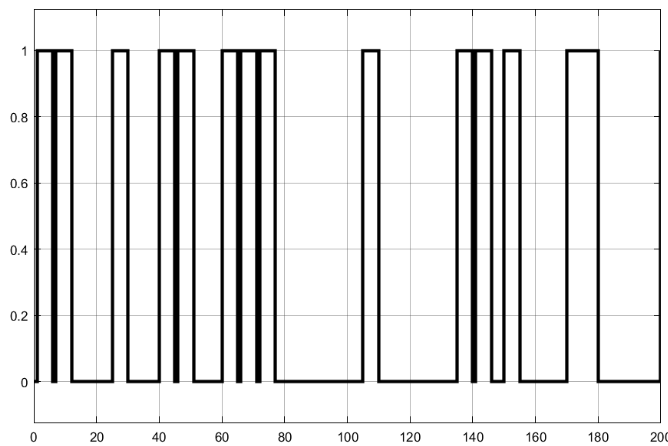


Fig. 4. Request signals for p=0.4 q=0.2.

In Fig. 5 we show a similar request pattern for p=0.8 q=0.2. The probability to turn ON is large, resulting in short bursts of motor ignitions while the probability to stay ON is rather small. Continuous motor running can be identified at t=5, 80 and 170 sec of the simulation.

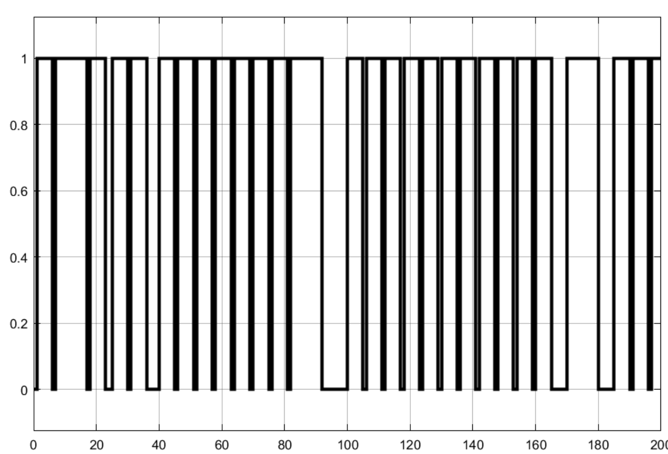


Fig. 5. Request signals for p=0.8 q=0.2.

In Fig. 6 we show a request pattern for p=0.3 q=0.8. Here, the probability of the motor to turn ON is rather small but the probability to stay ON is relatively large. Large q results in a prolonged motor operation, such as seen at t=60 sec.

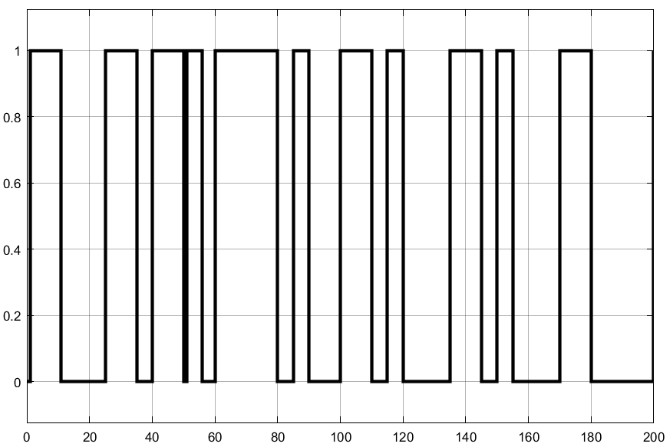


Fig. 6. Request signals for p=0.6 q=0.8.

D. The Role of the Super-Capacitor

As stated earlier, the super-capacitor has two roles: (1) as a booster to the motor ignition and (2) aiding the FC in case there is not enough energy to run the motors. The former case is much more important than the latter: while SC can quickly be charged and discharged and deliver large currents, they cannot hold much energy and thus are not considered good power sources.

A comparative study on the effect of the SC is presented below. Here we show the micro-grid's performance with a very small (Fig. 7 with SC capacity of 0.001 Farad) and a rather large SC (Fig. 8, with SC capacity of 30 Farad). Shown is the energy dissipated by each motor. As suggested by the simulations, many more motors may be triggered ON when the SC is added to the micro-grid.

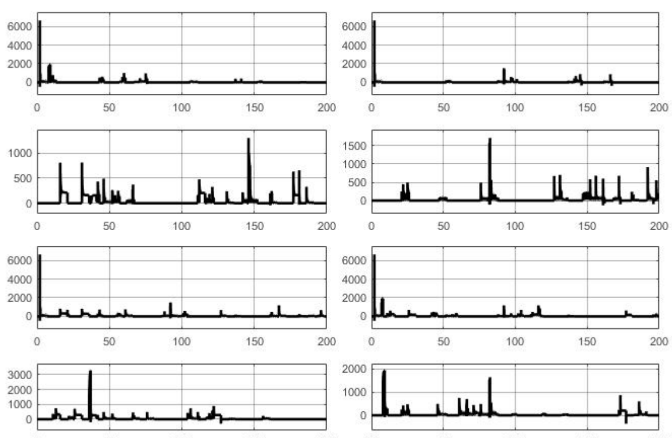


Fig. 7. Energy dissipated (in Watts) by the motors for a very small SC capacity (0.001 Farad).

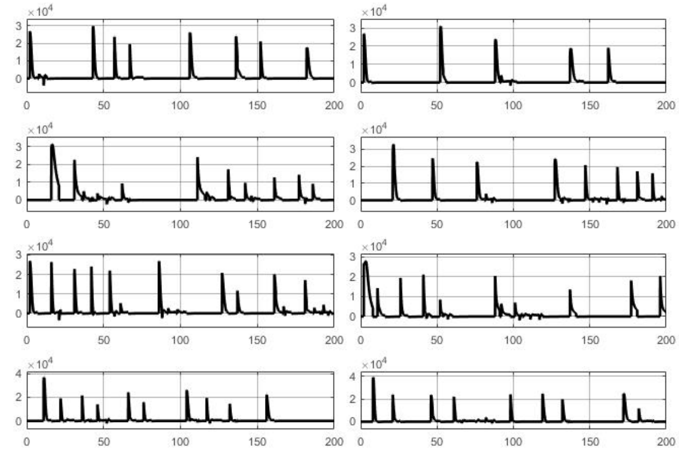


Fig. 8. Energy dissipated (in Watts) by the motors for a very large SC capacity (30 Farad); many more motors are able to ignite.

Finally, in Fig. 9 we provide a comparative power distribution of each system's element: the motors, the generator and the SC. The most important panel is the middle one. It exhibits the continuous and almost constant energy delivery by the FC throughout the fluctuating energy requests made by the motors.

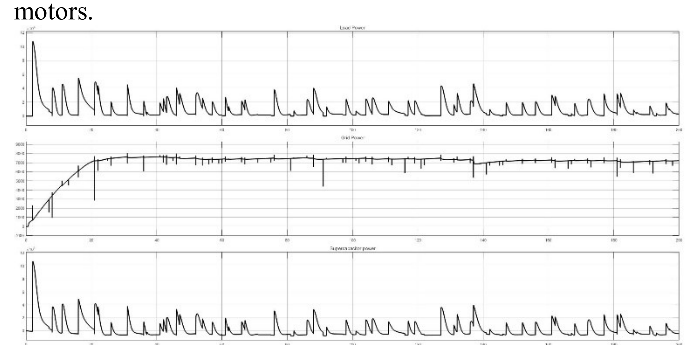


Fig. 9. Power distribution in the system. Top Panel: power consumed by the motors. Middle Panel: power delivered by the grid. Bottom Panel: power supplied by the SC during the ignition (the majority of cases) and steady states (the minority of cases) stages.

III. RESULTS

In previous sections we established the importance of a wholly approach in the optimization process of energy dissemination. The generator FC, the energy storage SC and each motor has an address. The system may then select the role for each element as appropriate for the various situations. For example, if the SC is drained, then it becomes a load and thus consumes energy; it therefore generates energy requests to the generator (FC). Conversely, if the SC is charged, it participates in the ignition process of the motors.

In the following, we examine the percent satisfaction of energy requests as a function of triggering motor probability from an OFF state, p and the SC capacity in Farads. The probability of a motor to continue running is rather small q=0.2 meaning that the motors will turn OFF quickly. The percent satisfaction is defined as the number of granted per number of requested triggering events.

As seen from Fig. 7, the system of 8 motors barely functions without the SC. This is corroborate by Fig. 10; for very small

SC capacity, the satisfaction rate is below 20%). With the SC in place and working at low triggering rate (p<0.3), the system may reach a large satisfaction rate (Fig. 10). At high triggering rate, p>0.3, the satisfaction rate obviously deteriorates. It is also interesting to note that increasing the capacitance of the SC above 20 Farad does not impact the percent satisfaction as measured by the triggering events. From triggering point of view, there is a minimum capacitance for the SC above which, there is no advantage for a larger capacitor. This is an important point since large SC require longer time to re-charge.

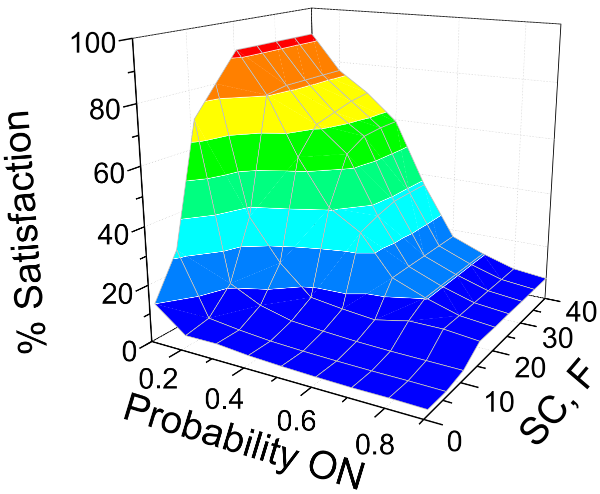


Fig. 10. Percent satisfaction as a function of probability to turn a motor ON from an OFF state, p, and as a function of SC capacity in Farads. Here, percent satisfaction is defined as the number of granted per number of requested triggering events. The probability for a motor to continue running is q=0.2.

The impact of longer re-charge times for the SC on the percent satisfaction is shown in Fig. 11.

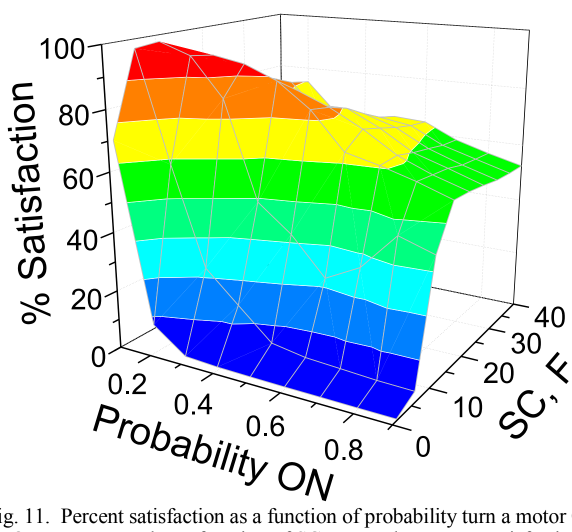


Fig. 11. Percent satisfaction as a function of probability turn a motor ON from an OFF state, p, and as a function of SC. Here, the percent satisfaction is defined as the duration of actual motor running time per overall time requested. The probability for a motor to continue running is q=0.2.

Here, percent satisfaction is defined as the actual duration of running motor per overall requested operation time. As can be seen from Fig. 11, a further increase in the SC capacity results in a penalty; above 20 Farad the percent satisfaction decreases. The satisfaction curve as a function of the probability to start, p, is more monotonous here if one chooses this criterion because large capacitance enables many more ignition events.

IV. Discussion and Conclusions

The DPN concept, as applied to micro-grids, offers many advantages over the current analog approach. The main advantage is in the ability to assess the energy demands ahead of time. This in turn, enables optimization of the energy dissemination process. Each element in the grid is addressable; therefore, the role of a source (say, energy storage as a power source) may be easily switched to a load (when the energy storage requires re-charging). Such approach removes uncertainties, reduces power fluctuations (see middle panel of Fig. 9) and increases the grid reliability during and after blackouts.

Adding a fast and short term energy storage proved critical to the functioning of the loads. Adding such element(s) may reduce the overall power generation levels, thus making the system more cost effective. At the same time, optimizing the SC capacity reduces its re-charge time and increases the percent of satisfaction.

Finally, and along with IoT, such approach is very suitable for micro-grids whose pattern of operation is relatively well-known and can be trained [5], e.g., office buildings. The integration of objects with an energy systems, in which the information carried is part of the power delivery, is very appealing. For example, the DPN can delay the operation of multiple ventilation units for a short time in favor of other units without a substantial loss of convenience, yet with a substantial cost savings. One may also consider cooperation between de-localized multiple energy storage elements (cloud energy storage) for the benefit of the entire system.

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