A PROBABILISTIC APPROACH FOR ADMISSION CONTROL OF SMART APPLIANCES IN SMART GRIDS

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Abstract
New generation electricity network called Smart Grid is a recently conceived vision for a cleaner, more efficient and cheaper electricity system. One of the major challenges of electricity network is that generation and consumption should be balanced at every moment. This paper introduces a new concept for controlling the demand side by the means of automatically enabling/disabling electric appliances to make sure that the demand is in match with the available supplies, based on the statistical characterization of the need. In our new approach instead of using hard limits we estimate the tail probability of the demand distribution and control system by using the principles and the results of statistical resource management.

Keywords:
Smart grid, Demand Side Management, Admission Control

1. Introduction

The main issue in electricity networks is keeping an almost perfect balance must be kept between electricity generation and consumption in every minute. Balance between demand and supply is crucial since oversupply means waste of energy, while undersupply causes performance degradation of the grid parameters (e.g. phase, voltage level, etc.). The balance can be satisfied by the control of the supply side, or by the demand side. Balance of the electricity generation and consumption can be maintained by utilizing several techniques. For instance, generation volume can be set according to predicted day-to-day consumption information. Random differences between real and predicted consumption can be dealt with only at the expense of deficit: on the one hand in case of oversupply, extra energy is dissipated, on the other hand, in the case of undersupply, costly auxiliary diesel generators are turned on. Financially, generation can be done in the most feasible way when power plants generate constant electricity in time; consequently it would be desirable to have a constant level of consumption as well. Unfortunately the control of the supply side is slow because of the large time constants of the fossil and nuclear plants. Additionally, the percentage of renewable resources should be increased which gives rise to uncertainty in the generation side. Hence, it turns out that the only way to keep the balance is to manage the demand side. Even though aggregate volume of the consumption can be predicted, it is basically also a stochastic process. Methods used today cannot take into account the stochastic nature of the demand side. It is clear that it is a great challenge due to its hard predictable nature.

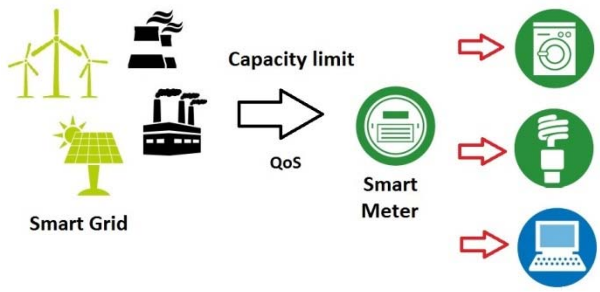

Figure 1. The structure of smart grid

Algorithmic solutions are used in Smart Grids, for instance the Direct Control of Smart Appliances. Its aim is to control consumption in short term (typically several minutes)[1]. Direct control can be used to remove the extreme values in electricity consumption (peak shaving, valley filling). Constant level of daily consumption can be also achieved by utilizing different pricing programs, for example Time Of Use tariffs [2]. In Smart Grid a new kind of pricing method is also emerging, called Real Time Pricing, which can affect the users' consumption by an indirect way. A new tariff is communicated with the households in the beginning of 15-60 minutes periods and the instantaneous price is in direct relation with the current wholesale prices (which also depends on the demand level). Demand side management with a longer time constant is also possible by using load scheduling (e.g. charging of the batteries of electric vehicles).

Our current approach tries to give a solution to the short time balance problem of the electricity generation, in a way that capacity limits and quality criteria of the whole network are controlled by algorithms running automatically on consumer level and requiring minimal user interactions. The proposed method estimates the statistical parameters with relatively low algorithmic complexity (these parameters are obtained from intelligent appliances or from measurements) taking into account the probabilistic nature of the consumption.

2. The Model

In the model the following assumptions have been made. All subscribers have a Smart Meter (SM). The SM has the following properties:

- 2-way communication to the service provider;
- 2-way measurement capability of energy consumption;
- the SM can measure the consumption of every connection points individually;
- the SM can enable/disable every connection points;
- the SM communicates with smart appliances;
- the SM can register the consumption statistics of the appliances (both smart and traditional ones);

In this paper, we assume that the service provider can calculate and communicate the parameters regarding the consumption of a subscriber in order to make balance between energy generation and consumption in the system level. Using these parameters, the subscriber's SM can enable/disable the appliances at a local level, resulting in a fully distributed solution to the problem. The parameters coming from the service provider are as follows: a capacity upper limit C_u in every time slot, which is allowed to be overloaded only by probability p. p is called the Quality of Service (QoS) parameter, because it can satisfy the stability of the grid parameters (such as frequency, voltage level, etc.). There is a capacity lower limit C_l as well, which is allowed to be underloaded only by probability p. The task of the SM is the admission control (enabling/disabling) of the appliances by such a way, that the probability distribution function (pdf) of the aggregate consumption satisfies the prescription of the service provider. (The cooperative attitude of the subscriber can be motivated by rewards). The underlying model is depicted in Figure 1.

The probability distribution function of the aggregate consumption of the appliances connected to a given SM can be influenced by shifting the consumption of appliances. Many type of appliances can tolerate some delay (e.g. executing the program of a washing machine later). Further possibility is the application of the batteries of PHEVs (Plug-in Hybrid and Electric vehicles) as electric energy storage devices (when vehicles are parked). As a result, there are (time) shiftable and non-shiftable demands in the system.

On the other hand most of the devices show very high level of uncertainty of consumption (neither the level of power nor the execution time of the device is known at the moment of switch on), that's why only a statistical approach can efficiently solve the control task. In this paper, the stochastic and deterministic behavior of appliances will be also used for categorization. (The devices executing a fixed program can be seen as deterministic). The reason of this categorization is the different method, by which these appliances are handled by the admission algorithm.

The defined categories and examples of appliances can be seen in Table 1.

	stochastic	deterministic
shiftable	electric heating, air conditioner, refrigerator	washing machine, dishwasher
non-shiftable	circulation pump	lighting, vacuum cleaner

Table 1. Device categories used in the model

In the model both stochastic and deterministic, shiftable and non-shiftable appliances are taken into consideration as described in Section 3 in details.

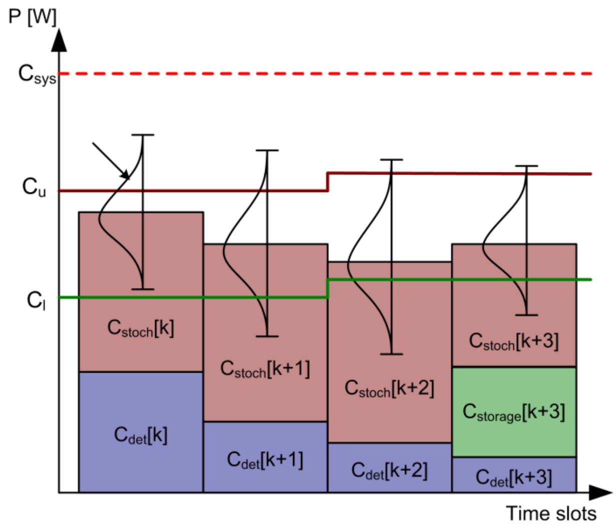

Figure 2. Measures used in the model

The admission control algorithm uses discrete time slots (denoted by k in Figure 2.), in which the enabled/disabled status of the appliances and the system parameters (capacity limits and QoS) are supposed to be unchanged – except the handling of new enable requests that must be handled continuously.

In Figure 2. the measures used in the model are depicted. In all time slots there is a deterministic component of the consumption and as well as a stochastic one (the possible consumption of enabled appliances). The stochastic part is descripted by its estimated (or calculated) probability distribution function (for details see Section 3.) The capacity limits C_u and C_l can be changed in every time slots by the service provider. In time slot k the upper tail probability of the aggregate consumption is larger than the legal value p, i.e. the probability of overload is larger than allowed. Hence, shiftable appliances will be disabled temporarily in time slot $k+1$, satisfying the system requirements. In time slot $k+2$ the probability of underload is larger than required, etc. C_{sys} denotes the system capacity. Note that C_u not equals C_{sys}. C_{sys} builds a natural upper limit on C_u.

3. Consumption and Storage Admission Control Algorithm

The Smart Meter calculates the aggregate p.d.f. from the individual p.d.f.-s of the appliances. The individual p.d.f. can be communicated to the SM by smart appliances, or it can be measured in the case of traditional ones.

Let X_j denote the random variable of the consumption of the jth appliance, while

$$X = \sum_{j=1}^{N} X_j \tag{1}$$

is the aggregate consumption random variable and N is the number of enabled appliances. The upper tail probability of the aggregate consumption should be kept under the limit p, which can be formulated as

$$\Pr(X > C_u) \le p = e^{-\gamma} \tag{2}$$

where Pr denotes the probability and $\gamma = -\log p$ is introduced for mathematical convenience. Note that the probability $\Pr(X > C_u)$ can be calculated using its pdf $f(X)$, which can be determined by the terms of convolution [3]

$$f(X) = f(X_1) * f(X_2) * \dots * f(X_N). \tag{3}$$

This calculation can be very time consuming in the case of large N, that is why it is suggested to estimate the tail probability by the terms of Large Deviation Theory, using the Chernoff-bound:

$$\Pr\left(\sum_{j=1}^{N} X_j > C_u\right) \le e^{\sum_{j=1}^{N}\mu_j\left(s^*\right) - s^* C_u} \le e^{-\gamma} \tag{4}$$

where $\mu_j(s) = \lg E\{e^{sX_j}\}$ are the so called logarithmic momentum generating functions and s^* is the parameter that satisfies the possibly tightest bound (5).

$$s^* : \inf_{s>0} \sum_{j=1}^{J} \mu_j(s) - sC \tag{6}$$

When a new demand of a shiftable appliance appears enabling or disabling will be calculated using the Chernoff-bound:

$$\operatorname{sgn}\left\{\sum_{i=1}^{N+1} \mu_i\left(s^*\right) - s^* C + \gamma\right\} = \begin{cases} -1 & \text{Accept} \\ +1 & \text{Reject} \end{cases} \tag{6}$$

where N is the number of the enabled (both shiftable and non-shiftable) appliances, but the test should be calculated taking into consideration the incoming appliance (N+1).

Algorithm (6) checks the upper capacity limit when a new consumption demand appears. The lower limit can be checked by the same manner at the beginning of each time slot. If the probability of underload is higher than p, The goal can be expressed as

$$\Pr(X < C_l) \ge p,$$

using the complementary probability

$$1 - \Pr(X > C_l) \ge p$$

and as a result

$$\Pr(X < C_l) \le p$$

for which the Chernoff bound can be used as given in (4).

4. Modules of the algorithm

The aim of our algorithm is to establish an automatic and distributed solution for enabling/disabling smart appliances in a smart grid environment in order to satisfy short-term balance between electricity supply and demand. The accept/reject decision is based on the CAC algorithm. The functional diagram of the algorithm can be seen on Figure 3. Modules of the algorithm are the followings:

Update Statistics – Updating probability distribution functions using prediction techniques. (The probability of usage depends on parameters such as date, time, temperature, light, etc.)

New Demand – In this point the algorithm checks whether a new appliance wants to start operating.

CAC algorithm – Checks whether the aggregate consumption of the currently enabled appliances satisfy the Quality of Service parameter of overloading; SAC – Storage Admission Control: Checks whether the aggregate consumption of the currently enabled appliances satisfy the Quality of Service parameter of underloading;
Switch On Storage Device: in the case of underloading storage capacities can be charged (PHEV batteries, or electric water heaters).
UPDATE Priority levels – Updating operation priority levels of appliances.
UPDATE Consumption vector – Updating consumption vector which contains the number of different type of appliances and its nominal consumption.
UPDATE Cdet[k+i] – Updating the sum of deterministic consumption value in time slot k+i.

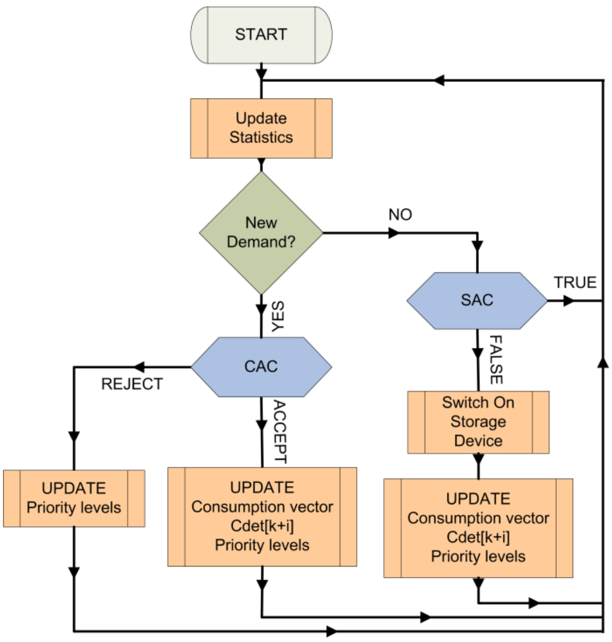

Figure 3. Functional diagram of the algorithm

Working of the algorithm can described as follows: In every iteration of the algorithm the statistics are updated first and that the CAC or SAC algorithm is running according to the existence of new demand. The CAC module can reject or accept the new demand. In case of rejection only the priority levels are updated, otherwise the consumption vector and the value of deterministic consumption also. The SAC module can return with true or false. In the latter case it tries to switch on storage devices to use the extra energy and updates the priority levels, the consumption vector and the value of deterministic consumption.

5. Conclusions

In this paper a new statistical approach has been introduced for managing the balance between demand and available supplies in smart grids. The smart meter of the subscriber performs the task of enabling/disabling of shiftable appliances based on three parameters, obtained from the supplier: lower and upper capacity thresholds and a probability value. The smart meter controls the probability distribution function of the aggregate consumption in order to keep the tail probabilities under a given threshold p. The new approach takes the uncertainty of the consumption into account, and furthermore it can work in a fully distributed manner, since the calculations can be performed in the smart meter. As a result the introduced consumption admission control method is a promising candidate for demand side management in smart grids.

6. Acknowledgement

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