A Delay Based Optimization Scheme for Peak Load Reduction in the Smart Grid

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ABSTRACT
A measurement campaign based on commodity wireless sensors shows that the majority of thermostatic loads in a user premise are described by periodic pulse waves. The superposition of these loads results in high peak power demand and costs in the network. We propose a novel first stage of optimization in the smart grid which reduces external on/off command flow for demand response between the controller and the smart appliances. A phase management scheme is developed that defines optimal time shifts (delays) on the periodic loads in order to provide peak power reduction over a limited time horizon. A gradient descent optimization technique, based on Taylor series, is utilized to minimize the maximum value of the superposition of the periodic loads so as to keep the instantaneous load as low as possible. A gradient descent optimization algorithm that can impose small phase delays in the duty cycle of the controller has within its administrative domain a group of smart devices that can be avoided. As a consequence, user discomfort is reduced and higher penetration of smart grid services is expected.

Categories and Subject Descriptors
C.4 [Performance of systems]: Modeling Techniques; J. 7 [Computers in other systems]: Process Control; G.1.6 [Optimization]:

General Terms
Smart Grid, Demand Load Control, Smart Sensors/Actuators Network.

1. INTRODUCTION
One of the most important characteristics of the smart grid is the support of data and command flow between the user premise and the operator via a bi-directional communication link. Smart devices are deployed within the user premise to provide the communication interface of the appliances to the smart grid. New standards and smart sensor/actuator networks have been developed to form the communication infrastructure between the smart grid and the smart devices/appliances [1] and support the basic operations of the smart grid which are the supply load control [2] and the demand response [3, 4]. The majority of papers presented in the literature, focus on load control based on real time pricing [4], scheduling of power tasks to off peak hours [5, 6], dynamic on/off control schemes of flexible loads [7] and game theoretic approaches for demand response [6, 7]. Furthermore, the energy routing concept is explored in [9].

The above mentioned techniques are related to optimization algorithms for demand response. These algorithms change the state of operation of the devices, thus creating discomfort or dissatisfaction at the user side that can reduce the penetration of smart grid services. In our work we measure, through a measurement setup unit of commodity smart sensors, the power loads of typical energy consuming devices and we observe that they can be very accurately described as periodic pulse waves. Based on this observation we propose a novel ‘synchronization’ algorithm that can impose small phase delays in the duty cycle of the smart devices, in a transparent to the user approach. The main objective is to manipulate the superposition of the periodic loads and minimize the maximum value of the superposition of the periodic pulses so as to keep the instantaneous load as low as possible. A gradient descent optimization algorithm, based on expansion to Taylor series, is utilized and simulation results are obtained through a stochastic model describing a portion of users in the network. The proposed control strategy is centralized and is performed at the controller of the smart grid. This approach yield high gains but it can impose delays and redundant data traffic.

2. THE SYSTEM MODEL
2.1 General Architecture
The general architecture of the system is presented in Figure 1. The smart grid comprises controllers and agents [10]. Each controller has within its administrative domain a group of smart buildings whose intelligent unit is the agent. The smart building comprises appliances that are connected to smart meters/actuators. They form a Home Area Network (HAN). Each smart meter monitors in real time critical parameters, such as instantaneous power load and environmental information and transmits data to the agent. The agent aggregates the data and transmits to the controller. A bi-directional TCP/IP communication link is usually used. The target is to support command flow in the network and to control devices under given objectives. There are two types of devices/appliances in the administrative domain of the agent. The non-flexible devices are the loads of the premise that can not be controlled by the smart grid. These loads are usually lights, entertainment equipment, PCs, etc. The flexible devices can be
Power demanded by the devices in the network over a defined time interval. This problem aims to avoiding the occurrence of blackout or energy import in the case that the required power exceeds a max permissible value. It is an important operational problem posed to the operator or the prosumer of the energy distribution network having limited power capacity and aiming to energy cost savings. The operator has to synthesize algorithms in order to solve the optimization problem with unknowns the particular values of the transposition in time ($\delta_i$) of the functions $f_i$, referring to the flexible devices, for each of the $N$ clients.

We assume at this stage that the only constraints posed on the transpositions is that $\delta_i << T_w$ and $\delta_i < T_c$. We also assume that the whole procedure is characterized by periodicity, i.e. if we operate on a specific time interval $T_w$, then the transposition of any $f_i$ beyond the right boundary of the interval $T_w$ implies that the $f_i$ values exiting the interval through its right boundary are entering through the left boundary of the interval $T_w$.

### 2.3 Measurements on Typical Loads

Three smart plug sensors were connected to the agent PC through a Zigbee mesh network and machine to machine (M2M) communication was established with webservers (Figure 1). The load measurements were sampled at every time step $dt=2secs$ (Figure 2). The device under investigation was an air conditioning unit placed in an apartment of size 65m$^2$ during summer period. The temperature of the air conditioning unit was set to 24$^o$C and the outside temperature during the measurements was 30$^o$C. The mode of operation of the air-conditioning unit was set to auto mode. This means that the aircondition unit switches on or off automatically to maintain the air temperature near a constant value (24$^o$C). The air condition presented periodic pulse shape with duty cycle 39% and $\tau = t_{ON}=3.53mins$ and $T=9.1mins$. The amplitude in watts is approximately 1050W. Another appliance was the oven and was set to 240$^o$C. The oven consumes constant power with time during the stabilization period. This period is the necessary time to reach the required temperature and is met in all thermostatic devices, during their first period of operation. The same time period exists for the air conditioning unit but is not presented in the figure. After the stabilization period, the power curve is a periodic pulse shape function with function $f_i(t)$ transposing the “switching on” of each one over a specific time interval $\delta_i$. The transposed function can take the form $f_i(t+\delta_i)$.

From the operational point of view we can distinguish a discrete optimization problem. It refers to the minimization of the max power profile of a given device is periodic with period $T_i$, $f_i(t+T_i)=f_i(t)$ and is presented in (1).

$$f_i(t) = \begin{cases} A_i, & 0 \leq t \leq \tau \\ 0, & \tau < t \leq T_i \end{cases} \quad (1)$$

In the above formulation, $A_i$ is the amplitude in watts and $\tau$ indicates the activation time of the device and is related to the duty cycle $\tau/T_i$.

We use a discrete time model with a finite time horizon that models a time window of observations. Each time window is divided into $T_{w}$ periods of equal duration, indexed by $t = 1,2,3,...,T_{w}$. We assume a group of $N$ ‘clients’ operating energy consuming devices. Some of those devices have a fixed in time schedule of operations but others are flexible. The latter are described by power consumption functions $f_i (i \in D)$ while the former by “base line” ones, $s_i(i \in D)$. The flexibility refers to the possibility of changing the time of operation of the $f_i$ by transposing the “switching on” of each one over a specific time interval $\delta_i$. The transposed function can take the form $f_i(t+\delta_i)$.

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$T=89.7\text{ mins}$. For the simulation process, the amplitude in watts was described by a constant value of approximately 155W.

3. OPTIMIZATION ALGORITHM

This section introduces the proposed optimization algorithm. The proposed algorithm does not impose external on/off control to the devices and thus energy is conserved over time $T_w$. This is written in a mathematical form as:

$$\int_{0}^{\tau_w} \left( \sum_{i \in D} f_i (t + \delta_i) + s_i \right) dt = \text{const.}, \forall \delta$$

3.1 Minimization of Max Power

Assume $N$ functions $f_i(t)$ defined on the interval $0 < t < T_w$. The phase of each function can be managed (undergo a transposition in time) according to a parameter $\delta_i$. The superposition of the functions is then given by:

$$F(t) = \sum_{i \in D} f_i (t + \delta_i)$$

We attempt to find optimal $\delta_i$, in order to minimize the maximum of the summation ($F(t)$) over the time window $0 < t < T_w$. In a mathematical form this is given by:

$$S(\delta_i) = \min \left( \max \left( F(t) \right) \right), \quad 0 \leq t \leq T_w$$

The above formulation states that the objective is to minimize the maximum value of the superposition of the power profiles of the devices. The procedure is based on the expansion of functions to Taylor series and on the basic principle of the gradient method of the optimization theory, deviating from the strict formalism, due to the special character of the problem. If we perform a Taylor series expansion on $f(\delta)$ at point $t_i$, we have:

$$f(\delta) = f(t) + f'(t)(\delta - t) + ...$$

Keeping only the first order term and replacing $\delta$ with $t+\delta$, the function $f(t+\delta)$ can be approximated as:

$$f_i(t + \delta_i) = f_i(t) + \frac{df_i}{dt} \delta_i$$

For the superposition of all $f_i$ based on (4) it holds:

$$F(t) \approx \sum_{i \in D} f_i(t) + \sum_{i \in D} \frac{df_i}{dt} \delta_i$$

Based on gradient descent method and on (4), (5) the following conditions must be satisfied:

$$\sum_{i \in D} f_i(t + \delta_i) < \sum_{i \in D} f_i(t), \quad \forall t \rightarrow 0 \leq t \leq T_w$$

If $\frac{df}{dt} < 0$ then $\delta > 0$

If $\frac{df}{dt} > 0$ then $\delta < 0$

In order to approach gradually to the required minimization of (3), the increments $\delta_i$ are selected to be unitary, something easily defined in the case that the $f_i$ and $\frac{df}{dt}$ functions are given as a series of $n$ discrete values with a time step $dt$ ($T_w=n \cdot dt$). This step is used for the transpositions of the $f_i$ towards their final positions, achieving minimization of $S(\delta)$. For the special case of periodic pulse functions, which are not differentiable, as shown in (1) a simplified procedure can be followed. We can heuristically set $\frac{df}{dt}=1$, for $0 < t < \tau/2$ and $\frac{df}{dt}=-1$, for $\tau/2 < t < \tau$ and $\delta_i=dt$. The iterative procedure is then updated, as follows:

$$t^* = \arg \max_t F(t)$$

$$\delta_i^{\text{new}} = \delta_i^{\text{old}} + \text{sign} \left( \frac{df_i}{dt} \right) \cdot dt$$

The complexity of the centralized algorithm is similar to $O(N \cdot T_w)$ where $N$ is the number of devices and $T_w$ is the observation window that incorporates all time steps of duration $dt$.

3.2 Device Phase Delay

Since some devices might have $\delta_i<0$ and for operational purposes, the final time shift of all the devices can be assumed equal to:

$$\delta_i^{\text{final}} = \delta_i^{\text{iter}} + \min(\delta_i), \quad \delta_i^{\text{final}} > 0$$

where

$$\delta_i^{\text{iter}} = \sum_{i \in D} \delta_i$$

and $\delta_i^{\text{iter}} = \left[ \delta_1^{\text{iter}}, \delta_2^{\text{iter}}, ..., \delta_n^{\text{iter}} \right]$ is a row matrix of size $1 \times N$ containing the total phase delays for each device ($IT$ is the iteration number of the algorithm).

4. RESULTS

To explore a great diversity of possible scenarios, randomly generated network configurations of smart devices were simulated, in a Monte Carlo procedure. For the purpose of the simulations each smart device is characterized by the amplitude $a_i$, the activation time $t_i$, the period $T_i$ and an initial phase shift that defines the activation point in time within the observation window ($T_w$). For simplicity, only periodic pulse shape devices were explored. The examined devices are the fridges described by set $NF$, the ovens described by set $O$ and the air conditioners described by set $AC$. At each simulation run, a random number generator defines the number of smart devices such that $\|NF\| + \|O\| + \|AC\| = N$

where $\|\|$ defines the cardinality of set and $N$ is the number of smart devices. To capture different types of appliances, the statistics of the parameters are defined by the measured values of Figure 2 and normally distributed random numbers.

The first simulation result concerns the effect of the proposed optimization algorithms on a given randomly generated snapshot of the network. The network comprises 16 fridges, 14 ovens and 15 air conditioners. Figure 3 presents three subplots. In the first subplot, the superposition of the periodic pulses is simply presented. It can be observed that the maximum peak load is approximately 20kWatts. The second subplot presents the superposition of the phase managed periodic pulses after performing the peak load minimization algorithm. The maximum peak load is given by the dash line and is equal to 16.2kWatts (almost 20% reduction). The third subplot presents the phase management scheme of the 45 active devices. The translation of the figure in real life scenarios is twofold. One can use equation (8) to find the total phase delay. The second approach is to
translate the negative times into continuation of the current state of operation of the device. Taking into account that for the simulation tests one time step is equal to 1/10 minutes, the delays that are imposed to the system is for the worst case equal to 2.8 minutes. Taking into account the operational periods of the measured devices of Figure 2 one could say that the phase management scheme yield great load reduction without significantly affecting users’ comfort. The second simulation results compares the performance of the centralized control algorithm over randomly generated networks (simulation runs). At each simulation run, randomly generated normally distributed values of the amplitudes, activation times and periods were used based on the measured values of Figure 2. Figure 4 presents the peak load reduction, in percent, compared to the initial maximum value of the superposition of the pulses that are not processed (no algorithm imposed). The results are obtained by 100 randomly generated network configurations.

5. CONCLUSIONS

This paper presented an optimization algorithm that can be implemented in the smart grid to provide peak load minimization without affecting users’ comfort. The novelty of the work is twofold. First of all, measurements of typical flexible loads show a periodic pulse shape pattern. Thus, peak savings can be achieved without performing external on/off schemes that might cause user dissatisfaction and low penetration of smart grid services in the future. The idea is to manage the phases of the periodic loads in such a way, to provide peak reduction that reduces the imported energy or enables better usage of renewable energy that will create cheaper services to customers. The paper proposed a gradient descent technique that is adapted to non differentiable periodic pulse functions. The objective function was the peak reduction of the power curve over a pre defined observation time period. A centralized control scheme was investigated where the controller of the smart grid broadcasts command flow to all smart devices in the network. It was proved that for the proposed centralized algorithm, a reduction of the peak power load of approximately 10%-20% can be achieved, for most cases. A subsequent cost reduction of the order of 3%-5% was also observed taking into account that cost is a quadratic function of load. In the future version of the paper, we will explore cost minimization and power load flattening algorithms in centralized and distributed control schemes.

6. ACKNOWLEDGMENTS

The authors would like to thank Dr. N. Mitianoudis for the fruitful discussions and Mr. Th. Stavropoulos for the measurements. This work was funded by the European Union under grant agreement n. 257740 (Network of Excellence TREND) and from the European Social Fund ESF and Greek national funds - Operational Program "Education and Lifelong Learning", National Strategic Reference Framework FP7/2007-2013.

7. REFERENCES