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

George Koutitas
School of Science and Technology
International Hellenic University
14 Km Thessaloniki-Moudania
57001, Thessaloniki, Greece
+302310807533
g.koutitas@ihu.edu.gr

Leandros Tassiulas
Computer Eng. Telecommunications
University of Thessaly
38221, Volos, Greece
leandros@inf.uth.gr

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 to 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 applied to determine the phases of the pulses in discrete time steps. A centralized control scheme is explored, applied from the controller of the smart grid to smart devices that fall within its administrative domain. It is found that respectable peak power reduction can be achieved by the centralized scheme with a drawback the redundant data transfer in the network. The main advantage by implementing the proposed algorithm is that direct on/off control of the smart grid upon the smart devices of the users 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

e-Energy 2012, May 9-11 2012, Madrid, Spain.

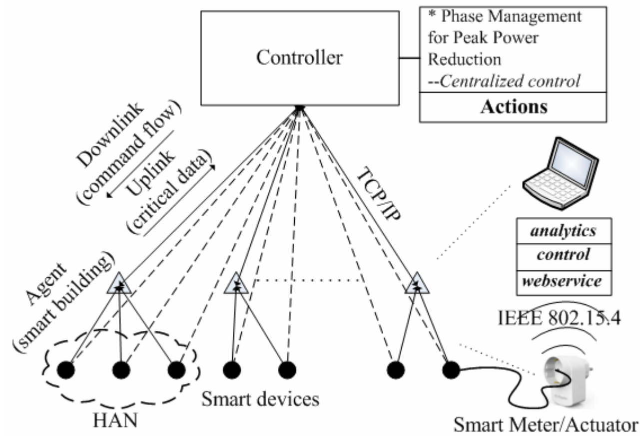

Figure 1. General architecture.

externally controlled by the smart grid to balance the operation of the network, without significantly affecting users comfort. The flexible loads are usually thermostatic and are responsible for the peak power of the network. These devices usually present power loads described by periodic pulse shape waves. Based on the thermal capacity phenomenon, these devices can be controlled under on/off schemes without affecting users' comfort [6, 7]. In order to avoid continuous command flow between the controller and the smart devices, and thus create discomfort, we focus on the 'synchronization' of these periodic pulse shapes to fulfill self adaptable smart grid operation.

2.2 Definition of Parameters

The power load of the system is the superposition of N energy consuming devices creating a set D with identifiers $i \in D, i \in \{1,2,...N\}$ where N is the maximum number. These devices are deployed in the smart buildings of the network. Non-flexible devices usually consume almost constant power with time s_i, whereas flexible loads are periodic pulse shapes $f_i(t)$. In our study we focus only to the second type of loads and so from this point forward any device is assumed of the second type. The power profile of a given device is periodic with period T, $f(t+T)=f(t)$ and is presented in (1).

$$f_i(t) = \begin{cases} A_i, & 0 \le t \le \tau \\ 0, & \tau < t \le T \end{cases} \qquad (1)$$

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

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 δ_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 demanded by the devices in the network over a defined time interval. This problem aims to avoiding the occurrence of black out 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 (δ_i) of the functions f_i, referring to the flexible devices, for each of the N clients.

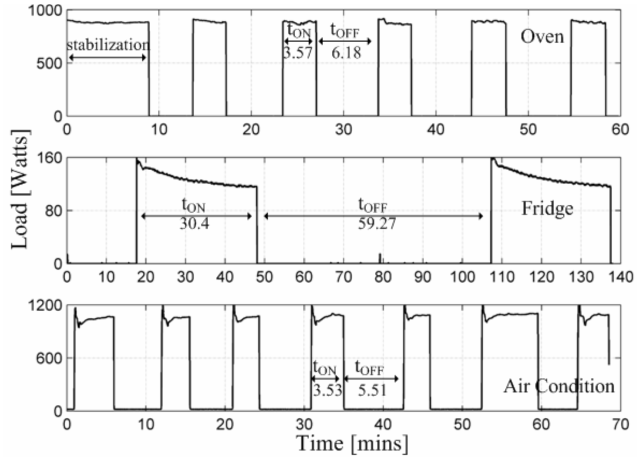

Figure 2. Measurements of pulse shape loads.

We assume at this stage that the only constraints posed on the transpositions is that $\delta_i << T_W$ and $\delta_i < T_i$. 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 webservices (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^{0}C and the outside temperature during the measurements was 30^{0}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^{0}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^{0}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 activation time $\tau=t_{ON}=3.57mins$ and total period of $T=9.75mins$. The amplitude in watts is approximately 975W. The fridge operation is also described by periodic pulse shape with $\tau=t_{ON}=30.4mins$ and

T=89.7mins. 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:

$$\int_0^{T_W}\left(\sum_{i\in D} f_i(t+\delta)+s_i\right)dt = const., \forall \delta$$

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 δ_i. The superposition of the functions is then given by:

$$F(t)=\sum_{i\in D} f_i(t+\delta_i) \tag{2}$$

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

$$S(\delta_i)=\min\left(\max\left(F(t)\right)\right),\quad 0\le t\le T_W \tag{3}$$

The above formulation states that the objective is to minimize the maximum value of the superstition 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, we have:

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

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

$$f_i(t+\delta_i)=f_i(t)+\frac{df_i}{dt}\delta_i \tag{4}$$

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

$$F(t)\approx\sum_{i\in D} f_i(t)+\sum_{i\in D}\frac{df_i(t)}{dt}\delta_i \tag{5}$$

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

$$\sum_{i\in D} f_i(t+\delta_i)<\sum_{i\in D} f_i(t),\quad \forall t\to 0\le t\le T_W \tag{6a}$$

$$\begin{aligned} &if \quad \frac{df_i}{dt}<0 \quad then \quad \delta_i>0\\ &if \quad \frac{df_i}{dt}>0 \quad then \quad \delta_i<0 \end{aligned} \tag{6b}$$

In order to approach gradually to the required minimization of (3), the increments δ_i are selected to be unitary, something easily defined in the case that the f_i and df_i/dt functions are given as a series of n discrete values with a time step dt (T_W=$n\ dt$). This step is used for the transpositions of the f_i towards their final positions, achieving minimization of $S(\delta_i)$. 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 $df_i/dt=1$, for $0<t<\tau/2$ and $df_i/dt=-1$, for $\tau/2<t<\tau$ and $\delta_i=dt$. The iterative procedure is then updated, as follows:

$$t^*=\arg\max_t F(t) \tag{7a}$$

$$\delta_i^{new}=\delta_i^{old}+sign\left(\left.\frac{df_i}{dt}\right|_{t=t^*}\right)\cdot dt \tag{7b}$$

$$sign(a)=\begin{cases}-1, & a<0\\ 1, & a>0\end{cases}$$

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 n 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:

$$\delta_i^{Final}=\delta_i^{IT}+\left|\min(\boldsymbol{\delta})\right|,\quad \delta_i^{Final}>0 \tag{8}$$

where

$$\delta_i^{IT}=\sum_{k=1}^{IT}\delta_i^k \tag{9}$$

and $\boldsymbol{\delta}_{1xN}=\left[\delta_1^{IT},\delta_2^{IT}...\delta_N^{IT}\right]$ is a row matrix of size *1xN* 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 α_i, the activation time τ_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 $\|\cdot\|$ 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

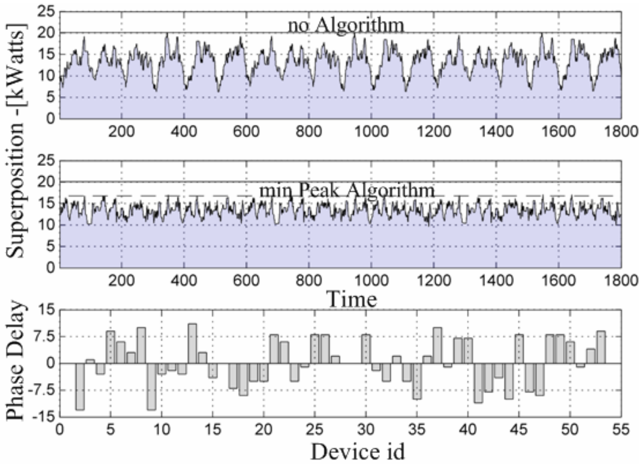

Figure 3. Snapshot of superposition of pulses and phase management scheme.

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.

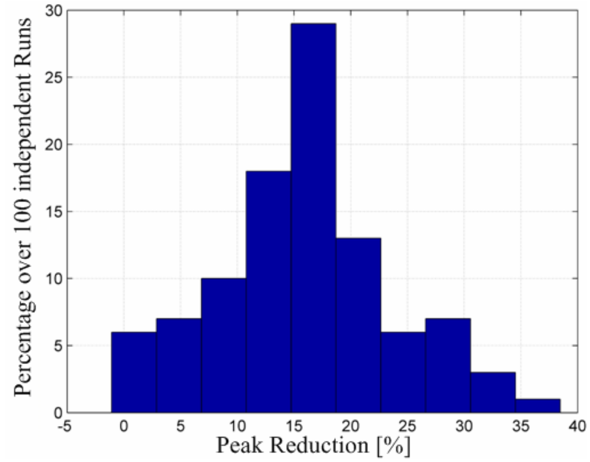

Figure 4. Power peak reduction over randomly generated networks configurations.

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

[1] IEEE Standards, IEEE P.1701-1705, 2011.

[2] M. J. Neely, A. S. Tehrani, A. G. Dimakis, 'Efficient algorithms for renewable energy allocation to delay tolerant consumers', *in Proc. IEEE Conf. Smart Grid Communic.* , Oct. 2010.

[3] K. Hamilton and N. Gulhar, "Taking Demand Response to the Next Level", *IEEE Power and Energy Mag*.,vol.8, no.3, pp.60-65, May / June 2010.

[4] L. Chen, N. Li, L. Jiang, S. H. Low, 'Optimal demand response: problem formulation and deterministic case', *in Control and Optimization Theory for Electric Smart Grids*, Springer, 2011.

[5] Jean-Yves Le Boudec, D. C. Tomozei, 'Satisfiability of elastic demand in the smart grid', *in Proc. Int. Conf. on Smart Grids, Green Communications and IT Energy-aware Technologies*, ENERGY 2011, May 2011.

[6] I. Koutsopoulos and L. Tassiulas, "Control and Optimization meet the Smart Power Grid: Scheduling of power demands for optimal energy management", *Proc. Int. Conf on Energy-Efficient Computing and Networking* (E-Energy), 2011.

[7] G. Koutitas, 'Control of flexible smart devices in the smart grid', *IEEE Trans. Smart Grids*, (under review).

[8] L. Chen et al., "Two Market Models for Demand Response in Power Networks," *Proc. IEEE Int'l. Conf. Smart Grid Commun*., 2010.

[9] M. Baghaie, S. Moeller, B. Krishnamachari, 'Energy routing of the future grid: A stochastic network optimization approach', *in Proc. Power System Technology*, 2010.

[10] http://www.beywatch.eu