A SMART HOME CONTROLLER USING AN INTEGER PROGRAMMING APPROACH FOR THE OPTIMIZATION OF CONSUMER ECONOMIC SAVING AND COMFORT

Conference Paper · October 2015

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A SMART HOME CONTROLLER USING AN INTEGER PROGRAMMING APPROACH FOR THE OPTIMIZATION OF CONSUMER ECONOMIC SAVING AND COMFORT

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Abstract — Energy efficiency is a vital subject for the world. In the years to come it is expected that residences and industries will become smart consumers and the grid will be used more efficiently. A smart home controller can help the residential consumers to achieve economic savings by moving the start of each load to times of low tariff. A side effect yet to be studied is the impact on the customer comfort of such controller. In this paper the comfort problem will be mathematically described as a integer programming optimization problem and it will be demonstrated by computer simulations that it is possible to achieve high levels of economic saving without a great impact on the user comfort level by making the controller optimize a combination of both objective functions.

Keywords— Automation, Energy Efficiency, Demand Side Management, Combinatorial Optimization.

Resumo — O primeiro capitulo apresenta uma revisão da litetura sobre eficiência energética e *demand side management*. No capítulo dois é apresentado a formulação matemática de um controlador residencial para economia de energia e é introduzido o nível de conforto como função-objetivo. O capítulo três apresenta simulações realizadas sobre o modelo matématico do controlador para diferentes cenários e configurações. O capítulo quatro discute os resultados das simulações com foco nas consequências da introdução da nova função-objetivo. No capítulo cinco as contribuições deste artigo são apresentadas. O capítulo seis apresenta as conclusões do trabalho e os próximos melhoramentos a serem implementados. No capítulo sete constam as referências bibliográficas.

1 Introduction

Over the past years has emerged the concept of smartness as a basic feature of the home automation systems. In this context, smartness means that systems of different manufacturers must work in an integrated form, aiming to guarantee to the user safety and the simplicity of utilization for the adopted solutions. In this way, a building can be automated but it may not be an intelligent building case it does not ensure the interoperability between its systems.

New methods for costs reduction in energy systems have been proposed in the most diverse areas. Several researchers have reported the proposition of home automation technologies, like Smart Home (SH) systems (Vainio, 2012; Fitzpatrick, 2009; Carreiro, 2011; Corno & Razzak, 2012; Di Giorgio & Pimpinella, 2012; Gellings & Samotyj, 2013; Panna et al. 2013).

The application of the concept of intelligent networks, which are also called Smart Grids (SG), among other tools, have used integrated and intelligent actions between producers, distributors and clients, by means of control and communication systems with bidirectional networks, thus ensuring, in an efficient way, the sustainable, economic and safe energy supply (Momoh, 2008; Pasand et al., 2009; Heydt, 2010; Jackson, 2010; Bezerra et al., 2013). Based on the concept of SG, it was proposed the application of residential automation (Suh & Ko, 2008; Han & Lim, 2010; Son et al., 2010; Kofler et al., 2012; Li, 2012; Hernández et al., 2013).

In particular, the search of solutions aiming to improve the energetic efficiency in SH`s has been approached for several authors (Choi et al., 2005; Fitzpatrick et al. 2009; Begovic, 2013; Gellings & Samotyj, 2013; Panna et al., 2013; Figueiredo et al., 2014).

Although the literature on Smart Home concept in a home automation perspective is vast, the proposition of methods which consider the interests of the customers is very limited.

This paper aims at presenting an integer programming approach for the optimization of a Smart Home Controller considering consumer economic saving and comfort. The proposed approach can considers three possibilities: (i) the minimization of energy costs, (ii) the maximization of the consumer comfort, and (iii) a multiobjective approach which uses the weighted sum of the above mentioned objective functions.

The remaining parts of this paper are structured as follow. In the second section, the mathematical formulations are presented. In the third section, computational simulations are presented. In the fourth section is presented the results discussion. At the end, the paper presents some conclusions and recommendations for future research.

2 Mathematical Formulations

2.1 Minimization of Energy Costs

Di Giorgio and Pimpinella (2012) presented a strategy for optimization of the electrical power consumption based on a Smart Home Controller (SHC). Such SHC selects the time of start of each load presented in a residence in such a way that the power consumption costs will be minimum.

The proposed SHC takes decisions based on the following parameters:

- costs (Tariff) along the day
- maximum demand along the day
- power consumption of each load, and
- minimum starting time of each load (decision of the user)

Given that such SHC is a discrete-time system that works on a certain sample rate (T_s), that a day is divided in N samples and that the residence has M plannable loads, the mathematical model of the SHC, as an integer programming problem, can be described as follow. Each symbol is described on table 1.

$$f_1(x) = \min\left\{\sum_{m=1}^{M}\sum_{i=I_{Sm}}^{I_{Em}-N_m}\left(\sum_{n=i}^{i+(N_m-1)}\bar{P}_m[n-i]T_sC[n]\right)u_{mi}\right\} \quad (1)$$

$u_{mi} \in \{0,1\}$
$M = 1, 2, 3, \dots, M$
$i = I_{Sm}, I_{Sm}+1, \dots, I_{Em}-N_m$

subject to

$$\sum_{I=I_{Sm}}^{I_{Em}-N_m} u_{mi} = 1 \qquad m = 1, 2, 3, \dots, M \quad (2)$$

$$\sum_{m\in M_k}\left(\sum_{i=(k-(N_m-1)}^{k-(k-I_{Em}+N_m)^+}\hat{P}_m[k-i]u_{mi}\right) \le P_k \quad (3)$$

$k = S, S+1, \dots, E-1$

In Table 1 is presented the list of used symbols.

The objective function $f(x)$ states that the SHC should select one starting time for each load granted that this starting time is greater than the minimum starting time and that the load finishes before its final ending time. The SHC finds the starting times of each load such that the sum of the economic costs of all the loads is minimum.

The set of constraints of type (2) guarantees that only one starting time per load will be selected. The set of constraints of type (3) imposes that the power consumption in any given moment will be less or equal the maximum peak power permitted.

Table 1 - List of symbols

Symbol	Meaning
M	Number of plannable loads
$\bar{P}_m$	Average power time sequence of mth load
$\hat{P}_m$	Peak power time sequence of mth load
N_m	Duration in samples of mth load
I_{Sm}	Sample associated with the minimum starting time of the mth load
I_{Em}	Sample associated with the maximum ending time of the mth load
S	Planning period starting time
E	Planning period ending time
u_{mi}	ith decision variable of the mth load
P_k	Virtual power threshold at kth time instant
C	Daily energy price sequence
I_{Bm}	Best starting time of the mth load
C_{Lm}	Comfort level of the mth load
w_1	Controller weight of economic optimization
w_2	Controller weight of comfort optimization

2.2 Introducing New Objective Function: Comfort

The stated SHC is efficient in minimizing the power consumption costs of plannable loads but, as it will be demonstrated, it can lead to a great level of discomfort if the starting time of the loads vary greatly from the best (from a user's perspective) possible starting time.

To perform analysis about the level of discomfort generated by the SHC the following parameters will be introduced on the problem.

- Comfort level of each load (C_{Lm}). Vary from 0 (changing the starting time of the load as no effect on the generated discomfort) and 1 (changing the starting time of the load as great impact on the generated discomfort)
- Possible best starting time of each load (I_{Bm})
- Controller weights for economic and comfort optimization. (w_1) and (w_1)

All those new variables are user's decision since there's no way for the SHC to determine the comfort level or the best starting time for each load. It gives the user the possibility to set the SHC as a full economic optimizer or a full comfort optimizer by simple varying the value of such variables.

The mathematical model for the minimization of the discomfort of all loads in a residence can be stated as follow.

$$f_2(x) = \min\left\{\sum_{m=1}^{M}\sum_{i=I_{Sm}}^{I_{Em}-N_m}(C_{Lm}|i-I_{Bm}|)u_{mi}\right\} \quad (4)$$

The proposed enhanced SHC will aim to minimize the economic costs of running all loads while maintaining an acceptable level of discomfort from the user's perspective. To achieve such result the SHC will minimize the linear combination of the two objective-functions creating a new one. This new objective function is stated as follow.

$$f(x) = w_1 f_1(x) + w_2 f_2(x) \quad (5)$$

Where

$$w_1 + w_2 = 1 \quad (6)$$

$$w_1 \geq 0 \quad (7)$$

$$w_2 \geq 0 \quad (8)$$

By varying w_1 and w_2 the user can achieve both, economic saving and comfort level that will satisfy him the most.

Setting w_1 to 1 the user determines to the SHC that the discomfort generated is not important and the controller should do all efforts to minimize the economic costs.

Instead, setting w_2 to 1 the user decides that the controller should only takes comfort into account, making sure that all loads will start as close as possible to their best starting time.

3 Results

The same four original simulations performed by Di Giorgio and Pimpinella (2012) were remade here to demonstrate the impacts of using a SHC with and without comfort analysis. MATLAB and IBM CPLEX were used as the tools for the simulations.

Table 2 summarizes the four simulations tariff differences.

Table 2 – Simulation's Tariffs

Simulation	Fare	Time period	C [cent/kWh]
1	Standard	[00:00 – 24:00]	18.00
2	Off-peak	[00:00 – 08:00] [19:00 – 24:00]	16.75
	Peak	[08:00 – 19:00]	21.22
3	Off-peak	[00:00 – 08:00] [19:00 – 24:00]	16.75
	Peak	[08:00 – 16:00] [18:00 – 19:00]	21.22
	DSM	[16:00 – 18:00]	12.00
4	Off-peak	[00:00 – 08:00] [19:00 – 24:00]	16.75
	Peak	[08:00 – 19:00]	21.22
	DSM	[16:00 – 18:00]	12.00

The simulations were performed on a residence with nine plannable loads. The new parameters C_{Lm} and I_{Bm} are added on each load. In the Table 3 is described the load's profile.

The sample interval used is 5 minutes. The best starting time of each load is set at 18:00. The minimum starting time of each load is set at 14:00 and maximum end time at 23:59.

Table 3 – Load Profiles

Load	Phases	Δt (min)	P[kW]	P[kW]	C_{Lm}
1	6	[5,10,15, 5, 5,10]	[0.02, 1.96, 0.02, 0.02, 0.02, 0.05]	[0.15, 2.1, 0.15, 0.15, 0.2, 0.55]	1.0
2	1	[105]	[2.36]	[2.7]	0.9
3	7	[5,25, 20,5,10, 10,20]	[0.04, 1.99, 0.28, 0.06, 0.06, 0.06, 0.08]	[0.2, 2.1, 2.1, 0.2, 0.3, 0.25, 0.5]	0.8
4	6	[15,30, 10,5, 20,50]	[0.07, 1.4, 0.10, 0.07, 2.02,0.01]	[0.1, 2.1, 1.2, 0.1, 2.15, 0.02]	0.7
5	8	[25, 5, 60,20, 10,10,10,20]	[0.27, 0.05, 2.1, 0.11, 0.11, 0.10, 0.10,0.26]	[2.1, 0.3, 2.2, 0.2, 0.6, 0.8, 0.8, 1.1]	0.6
6	6	[20,15, 35,10, 20,50]	[0.07, 2, 0.07, 0.07, 1.8,0.01]	[0.1, 2.1, 0.1, 0.25, 2.3, 0.02]	0.5
7	3	[50,20,50]	[0.8, 0.5,1]	[1, 0.8, 1.2]	0.4
8	4	[20,20, 10,15]	[1.4, 0.5, 0.6, 1]	[1.6, 0.8, 0.6,1]	0.3
9	3	[30,20,30]	[0.6, 0.7,1]	[0.6, 0.7,1]	0.2

Each simulation was run four times. One time using only cost as the objective-function and other three times using the proposed approach of mixing cost saving and comfort enhancement. The difference between those three are the values of w_1 and w_2. Table 4 summarizes the simulations results.

Table 4 – Simulation Results

Simulation				1	2	3	4
Original SHC (Di giorgio and Pimpinella (2012)		Cost		248,7	236,965	199,781	241,546
		Discomfort		16,05	14,51	10,71	16,56
New SHC	(w_1 = 0.3 and w_2 = 0.7)	Cost		248,7	241,073	201,281	244,109
				0%	1,73%	0,75%	1,06%
		Discomfort		6,18	9,99	7,09	9,66
				-61,49%	-31,15%	-33,80%	-41,67%
	(w_1 = 0.5 and w_2 = 0.5)	Cost		248,7	237,032	201,281	247,365
				0%	0,03%	0,75%	2,40%
		Discomfort		6,18	13,52	7,09	9,54
				-61,49%	-6,82%	-33,80%	-42,39%
	(w_1 = 0.7 and w_2 = 0.3)	Cost		248,7	237,032	199,796	243,088
				0%	0,03%	0,01%	0,64%
		Discomfort		6,18	13,52	9,3	10,8
				-61,49%	-6,82%	-13,16%	-34,78%

3.1 Discussion

We can see from the obtained results that the new SHC produces, on average, an increase of 0,62% on the economic cost and an improvement of 35,74% on the comfort level. The largest increase of costs were 2,4% (for a 42,39% increase in comfort) and the lowest increase in comfort was 6,82% (for an increase of 0,03% in costs). In the Table 5 is summarized the average of energy cost and comfort, obtained by varying the weights of the above mentioned criteria.

Table 5 – SHC average result by weights

Weights	Cost Average Increase	Comfort Average Increase
($w_1 = 0.3$ and $w_2 = 0.7$)	0,885%	42,03%
($w_1 = 0.5$ and $w_2 = 0.5$)	0,795%	36,13%
($w_1 = 0.7$ and $w_2 = 0.3$)	0,17%	29,06%

We can see from Table 5 the new SHC is able to greatly increase the comfort level while keeping the increase in economic costs on a minimum.

The user could decide the values of the weights, meaning that he could decide to use the SHC as a full economic saving device, as proposed by Di Giorgio and Pimpinella (2012) by setting w_1 to 1 and w_2 to zero.

Alternatively the user could use the SHC as a full comfort device, meaning it would work as a scheduler turning the loads on when the user intended them to. To do that the user would set w_1 to zero and w_2 to 1.

The user could use a mixed approach selecting w_1 and w_2 to values to accomplish both economic saving and comfort increase according to the user's preference.

All three runs of simulation 1 using the new SHC accomplished a 61,49% reduction on the discomfort level, meaning the loads are, in average, 61,49% closer to their best starting time, giving the user the feeling that the loads are starting when he originally wanted to.

The most interesting aspect of simulation 1 though is that it accomplished this great increase on comfort without increasing the economic cost. In other words the user is saving just as much money as before but with way more comfort. That is true for any value of w_2 other than zero.

This happens because in simulation 1 the tariff is constant throughout the day so there is no economic saving on moving the loads far away from their best starting time. The original SHC worked just to find a solution under the constraints. The new SHC finds the solution under the constraint that maximizes the comfort level. Figure 1 shows how each load was distributed over the day using the original SHC. Figure 2 shows the same scenario using the new SHC. The red line represents the maximum allowed peak power, the curve goes down in specific times to simulate the loads that cannot be controlled by the SHC.

It is important to notice that simulation 1 represents a scenario very common worldwide. In many countries, as in Brazil, the residential user pays a standard fixed tariff during the day.

In some scenarios, the original SHC could find many solutions for the same problem. It could select the worst (from a comfort level view) of those solutions. The new SHC guarantees to select the best one while still maximizing the economic saving.

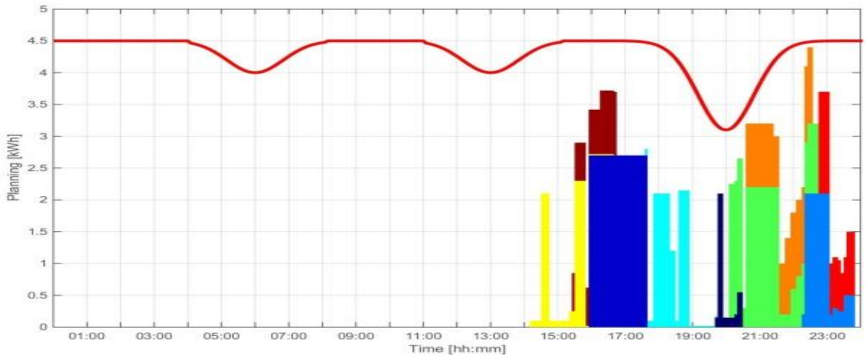

Figure 1 - Old SHC result for simulation 1

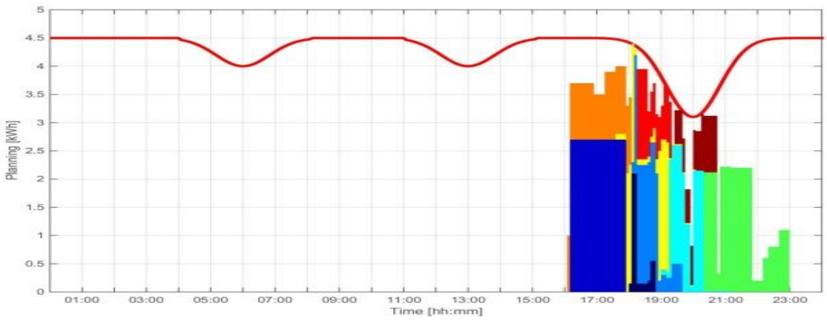

Figure 2 - New SHC result for simulation 1

4 Article's Contributions

This article improved the mathematical model of a smart home controller by adding the user's comfort as an objective function. The enhanced controller gives the user the choice to configure the controller from only economic saving to only comfort maximization including any range between them. This was accomplished by making the controller a multi-objective one where a combination of comfort and economic saving is optimized.

5 Conclusions

As demonstrated by the simulation's results, adding the comfort as an objective function qualitatively improved the smart homer controller performance by minimizing the deviation of the start time of each load from the desired user's best starting time without compromising too much the economic savings.

For the scenarios when the tariff is constant throughout the day the new smart home controller guarantees to find the best solution, from a comfort side of view. Those scenarios are quite common, like today in Brazil.

The next improvements, in development by the authors, to be made on the smart home controller are:

- Add the functionality for the same load to run more than once in the same day: the actual SHC mathematical model is not able to run the same load more than once. The user could add two equal loads and make their possible starting time to be mutual exclusive but in that way it is not guaranteed that the best solution will be found.
- Add the possibility to use the peak power as an objective function instead of a constraint: it is quite common that a user, specially an industrial one, to be charged by the maximum medium peak power consumption over a given interval (commonly known as demand). The demand shall be added as an objective function so the controller will be able to effectively optimize industrial user's economic cost.

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