APPLICATION OF EVOLUTIONARY ALGORITHM FOR CONSTRUCTION OF TOU TARIFFS FOR LOW-VOLTAGE CONSUMERS

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ABSTRACT

In a multi-tariff scenario, it should be considered several variables to set the tariff prices, such as market signals, price ratios and variation of distribution utility revenues, which makes the problem difficult to solve by usual algebraic methods. In light of these circumstances, this paper presents a methodology based on evolutionary algorithm for constructing complementary time-of-use (TOU) tariffs aimed to low-voltage consumers, which will be subsequently applied on a pilot program of Elektro, a distribution company located in the southeast of Brazil.

INTRODUCTION

Regarding to the demand side, hourly tariffs play important roles to promote the optimal use of existing electrical systems, through rates that encourage both consumption during periods of lower demand and charging more those who make use of the network during peak hours. The reduction of idle capacity postpones the expansion of the transmission and distribution systems, which ultimately reflects in lower tariffs to consumers. Moreover, efficient pricing structures can contribute to the stabilization of electricity prices, increases the stability of electrical systems and reduces the power generation during peak hours [1,2].

In Brazil, power regulation services are exercised by ANEEL (*Brazilian Electricity Regulatory Agency*). Currently, only the standard rate (uniform pricing) is available for low-voltage consumers supplied by the distribution utilities. As result, the present pricing structure does not promote the management on the demand side, culminating in inefficient consumption as well as high demand peaks [3].

In light of these circumstances, this study aims to provide subsidies for the construction of complementary tariffs for low-voltage consumer groups in a multi-tariff scenario, in addition to the existing tariffs. It is important to emphasize that calculation of prices is not a trivial task, due to several factors that must be considered such as avoiding the risk of market concentration in a few options at the expense of others, and potential distribution utility revenue reductions caused by consumer migration to these new tariffs. All these issues are herein considered in this paper.

METHODOLOGY

First, it was carried out a measurement campaign and a field survey in order to determine the typical load profiles and consumption habits found in the concession area of Elektro. Once known the typical consumption patterns of the population, it was developed a methodology divided into three parts to calculate the values of new tariffs.

Step 1

This step proposes that consumers, by adopting the new tariffs, would have the same bill as if they remained in the standard rate, assuming no load shifting. Thereby, significant financial advantages would be only perceived when they effectively changed their consumption habits. This premise has been adopted by several regulators around the world [4].

From the aggregate load curves (weekday, Saturday and Sunday/holiday) of the low-voltage market, it is possible to equal the annual revenues that would be obtained from the application of the standard rate and a TOU tariff composed by *n* period of times, according to equation (1). In this example, the hourly tariffs would be applied only in weekdays.

$$Revenue_{std} = Revenue_{TOU} \quad (1)$$

$$(d_W \cdot E_W + d_T \cdot E_T + d_D \cdot E_D) \cdot R_{std} = d_W \cdot \sum_{i=1}^{n} \left(E_W^i \cdot R_{TOU}^i\right) + (d_T \cdot E_T + d_D \cdot E_D) \cdot R_{TOU}^{off}$$

Where:
E_W = energy consumed on weekday (kWh/day);
E_T = energy consumed on Saturday (kWh/day);
E_D = energy consumed on Sunday (kWh/day);
R_{std} = standard tariff rate ($/kWh);
R_{TOU}^{i} = TOU tariff rate in period time i ($/kWh).
R_{TOU}^{off} = off-peak tariff rate ($/kWh);
(d_W, d_T, d_D) = number of annual weekdays, Saturdays and Sundays (days/year).

The resolution of equation (1) involves a problem of n variables, which one corresponds to the tariff of a time period. In general, a standard procedure adopted by regulators consists to define fixed price ratios in order to reduce the problem to single variable. Selecting the off-peak rate as the basis of the problem, its value can be determined by equation (2).

$$R_{TOU}^{off} = \frac{Revenue_{TOU}}{d_W \cdot \sum_{i=1}^{n} \left(E_W^i \cdot n^i\right) + d_T \cdot E_T + d_D \cdot E_D} \quad (2)$$

Where n^i corresponds the price ratio between the rate of period time i and the off-peak rate.

Step 2

Once the new rates are calculated using equation (2), it is necessary to establish additional mechanisms to set their final values. These adjustments are motivated by the use of aggregate load curves in the first step, as these curves are composed by the sum of several load profiles found in the concession area, which could considerably differ from each other. Thus, aggregate load curves may not properly represent the profiles of some segments of the market.
To elucidate this problem, Figure 1 shows a hypothetical aggregate load curve, composed by the arithmetic sum of four distinct consumer groups.

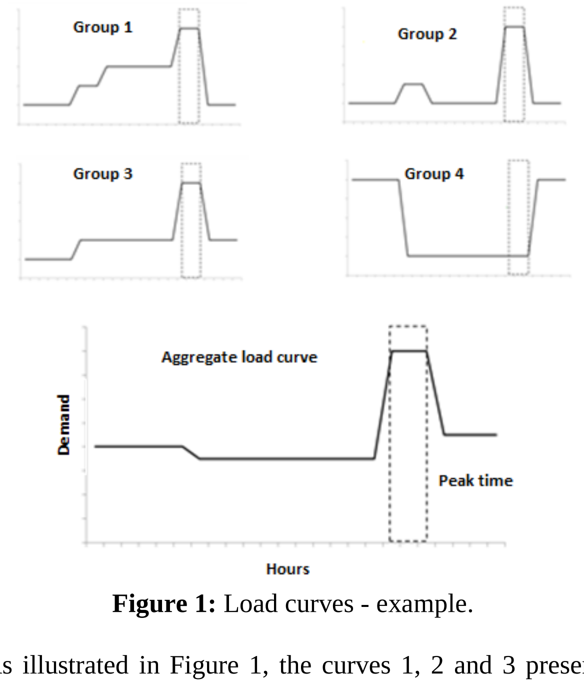

Figure 1: Load curves - example.

As illustrated in Figure 1, the curves 1, 2 and 3 present load profiles similar to the aggregated curve, despite the curve 4. Thus, there is a risk to set inappropriate tariffs to fourth group in absence of any rate adjustments.
In this context, this step involves the use of curves of several segments in order to establish more adherent rates to the various low-voltage market profiles found in the concession area.

Additionally, when new tariffs become available to consumers, it is observed initially a revenue reduction of the utility due to tariff migration. To minimize such loss and control the competitiveness among the tariffs, this step proposes the application of adjustment factor. For each tariff, the hourly rates would be multiplied by this variable, so the all prices would vary proportionally to this factor.
Hence, if a new tariff option would concentrate most of the market at the expense of others, it would be applied a factor greater than 1, in order to increase their prices and consequently reduce their competitiveness. However, for the least attractive options, their rates would be multiplied by a factor less than 1, decreasing their prices and enhancing their competitiveness.

Step 3 - Simulation

The insertion of the adjustment factors in a multi-tariff scenario makes the problem difficult to be solved by usual algebraic methods, as the creation of n new tariffs involves solving a problem of n variables. Thereby, the competitiveness among the tariffs should be constantly adjusted as well as the potential revenue reduction must be within acceptable limits. In this context, it was developed an optimization algorithm based on evolutionary technique using computer application. The choice of the evolutionary algorithm was motivated by its capacity to solve highly complex problems from repeated application of operators (recombination, reproduction, mutation and selection) as well as the quality of the results [3].
In this paper, the most appropriate option for each consumer group solely depends on their bill discount. In practice, the tariff choice is also influenced by a sum of several external factors, such as load shaping capability, willingness to change consumption habits, economic activity, income, level of information, public campaigns, acquisition of new equipment, and so on [5,6]. If all these variables were considered in this study, it would require a large volume of information and would greatly increase the complexity of the model.
The algorithm developed in this paper has the following characteristics:
(I) Objective function: in accordance with the principles of efficient pricing, it is aligned with the purpose to set competitive and attractive tariffs for the segments of the low-voltage market in order to maximize the welfare of both consumers and producers. Nevertheless, it would require the knowledge of their consumption elasticity or their respective demand functions, which are difficult to obtain in practice [3]. This paper proposes to maximize the market distribution in the tariffs as a proxy for the maximization of the welfare.
Considering the distribution of N consumer groups in m tariff options, it is possible to calculate the square error according to equation (3), where p_i represents the amount of groups that selects tariff i.

$$Square\ error = \sum_{i=1}^{m} (p_i - N/m)^2 \qquad (3)$$

The equation (4) indicates that the square error decreases as the groups become more evenly distributed, so the objective function (OF) involves its minimization:

$$Obj.Function = Min\left\{\sum_{i=1}^{m} (p_i - N/m)^2\right\} \qquad (4)$$

(II) Input parameters: correspond to the dataset of the model, such as the initial TOU rates, existing tariff rates, load profiles of group consumers, price ratios, time periods of TOU tariffs.
(III) Restrictions: involve the maximum acceptable value of the utility revenue reduction resulting from the availability of new tariffs to its customers. Also, the limits of the variables (adjustments factors AF) are pre-defined before computational simulation.
(IV) Setting parameters: correspond to the evolutionary algorithm parameters, such as mutation rate, population size, random propagation, convergence of the method and maximum time for improvement.
The algorithm flowchart is depicted in Figure 2.

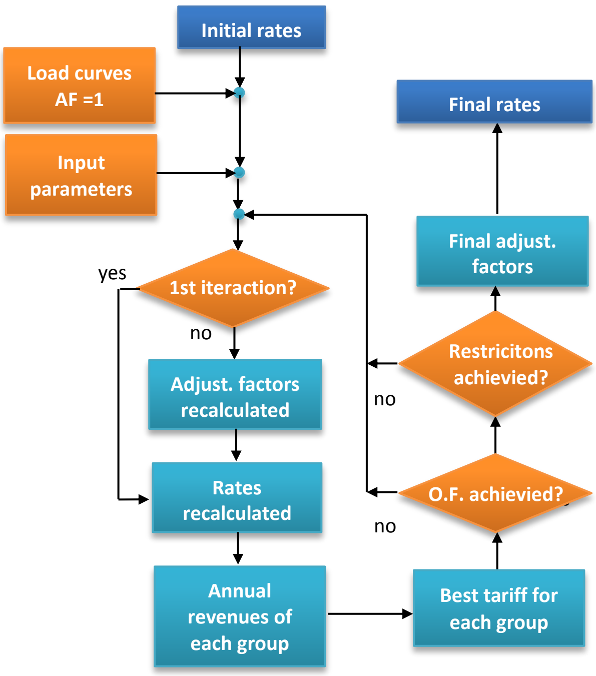

Figure 2: Evolutionary algorithm flowchart.

For each iteration, the method selects the variables, in this case the adjustment factors (initially equal to 1), which provide the best solution, so the next generation is the recombination of the fittest individuals. This process is repeated continuously until the method convergence is achieved or the maximum time for improvement runs out.

Finally, the optimal factors, when multiplied by the initial rates, result in the prices of final tariffs.

TARIFF OPTIONS

It is important to point out that ANEEL has already defined a TOU tariff, named White Tariff, aimed for low-voltage consumers. It is composed by three time periods (peak, intermediate, off-peak) which are valid only on weekdays. However, it is not yet approved to public due to technical metering restrictions, so the standard rate is the only available option.
Based on the survey carried out in this project, this paper proposes the creation of three TOU tariffs in addition to the current options:
(I) Simple Peak Tariff: consists in an alternative to the White Rate, with the elimination of the intermediate period. It intends to offer a simpler option and test its effect on the demand management.
(II) Early Morning Tariff: composed by three time periods (peak, off-peak, early morning) with discount for energy consumed during midnight to 5a.m. in all days. It is aimed for those who have interest to expand and shift their electricity consumption in early morning. Regarding to technical perspective, it offers an incentive to use the electrical system when it states great idleness.
(III) 6x7 Tariff: presents a structure similar to Simple Peak Rate, except for the application of peak rate on Saturdays.

SIMULATION AND RESULTS

Considering the large number of low-voltage consumers supplied by Elektro, it was carried out a measurement campaign in order to identify the typical load curves of residential (B1) and industrial/commercial low-voltage segments (B3). This campaign involved the metering readings of 338 and 529 clients of tariff subgroups B1 and B3, respectively.
Load curves that presented similar profiles were gathered in the same group using the k-means clustering. At the end of the process, it was respectively defined 24 and 30 clusters for the B1 and B3 tariff subgroups.
Tables 1 and 2 show the new tariffs rates after performing the evolutionary algorithm, considering the official and proposed tariffs. As input parameters, the price ratios peak/off-peak (PR_1) and early morning/off-peak (PR_2) were previously set arbitrarily at 3 and 0.65, respectively.

Table 1: Tariff Rates – B1.

Time Periods	Standard	White	Simple Peak	Early Morning	6x7
	R$/kWh	R$/kWh	R$/kWh	R$/kWh	R$/kWh
Early Morn.	287,13	216,69	214,72	146,10	205,18
Off-Peak	287,13	216,69	214,72	224,76	205,18
Intermediate	287,13	349,90	214,72	224,76	205,18
Peak	287,13	563,02	644,15	674,29	615,53

Table 2: Tariff Rates – B3.

Time Periods	Standard	White	Simple Peak	Early Morning	6x7
	R$/kWh	R$/kWh	R$/kWh	R$/kWh	R$/kWh
Early Morn.	287,13	216,69	214,72	146,10	205,18
Off-Peak	287,13	216,69	214,72	224,76	205,18
Intermediate	287,13	349,90	214,72	224,76	205,18
Peak	287,13	563,02	644,15	674,29	615,53

Additionally, it was evaluated possibly impacts of load shifting into the distribution of clusters among the tariffs, as well as variations of the utility revenue. In this study, it was defined two scenarios: load shifting from peak to off-peak and off-peak to early morning.
Figure 3 presents the effects of the distribution of clusters of subgroups B1 and B3 for different scenarios of load shifting, assuming each cluster would select the most economic option to itself.

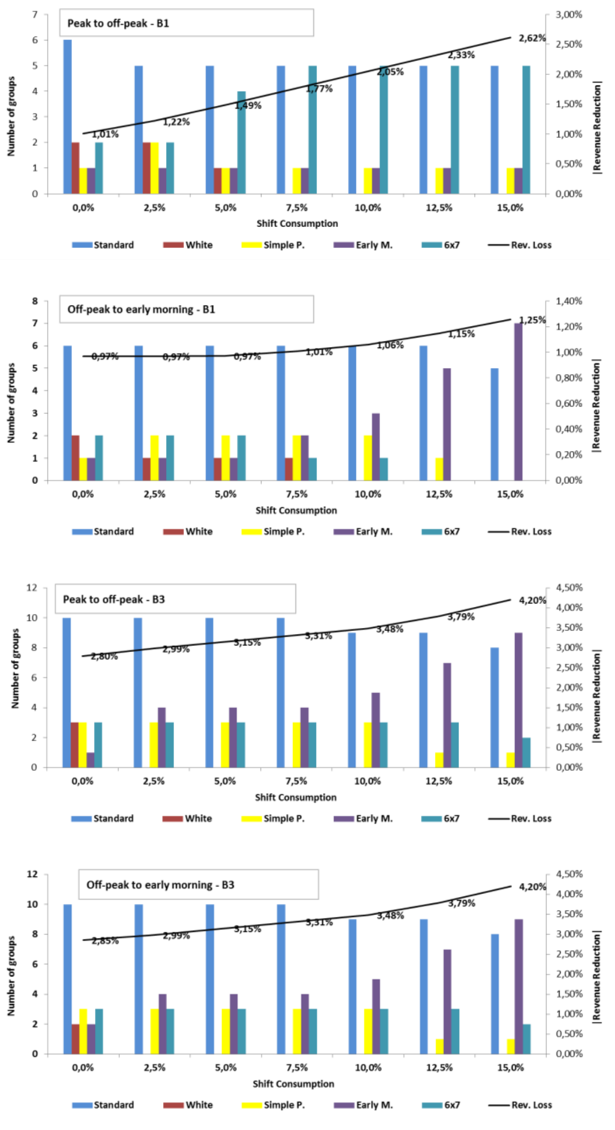

Figure 3: Distribution of groups among tariffs.

As shown in Figures 3, the revenue reduction increases as the load modulation rises, while the clusters tend to migrate Early Morning and 6x7 Rates for subgroups B1 and B3, respectively.
It is important to point out that these tariffs will be applied to low-voltage consumers supplied by Elektro, in a pilot program. Therefore, subsequent analysis will be carried out in order to compare the results obtained by simulation with those verified in practice.

CONCLUSIONS

To sum up, the results obtained from the simulation of the proposed methodology indicate its potential use for low-voltage markets, making this proposal an embracing method to any Brazilian and worldwide distribution utility.
The evolutionary algorithm satisfactorily fulfills the objectives of the project, by calculating the rates from a high complex problem with large number of input parameters, restrictions and variables to be set. Therefore, the complementary new tariffs were both competitive and attractive to some segments of the market, without eliminating the economic viability of the official tariffs.
It should be noted that such migrations invariably cause an initial revenue reduction for the distribution utility, considering the consumers would select the tariffs which would result in lower bills. However, this initial loss can be reversed into benefits for all stakeholders in a long run scenario: for clients, by increasing their welfare, whereas for the utility, by raising its revenue. Also, the optimized use of the existing electric system tends to postpone investments which later reflect in lower tariffs, stimulating the electricity consumption.

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