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Evaluation of supply interruption costs for residential sector in Serbia

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ABSTRACT

The evaluation of the costs associated with the interruptions of the supply with the electrical energy is very important in planning of power system operation and structure using the cost–benefit approach. Many detailed studies have been performed in the past in order to evaluate the supply curtailment effects with particular concern about residential customers. The consequences of supply curtailments have been assessed using surveys asking the customers to perceive the costs to households for a fixed scenario regarding the season of the year, day and time of interruption occurrence. This paper makes an attempt to enhance this analysis by treating the household activities as flows of events overlapping by chance with supply interruptions. Household activities have been modeled separately for various seasons of the year during weekdays and holidays in order to evaluate the interruption consequences in all possible circumstances. These data have been then used to determine the expected customer interruption costs on annual base.

1. Introduction

The customer costs incurred due to interruptions of the supply with electrical energy have been extensively studied in the past as an inevitable part of the reliability assessment of electrical power systems. The surveys have been conducted by mail and/or by direct interviews of the customers in order to form a base for assessing the costs of the interruptions of supply with various duration and frequency. The interruption costs incurred by the residential customers, being an important sector of the distribution system consume, have been of the particular concern. The surveys by mail [1–4] and by direct interviews [5] have been conducted among households with questions on the willingness to pay to avoid the supply outages of various durations and frequencies, in case that the curtailment has occurred at a fixed time, day and season of the year implying that the interruption of all household activities will last as long as the interruption. For the quantification of the severity of system outages the costs per curtailed load [6] and/or the costs per undelivered energy [7–11] have been used in the power system reliability cost studies based upon the data collected by conducted surveys. Some surveys have also included the questions on the undesirability degree of interruptions of various household activities on a defined scale [3–5,12]. The comparison of investigations performed in various countries has shown that the perceived residential costs are very country specific as they primarily depend on the ways of heating, climate, availability of different energy sources and the selected referent interruption scenario [11,13]. Also, it has been shown that the various methods of inquiry give different results for the same curtailment cases. The main idea of this paper was to enhance the methodology of the evaluation of the consequences of supply interruptions for residential customers by modeling more detailed the household activities. The data on the failure frequencies and durations are combined with such data for various daily household activities by treating these activities as flows of events overlapping by chance with distribution system failures. This makes it possible to calculate the mean duration and frequency of the interruptions of all household activities and, consequently, to perceive the associated costs more realistically. The evaluation of customer supply interruption costs has been performed by averaging these costs for different year seasons and weekdays and holidays as the daily cycles of activities are season and day specific.

2. Mathematical model

2.1. Notation

C	total annual customer interruption cost
C_j	total annual customer interruption cost due to failure j
C_{ji}	annual customer cost due to the interruption of activity i by failure j
D_{ji}	duration of the interruption of activity i by failure j

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d_i duration of activity i
d_{pi} tolerated postponement of activity i
E_j undelivered energy to the customer due to failure j
f_i frequency of performing activity i
f_j frequency of failure j
f_{ji} frequency of overlapping of failure j and activity i
n_j number of customers affected by failure j
n total number of customers
P_{av} average customer load demand
r_j duration of failure j repair
λ_i activity i performance rate that is equal to the reciprocal of the time between two succeeding performances of this activity
λ_j rate of occurrences of failure j

2.2. Customer interruption costs

The curtailments of supply cause costs to the customers by interrupting various daily activities.

All household activities are characterized by their daily frequency f_i and mean duration d_i. If the household activities and interruptions are treated as flows of events, then the mean duration of the interruption of activity i by a failure j is determinable from the corresponding Markov state transition diagram and equals (Appendix):

- for not postponable activities

$$D_{ji} = \frac{d_i r_j}{d_i + r_j} \tag{1}$$

- for postponable activities

$$D_{ji} = \begin{cases} r_j - d_{pi} & r_j > d_{pi} \\ 0 & r_j \le d_{pi} \end{cases} \tag{2}$$

The frequency of interruption of activity i equals

- for not postponable activities

$$f_{ji} = f_j f_i (d_i + r_j) \tag{3}$$

- for postponable activities

$$f_{ji} = f_j f_i d_i \tag{4}$$

The expected customer interruption cost caused by the considered interruption is

$$C_{ji} = f_{ji} F(D_{ji}) \tag{5}$$

Function $F(x)$ is constructed from the data provided by the survey of customers' perceptions, using linear interpolation when necessary.

The total cost caused by interruption j can be calculated as

$$C_j = \sum_i C_{ji} \tag{6}$$

with index i including all household activities.

Index C_j should be determined for each season of year and separately for weekdays and holidays, as the household activities are time specific. The values of indices calculated for each characteristic day should be multiplied by the number of these days during a year and divided by 365. By summing this data for all characteristic days during a year we obtain the expected value of the considered index on annual base.

The total annually incurred customer cost due to supply interruptions is determinable by applying the following expression

$$C = \sum_j C_j \tag{7}$$

where index j runs over all failures that can occur.

The electrical energy not delivered because of supply interruption with duration r_j equals

$$E_j = r_j \cdot P_{av} \tag{8}$$

The incurred customer interruption cost per unit of energy not delivered due to failure j is

$$c_j = \frac{C_j}{E_j} \tag{9}$$

2.3. Reliability indices

The reliability of supply of customers in distribution systems is usually assessed by System Average Interruption Duration Index (SAIDI) and System Average Interruption Frequency Index (SAIFI). These indices are calculated using the expressions

$$\text{SAIDI} = \frac{\sum_j f_j r_j n_j}{n} \tag{10}$$

$$\text{SAIFI} = \frac{\sum_j f_j n_j}{n} \tag{11}$$

3. Application

3.1. Survey data

The Electricity Board Belgrade, Serbia initiated and supported a study of the effects of the interruption of the electrical energy supply as perceived by the residential customers in order to adequately conceive its maintenance activities and further investments and avoid complaints. The supervision and guidance of this research have been confided to the Faculty of Electrical Engineering, University of Belgrade and the High School of Engineering of the same University. The residential customers in cities Belgrade, N. Sad and S. Palanka have been interviewed. The interviews in person have been conducted by the graduated students of the High School of Engineering supervised and guided by the teaching staffs of previously mentioned schools. The households are prevailing included in a district heating system (type A households), whereas a number of them use electric storage heating (type B households). In this survey, 350 households of both types have been interviewed and various scenarios have been discussed with the customers by considering available remedies and associated costs. It is important to stress that the great majority of the interviewed persons has experienced supply curtailments in the past, which has helped in perceiving the consequences of such events. The customers are asked to asses, for each activity i listed in Table 1, the longest maximum duration that causes no cost, and the minimum interruption duration that causes the highest cost by overlapping with this activity. Based upon these data and further discussions with the customers, the perceived costs for interruptions lasting within the before mentioned interval are then evaluated. Table 1 presents the costs obtained by this approach. The postponable activities may be laundry washing, boilers heating, storage heating, freezers cooling and household care if the interruption lasts not longer than 3 h. To evaluate the maximum perceived costs, none among the activities has been considered as postponable in the analysis presented in