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CHOSEN ASPECTS OF ELECTRIC POWER SYSTEM RELIABILITY OPTIMIZATION

WYBRANE ASPEKTY OPTYMALIZACJI NIEZAWODNOŚCI SYSTEMU ELEKTROENERGETYCZNEGO*

Reliability is one of the most important criteria, which must be taken into consideration during planning and operation phases of an electric power system, especially in present situation of the power sector. This paper considers the optimization of electric power system reliability. The formalization of description of electric power system reliability level optimization is done as well as its practical solving components are given: diagram of value based reliability approach and estimation of customer damage costs resulting from insufficient reliability level.

Keywords: *power system reliability, reliability assessment, reliability optimization, outage costs assessment.*

Niezawodność jest jednym z najważniejszych kryteriów, które należy uwzględniać, zarówno podczas planowania rozwoju, jak też eksploatacji systemu elektroenergetycznego, szczególnie w obecnej sytuacji elektroenergetyki. Artykuł dotyczy optymalizacji niezawodności systemu elektroenergetycznego. Przedstawiono formalny opis matematyczny zagadnienia optymalizacji poziomu niezawodności systemu elektroenergetycznego oraz pewne elementy jego rozwiązania: schemat podejścia wartościowania niezawodności oraz szacowanie kosztów strat odbiorców z tytułu niedostatecznego poziomu niezawodności.

Słowa kluczowe: *niezawodność systemu elektroenergetycznego, ocena niezawodności, optymalizacja niezawodności, ocena kosztów przerw w zasilaniu.*

1. Introduction

Reliability of the electric power system (EPS) is defined by its ability to secure the supply of electricity of acceptable quality to the customers [2, 12].

Reliability is one of the most important criteria, which must be taken into consideration during planning and operation phases of a power system [3, 12, 14].

After 1990 deep structural changes occurred and still occur in the electric power systems: takes place disintegration, deregulation and advancing market orientation. This is a worldwide trend. Departure from the vertically integrated structures, deregulation and market solutions in electric industry create new conditions, in which the responsibility for the satisfaction of power demands of individual customers is not and cannot be attributed to the particular electric power company. The objective of the electric power system, which is the assurance of electricity supply of the required quality to the customers at the possibly lowest cost and acceptable reliability of delivery is now the task decomposed into many components, and into many subjects [3].

2. General formulation of the problem of reliability level optimization

Premises of the rational creation of the reliability level should be looked for on the background of economy. Let us use the following terminological convention. Let us divide a set of factors composing the usefulness of the system into two disjoin subsets: the first comprises attributes conditioning the scale, in which the goals of the system may be realized – combination of these attributes values we will call the **productivity of the system**, the second comprises attributes determining reliability level – combination of their values we will call the **system reliability**.

Both productivity and reliability of the system depend on the size, the way and the range of the use of various resources, and funds in the processes of system design, construction and exploitation. The models of resources and funds transformations into a system of specified productivity and reliability form so-called production and reliability functions, and at the same time that transformation comprises processes of laying out and spending funds, material means of various kinds and properties, a human work of various range and qualification level.

A specified system reliability level R^* may be accomplished at many alternative combinations of spending (utilization) of resources. For instance, a specified reliability of a power plant may be achieved by higher investment expenditure (use of better technologies and more expensive materials etc.) or by the higher exploitation costs (skilled and well paid staff, intensive plan of maintenance prevention). Thus a curve of equal (the same) reliability represents all the quantitative combinations of n factors conditioning reliability, resulting with the same effect in the form of reliability level. Neither of those combinations is better than the others, if we mean the final result, and the choice of optimal combination of resources is conditioned by two factors:

- Relative effectiveness of individual resources and/or methods of their utilization (in the sense of influence on reliability),
- Relative value or cost of individual resources and/or the ways of their utilization.

To describe the problem of optimal reliability there must be also introduced the concept of marginal reliability R' in relation to resources $\mathbf{X}$ (where $\mathbf{X} = \{X_1, X_2, ..., X_n\}$ is a vector of resources - funds) and considered valuable aspect of resources transformation into reliability.

Marginal reliability R' in relation to resources $\mathbf{X}$ describes the changes in system reliability R, when during its design, construction and exploitation units of individual resources are added or subtracted. Thus, in a specified point:

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

$$R_j' = \frac{\delta R}{\delta X_j} \tag{1}$$

where: R_j' – marginal reliability in relation to j-th resource,
R – reliability expressed by its measure (reliability index) of physical character (for instance undelivered energy, frequency of failures in supply),
X_j – j-th resource;

or, when the partial derivatives do not exist:

$$R_j' = \frac{\Delta R}{\Delta X_j} \tag{2}$$

In majority of cases marginal reliability R_j' decreases when X_j increases, which means that measured in categories of reliability marginal effect (product) of any resource decreases with the growth of quantity of utilized (spent) resource and remaining without changes quantities of the rest of resources. For example, in a power station the growth of funds on staff qualification level improvement, without modernization of equipment and/or raise of funds on planned maintenance, received increments of reliability will be smaller and smaller.

Valuable aspect of resources transformation is included with the help of suitable valuable model. Thus we have two models:

1. **Physical model**, in principle considered until now, in which we have:
   - Quantity of spent and/or utilized resources, $\mathbf{x} = \{x_1, x_2, ..., x_n\}$, where $\mathbf{x}$ is realization of resources vector $\mathbf{X}$;
   - Reliability represented by its measure (reliability index) of physical character, R;
   - Reliability function, $R = r(\mathbf{X})$;
2. **Valuable model**, in which we have:
   - Value of resources spent and/or utilized to ensure reliability, $V(\mathbf{X})$;
   - Reliability value, $V(R)$ or economic effect of its unsatisfying level (economic and/or social losses), $SL(R)$;
   - Objective function, determining value (profit) or cost of transformation of resources $\mathbf{X}$ into reliability R,

$$P = V(R^*) - V(\mathbf{X}) \to \max \tag{3}$$

$$C = V(\mathbf{X}) + SL(R) \to \min \tag{4}$$

with the constraints of the type:

$$R' \le r(\mathbf{X}). \tag{5}$$

The task described by the objective function (3) is a task of optimal choice, in the aspect of specified reliability level R^*, variant of spending and/or utilizing resources $\mathbf{x}$, and task (4) looks for optimal system reliability R.

Optimization tasks formulated by relations (3) – (5) have solutions, when values of reliability and resources can be measured by the same units, for instance by monetary units. If it is not like that, one of the following problems may be solved:

1. Minimization of values of spent and/or utilized reserves to achieve desired reliability level.

$$C = V(\mathbf{X}) \to \min , \tag{6}$$

with the constraints:

$$R^* = r(X_1, X_2, ..., X_n). \tag{7}$$

2. Maximization of reliability level with given or limited resources.

$$R = r(\mathbf{X}) \to \max, \tag{8}$$

with the constraints:

$$C^* = V(X_1, X_2, ..., X_n). \tag{9}$$

Using the method of Lagrange's multipliers the following conditions of extreme existence are received:

- for problem 1

$$\frac{R_i'}{C_i'} = \text{const.}, \quad \text{for } i=1, 2, ..., n ; \tag{10}$$

- for problem 2

$$\frac{C_i'}{R_i'} = \text{const.}, \quad \text{for } i=1, 2, ..., n ; \tag{11}$$

where: C_i' - marginal cost of i-th resource, understood as valuable measure of the increment of spending and/or utilizing of the i-th resource to achieve growth of reliability level by one unit.

Thus optimal reliability level is determined by a point, in which the ratios of marginal reliabilities to marginal costs are equal. For simplicity one representative measure for reliability R has been adopted here, but there is no obstacle to determine reliability level by the values of several indices.

Requirements for continuity, convexity, rationality and comparability of reliability function and spending and/or utilizing of resources function are very difficult to fulfill in practice. But successfully one may consider the problem of optimal, from the reliability point of view, expending of limited resources to satisfy certain needs. In that case we can distinguish three variants of the problem:

1. At defined quantity of resources and at given technical constraints we should maximize system reliability.
2. At defined, required system reliability level and at given technical constraints we should minimize expenditure and/or utilization of reserves necessary to gain and keep reliability.
3. It is necessary to achieve such combination of reliability and resources usage to reach it and keep it (reliability), which maximize the degree of system realization goals.

Real problems of system reliability optimization belong to the uncertain class of problems (rarely probabilistic) multi-dimensional and compound, dynamic and multi-criteria.

3. Optimal reliability of electric power system

The task of electrical power system is to ensure supply of electrical energy to the customers with required quality and at the possible lower cost and acceptable reliability of delivery. In this case, also, the cost of ensuring a certain level of reliability supply should be concerned to the value of reliability for a customer.

For a power system the relations (3) and (4) may be written as:

$$P(A, R) = VS(A, R) - CoS(A, R) \to \max \tag{12}$$

$$C(A, R) = CoS(A, R) + COC(A, R) \to \min \tag{13}$$

where: $P(A, R)$ – social value (profit) of covering request (demand) on electrical energy A with reliability R,
$VS(A, R)$ – the value of energy sale at the quantity of A with the reliability of R (it is the inclination of a customer for paying to use A energy at its reliability delivery R),

$CoS(A, R)$ – costs of covering the demand A with reliability R,
$COC(A, R)$ – losses costs coming from insufficient reliability R,
$C(A, R)$ – total (social) cost of covering the demand A with reliability of R.

In relations (12) and (13) the demand A is a function of reliability R, and economic quantities are annual values or the sums of discounted values for the whole long-term period of analysis.

From the necessary condition for the existing of extreme it comes that:

$$\begin{gathered} \frac{dP}{dR} = 0 \rightarrow \frac{dVS}{dR} = \frac{dCoS}{dR} \\ \frac{dC}{dR} = 0 \rightarrow \frac{dCoS}{dR} = -\frac{dCOC}{dR} \end{gathered} \tag{14}$$

which means that at optimal reliability there are equalities of two corresponding marginal economic values.

In practice the relation between the demand for electrical energy and reliability of its delivery R is usually neglected (non-flexibility of demand against reliability is assumed). Assuming that the reliability level R is represented by an index ensuring energy delivery EIR (Energy Index of Reliability), the illustration of relation (13) is shown in Fig. 1.

Higher reliability level R needs rising costs of ensuring that reliability – costs of "deliverer-supplier", but in result it gives decreasing cost of widely understood losses at "customer", coming from insufficient reliability. Comparison of these two economic categories leads to the definition of "optimal" reliability level or optimal value of, representative for reliability (in the given analysis), quantity characterizing power system as a whole or its subsystem (for example reserve or capacity margin).

Optimal reliability level R_{opt} means minimal total cost C:

$$R_{opt} = R\colon\ \frac{dC}{dR} = 0 \rightarrow \frac{dCoS}{dR} = -\frac{dCOC}{dR} \tag{15}$$

and it does not cover with the reliability level, at which the equalization of the cost of reliability insurance takes place, $R_=$

$$R_= = R\colon\ CoS = COC \tag{16}$$

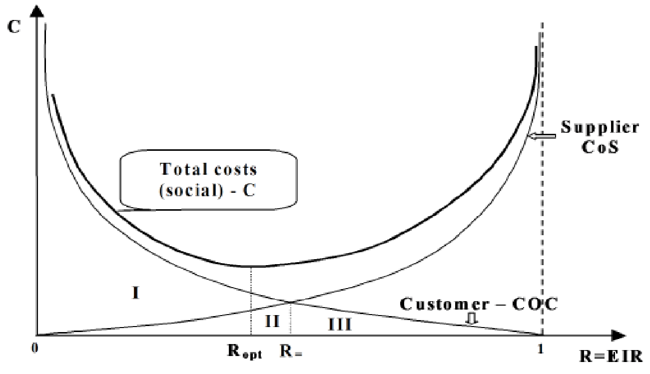

Fig. 1. Complete (social) reliability costs: C – cost; R – reliability level, represented by index EIR; R_{opt} – optimal reliability level; $R_=$ – reliability level, at which there exists equalization between the costs of ensuring reliability with the cost of losses, coming from its (reliability) insufficient level; I – effective area for actions to improve reliability; II – intermediate area; III – non-effective area for actions to improve reliability

In Fig. 1 we can distinguish three areas: I – area of action effectiveness to improve reliability, in which these actions give a result decreasing total cost and the rate of losses cost drop is higher than the velocity of growing costs of ensuring reliability, II – intermediate area, in which the total cost grows slightly, III – non-effective area for actions to improve reliability with the higher and higher rise of the total cost.

The goals of actions in the area of electric power system reliability are the following:

- Keeping the existing level of system reliability.
- Identification of investment projects which give the most important share into ensuring or improving system reliability.
- Defining and denomination of quantitative measures (indices) of reliability for the purposes of system development planning.
- Ensuring that the system parameters in the future will fulfill requirements of its reliability.
- Valuation of reliability in categories of costs of losses caused by the breaks and limitations of electrical energy supply.

Assessment of economic losses caused by unreliability of electric power system is, in particular, necessary for analyzing alternative plans of grid systems development. Advisability of undertaking investments rising system reliability may be assessed on the background of relation of costs and forecasted benefits. The tool in such understood system development planning is analysis cost – benefit, known as a reliability valuing (VBRA - Value-Based Reliability Approach) [19].

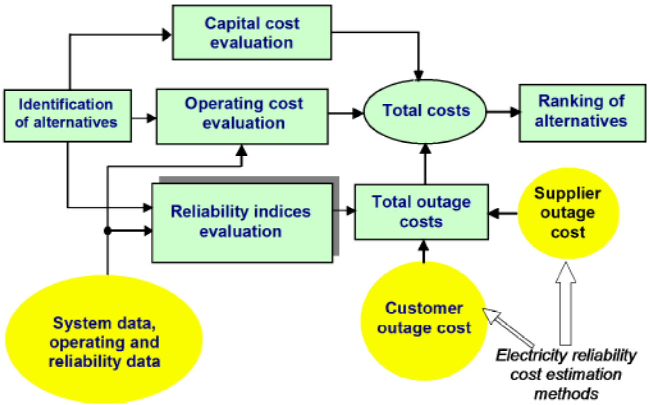

Fig. 2. General idea of reliability valuation

Basic components of reliability valuing are (Fig. 2):

- Identification of alternative projects.
- Assessment of capital and operational costs (connected with actions keeping or rising system reliability).
- Calculation of reliability indices for planned system structures.
- Assessment of costs of losses caused by interruptions and limitations of electricity supply.
- Ranking of alternative projects taking into account their total cost of solution.

Total costs are used to classify the variants of development or exploitation of a system. The total (discounted) cost is given by a formula:

$$C = CoS + COC = C_I + C_o + COC \tag{17}$$

where: C – total cost of a variant,
C_I – investment expenditure of a variant,
C_o – operational costs (exploitation),
COC – undelivered energy cost (customer outage cost).

Thus we are looking for a variant, which has got minimal costs including costs of losses at customers, caused by breaks and limitations, and necessary investment expenditures and exploitation costs in the whole perennial period of exploitation.

4. Costs of unreliability and their estimation

Important component that valuate variants of extending, modernization and exploitation of a power system are losses coming from breaks and limitations of electrical energy supply to customers, which were defined in equation (17) as the cost of undelivered energy [4, 5, 10]. These losses are difficult to estimate because there is no simple relationship between undelivered energy and economic losses (harms), which a customer is going to take. It depends on many factors; to the most important we can include varying intensity of a customer action. For example it may be in an industry – phase of technological process, kind of a shift, season of a year; in trade – intensity of buying and selling; at home – connection with other outside factors, time of break and so on. Thus we can say that there is not always strong correlation between undelivered energy and customer's economic losses. The same value of undelivered energy in different periods of firm's work may cause various economic losses. Those economic losses should be represented by a value of undelivered energy estimated by, e.g. a customer in public opinion poll, done in a wide scale (Fig. 2). A customer answers a range of questions and particularly the following question: how much he would pay to avoid a break in supply at given conditions? Value of undelivered energy usually settled in this way composes its marginal value for a break of defined duration, in given work conditions and situation of an enterprise – in other conditions losses at the same undelivered energy may be completely different [1, 6, 7, 8].

Despite of those reservations there is a need for such a rough measure as Interrupted Energy Assessment Rate (IEAR) – in Polish bibliography called economic equivalent of undelivered electrical energy, denoted by k_a [17], which multiplied by undelivered energy gives the assessment of economic losses.

Sufficiency of employing of this index comes from the fact that each improvement of power system reliability goes by leaps. For example change from unilateral feeding of a customer to double-sided one causes improvement of reliability in order of several dozen times. It means meaningful softening of requirements as to the precision of estimation of economic losses caused by breaks in supply – in many cases only approximate values are enough.

Investigations and analysis carried for groups of customers give information on costs of "interruption/outage" and not on costs of "kW interrupted or curtailed power", or on costs of "kWh undelivered energy". Then they are transformed into the form "cost/kW" or "cost/kWh" and given for distinguished groups of customers and characteristic values of interruption duration. For instance, in investigations conducted by University of Saskatchewan for Canada in eighties, there were distinguished 7 groups of customers: large customers, industry, commerce and services, agriculture, household, government institutions and public utilities, offices and buildings; and 5 characteristic values of interruption duration: 1 min., 20 min., 1 h, 4 h, 8 h. Received values determine so-called SCDF and may be used for analysis on the third hierarchical level of a power system (generation, transmission and distribution together) – HL III.

Newer studies were made in Great Britain on the area of three distribution companies (Manweb, MEB, Norweb) in the period from October 1992 to March 1993. In their effect SCDF was determined for four distinguished groups of customers: household (residential), commerce and services (commercial), industry, large users (above 8 MW) and seven characteristic values of interruption duration: momentary break, 1 min., 20 min., 1 h, 4 h, 8 h, 24 h. They are presented in Table 1.

The relation between $SCDF_A$ and $SCDF_P$ from Table 1 is as follows:

$$SCDF_A = \frac{SCDF_P}{8760m}\,, \tag{18}$$

where: m is average annual degree of sector load (load factor).

Extensive research, funded by the Department of Energy have been made in the United States, in the years 1989-2005. The synthetic results are summarized in Table 2. They provide an estimate obtained from the analysis of the results of 28 surveys carried out by 10 major U.S. energy companies, which included 11 970 firms and 7 963 households. The values in Table 2 are averaged, independent of the time of interruption (time of year, working day or holiday, the time of day).

To make analysis on the second hierarchical level of a power system – HL II (generation and transmission together) we must have CCDF, which determines costs of losses, as a result of interruptions and curtailments, of customers from certain area [\$/kWh, zł/kWh] as a function of failure duration. To construct such function we must have SCDF functions for specified groups of customers and the share of these groups in energy demand. We can also make aggregation and determine costs falling on a failure and on undelivered energy unit.

$$CCDF_A = \sum_{s \in ns} \frac{SCDF_{P,s}}{m_s 8760} \left(\frac{A_s}{\sum\limits_{s \in ns} A_s} \right) = \sum_{s \in ns} SCDF_{A,s} \left(\frac{A_s}{\sum\limits_{s \in ns} A_s} \right) \tag{19}$$

where: s – sector (group) of customers supplied from considered subsystem (node, bus),
ns – number of customer sectors in considered area,
m_s – average annual degree of sector load,
A_s – annual energy consumption by sector s.

Table 1. SCDF in Great Britain (UK, 1992) [9]

Duration	Household		Commerce & Services		Industry		Large customers	
	$SCDF_A$	$SCDF_P$	$SCDF_A$	$SCDF_P$	$SCDF_A$	$SCDF_P$	$SCDF_A$	$SCDF_P$
Momentary	-	-	0.46	0.99	3.02	6.15	1.07	6.74
1 min.	-	-	0.48	1.02	3.13	6.47	1.07	6.74
20 min.	0.06	0.15	1.64	3.89	6.32	14.27	1.09	6.86
1 h	0.21	0.54	4.91	10.65	11.94	25.26	1.36	7.18
4 h	1.44	3.72	18.13	39.04	32.59	72.22	1.52	8.86
8 h	-	-	37.06	78.65	53.36	120.11	1.71	9.71
24 h	-	-	47.58	99.98	67.10	150.38	2.39	13.35

$SCDF_A$, GBP/kWh – costs of losses per kWh of energy used during a year by an average customer of a sector;
$SCDF_P$, GBP/kW - costs of losses per kW of peak demand by an average customer of a sector.

Table 2. Estimating the average cost of losses caused by power outages in the U.S. (in USD_{2008}) [7]

Outage costs	Duration of interruption				
	< 5 min.	**30 min.**	**1 h**	**4 h**	**8 h**
Medium and large commercial and industrial customers*					
Cost per event, USD	6 558	9 217	12 487	42 506	69 284
Cost per kW average power demand, USD/kW	8	11.3	15.3	52.1	85
Cost per kWh of undelivered energy, USD/kWh	96.5	22,6	15.3	13	10.6
Cost per kWh of energy consumed in a year, 10^{-3} USD/kWh	91.8	1.29	1.75	5.95	9.7
Small commercial and industrial customers**					
Cost per event, USD	293	435	619	2 623	5 195
Cost per kW average power demand, USD/kW	133.7	198.1	282	1 195.8	2 368.6
Cost per kWh of undelivered energy, USD/kWh	1 604.1	396.3	282	298.9	296.1
Cost per kWh of energy consumed in a year, USD/kWh	0.00153	0.00226	0.00322	0.137	0.27
Households					
Cost per event, USD	2.1	2.7	3.3	7.4	10.6
Cost per kW average power demand, USD/kW	1.4	1.8	2.2	4.9	6.9
Cost per kWh of undelivered energy, USD/kWh	16.8	3.5	2.2	1.2	0.9
Cost per kWh of energy consumed in a year, 10^{-4} USD/kWh	1.6	2.01	2.46	5.58	7.92
** - with the annual consumption of more than 50 MWh, ** - with an annual energy consumption not exceeding 50 MWh*					

In case when there are problems to determine the degree of load value for each sector we can use the simplified relation:

$$CCDF_A = \sum_{s \in ns} SCDF_{P,s} \left(\frac{A_s}{\sum_{s \in ns} A_s} \right) \frac{1}{m8760}, \tag{20}$$

where m is the degree of load (load factor) of the considered area.

A global index, known as IEAR, and in Poland known as economic equivalent of undelivered electrical energy is used in power system analysis at levels HL I and HL II. It has dimension USD/kWh, zł/kWh and multiplied by an expected value of undelivered energy (*LOEE*, *EENS*, *EUE*) gives assessment of social costs of losses caused by inadequate reliability level.

In similar character, but with other name, parameter IEAR is used in models for planning development and for assessment of generation subsystem (WASP III - ELECTRIC, ICARUS, IPM, PLEXOS) and it is met in expressions on marginal costs.

On the other hand the parameter appearing until the year 2000 in expression on the price of energy purchase from generators in the electricity pool in England and Wales – VOLL[1] and the parameter appearing in expression on unitary offer price paid to generators in the project of Polish offer system of electrical energy market [20] - KNZ[2] are the measure giving, assessed by the customers, value of electrical energy in the situation of its lack. It is therefore marginal price, which a customer would be eager to pay in extreme conditions.

To find IEAR we can use functions CCDF or SCDF. The process may be brought to two steps:

Step 1: Determination of the IEAR as a function of interruption duration - IEAR(t_p).

$$IEAR(t_p) = \frac{CCDF(t_p)}{t_p m} \tag{21}$$

or

$$IEAR_s(t_p) = \frac{SCDF(t_p)}{t_p m_s} \tag{22}$$

and then

$$IEAR(t_p) = \sum_{s \in ns} IEAR_s(t_p) k_s \tag{23}$$

where: k_s – weighted coefficient, for example: relative annual energy consumption (the best), relative number of customers, relative peak load.

Step 2: Determination of expected value of the IEAR.

$$IEAR = \sum_{t_p=0}^{T_{gr}} IEAR(t_p) \mathrm{p}(t_p) \tag{24}$$

where: $\mathrm{p}(t_p)$ – probability of existence of interruptions lasting t_p,
T_{gr} – maximum time in which supply should be restored, e.g. it is required in Great Britain that the supply should be restored during 24 hours – in Poland from the year 2007 it is also 24 h, according to “system regulation” [15].

It is possible to use approximate value, which is the ratio of gross domestic product (GDP) to the total electrical energy consumption (EE) – in “Polish power industry statistics” [18] the inverse of that relation is given (EE/GDP). Values of economic equivalent – index of undelivered energy value (k_a – *IEAR*), determined in such a way, are listed in Table 3 (in zł/MWh and prices from the year 2005).

According to “tariff’s regulation” [16] a customer in Poland has right to compensation for each unit of undelivered electrical energy, equal to tenfold (customer connected to the network with voltage not higher than 1 kV) or fivefold (rest of customers) price of energy for

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[1] Value of Lost Load. Its initial value of 2 GBP/kWh adopted in 1989 by Electricity Supply Industry has been increased with *RPI* (Retail Price Index). Despite no objective reasoning for adopting this figure *VOLL* has had a very important role in the setting of England and Wales pool payments (Capacity Element of Pool Purchase Price).

[2] Cost of not covered demand (it should rather be: value of not covered demand). *KNZ* was established in 1997 as 1.45 zł/kWh.

Table 3. Approximate values of undelivered energy economic equivalent (GDP/EE) in Poland

Year	1995	2000	2004	2005	2006	2007	2008	2009	2010
k_a, zł/MWh	4138	5125	5767	5922	6925	7220	7570	7968	7918

the period, in which interruption took place. So it was assumed that there is proportional relationship between the values of losses caused by energy supply interruption and the quantity of undelivered energy. The cost of these losses, falling on the unit of undelivered energy, was assessed to be ten or five times higher that the energy price.

Losses occurring at the customer, resulting from interruptions and limitations of the supply of electricity are difficult to estimate because of the lack of a stable model of relationship between the undelivered energy and the losses suffered by the customer. One of the applied methods is the survey method, which allows the estimation of losses caused by not supplying electricity to customers and to obtain information about the worth of energy supply reliability for the customer.

A commonly accepted method of evaluating customer interruption costs is to directly survey electric utility customers. The basis of this approach is that customers are in best position to understand power interruption and limitations in power quality consequences in relation to their particular needs.

One of the goals of "TRELSS for the PPGC" project [13] was to create a base for the use of reliability evaluation approach at the Polish Power Grid Company. Special questionnaire, based on the experience of EPRI [5, 11], was prepared to realize that aim.

Customers were divided into two groups: residential and industrial/commercial. For each scenario of an interruption a customer is asked in the questionnaire to answer a question what would happen in his house (for residential sector) or in his firm (for industrial or commercial sector) as a result of the interruption and what his reaction is on that event. The customer is asked to evaluate that presumable event in zlotys (Polish currency). The value in zlotys may be clearly defined in one of the following three cases: direct costs, tendency to payment or desire for taking recompense. In the first case the customer is asked to determine direct economic costs of his activity (business), which was subjected to losses because of the interruption. Those costs may comprise: lost production costs and inactivity costs. Description of consequences of interruptions was enclosed to help the customer to think over all the cost components and choose the proper ones. In the second case the customer is asked to choose maximal value of payment from among given in the questionnaire that he would accept to avoid such event. In the third case the customer is asked to choose minimal value from among given in the questionnaire that he would accept as recompense for the cost of the event. Typical inclination to payment is defined as a fraction of the determined direct cost. The customer must decide himself, which of the given values he would use.

Customers are also asked in the questionnaire to give some information about themselves, their firms or families and, what is the most important, about the latest experiences with the interruptions and their service, i.e. liquidation of the interruptions. This information will be used in econometric analysis to identify factors, which have the greatest influence on costs of interruptions.

Residential customers

Residential (household) customers fullest recognize the importance of electricity in his apartment/house when an unexpected supply interruption or distortion of quality, such as flickering lights, voltage dips, etc. During the interruption the customers do not have access to electrical appliances. This forces them to change daily habits, schedule of activity and usually puts in a forced, painful situation. It may specify:

- coercion idle for lack of ability to perform normal household duties and any additional paid work, which (usually, or sometimes) we make at home;
- sometimes difficulties for children who cannot learn or make up your homework;
- impediment to rest;
- deterioration in comfort staying at home, for example, the simultaneous cessation of home heating in the winter, because it is dependent on the energy supply, the lack of ventilation or air conditioning in the summer, the lack of water, etc.;
- threat to health and life, when one member of the household is ill or requires constant care or medical apparatus's work;
- need to tune some devices (clocks, computers, protections, etc.) after restoring the supply of electricity;
- food spoilage, damage to other equipment, etc.;
- other problems.

Willing to pay / willingness to accept payment is a useful measure for assessing the cost of interruptions because the residential (household) customers have difficulty in estimating the direct costs of outages, especially unexpected. The questionnaire for the residential customers has about 50 questions divided into 5 sections.

Industrial/commercial customers

For these users the test of the cost of interruptions is made for power interruptions hypothetical situations. Cost of break can be determined by comparing two scenarios:

1. scenario **with interruption**, includes duration of interruption, time for interruption consequences' clearing until the conditions are reached close to existing before the break,
2. scenario **without interruption**, so-called "motion" normal, at the same time as in scenario 1 (with interruption).

The questionnaire for industrial/commercial customers contains about 80 questions divided into 6 sections.

Poll investigations of losses' costs, resulting from interruptions in electrical energy supply, carried until now may be divided into two phases:

- Test phase, checking the questionnaire itself and its acceptance by customers, which had been done during realization of the project "TRELSS for the PPGC" [13].
- Active phase, in which after some slight corrections in the questionnaire, investigations were carried on greater, but still not big enough, sample of customers, in two regions of Poland: in central part of Poland and on the south of the country.

Unfortunately, due to lack of interest from power utility companies and the regulatory authority, more extensive research on the cost of losses due to interruptions in the electricity supply, in the current realities of the functioning of the Polish power sector and the economy, have not yet been carried out.

5. Conclusions

Reliability of an electric power system decides about the quality of supply and consumers' trust, that they will get energy adequate to their requirements. Even, or rather particularly, in the present situation of the liberalization of electricity markets and unbundling of generation, transmission and distribution, questions on the present and future reliability level arise, and the interest in detailed investigation of electric power system reliability issues, especially taking into account possibly the whole power system, increases.

Real problems of power system reliability optimization belong to the class of uncertain problems (rarely probabilistic), multi-dimensional and compound, dynamic and multi-criteria. Their practical solution requires acceptance of far reaching simplifying assumptions.

The players in today's electricity market view economic processes in a short-term scale. However, improving supply reliability and power system reliability requires the management of longer-term financial and/or physical risks, which requires longer-term incentives. They could be justified only basing on the results of cost-benefit reliability analysis – reliability optimization.

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