

Evaluation of Customer Costs of Reliability with Time-variable Loads and Outage Costs

Aleksandrs Lvovs¹, Anna Mutule^{2, 1-2} *Riga Technical University*

Abstract – The paper deals with time-variable loads and outage costs usage for evaluation of customer costs of reliability (CCR). In the paper there is given justification of need to use time variable values of loads instead of average constant load when calculating CCR. Paper presents an approach for evaluation of CCR based on evaluation of effect of interruptions occurring at distribution network level.

Keywords – Life Cycle Analysis (LCA), reliability, power supply.

I. INTRODUCTION

Reliability of power supply is one the main parameters describing power system operation. Optimal power supply reliability level contributes to economically efficient work of power system. In ideal case optimal reliability level is reached when the sum of costs of network improvement and costs (expenses) of customers due to power supply interruptions are minimal. In real life it is simple enough to estimate expenses of network operators that are used for improvement of reliability level. On the other side it is quite hard to evaluate customer costs of reliability (CCR) and make decision on appropriate amount of investments in grid.

To evaluate CCR, information about power supply interruption costs, as well as amount of interrupted power and energy not supplied should be known.

Further the problem of CCR identification using time variable loads of customers instead of more traditional usage of average loads is discussed.

II. FORMULATION OF PROBLEM

In most of the cases the analysis of CCR and energy not supplied (ENS) is performed using average loads. In such case energy consumption is replaced by average load of load point during some long period of time – season, like in [4], year, like in [5] or other time period, like in [6]. For calculation of ENS average load of year/season/other period is multiplexed with average power supply interruption time of customers. In Latvia average power supply interruption time during summer of year 2010 was ~8.5 hours, but during summer of year 2011 – ~7 hours [7].

According to results of surveys of customer about power supply interruption related costs, the costs are not constant and they change not only in terms of seasons of a year, but also in short time periods – month and time of a day [1] – [3]. As stated in [1], the worst time for interruption occurrence time for Commercial sector is between 17:00 and 21:00. In [3], at the other side, time period between 9:00 and 17:00 is mentioned as period with high Commercial sector customer

interruption costs. [2] and [3] indicated similar time for Industry sector, during which power supply interruptions have the worst impact – between 9:00 and 17:00.

Usually the reason of power supply interruption costs changes during time are supposed to be those of load values.

Fig.1 and Fig.2 represent changes of ENS and interrupted load values in 24 hour period for Commerce and Services sector of Latvia at working day. To construct ENS value change for power supply interruption it was assumed, that duration of power supply interruption is 7 hours.

From Fig. 1 we can see that the highest ENS values for Commerce and Services sector will be if power supply interruption starts within time period from 7:00 to 17:00. Time from 10:00 till 20:00 represents period of a day with the highest values of possible interrupted load.

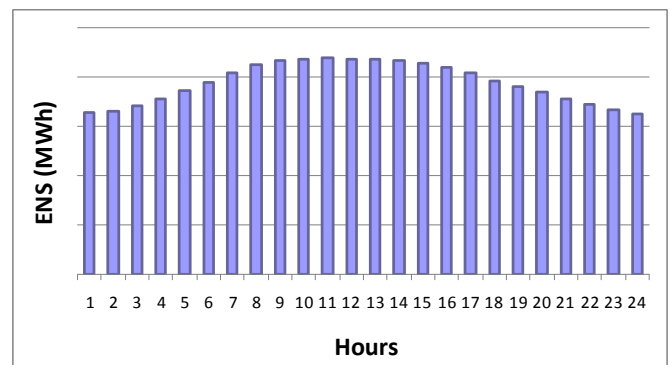


Fig. 1. ENS changes for Latvian Commerce and Services sector in case of 7 hour long interruption occurring during working day.

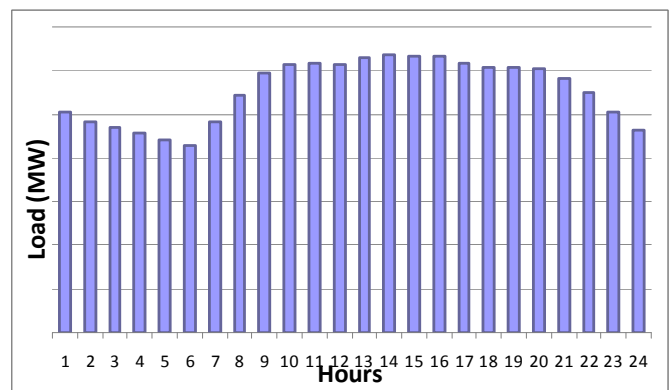


Fig. 2. Load diagram for Latvian Commerce and Services sector during working day.

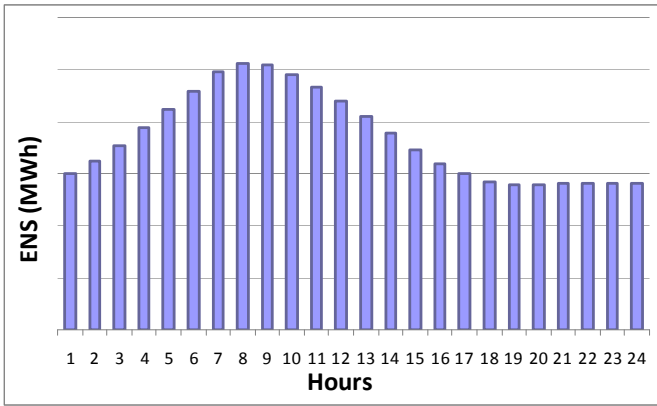


Fig. 3. ENS changes for Latvian Industry sector in case of 7 hour long interruption occurring during working day.

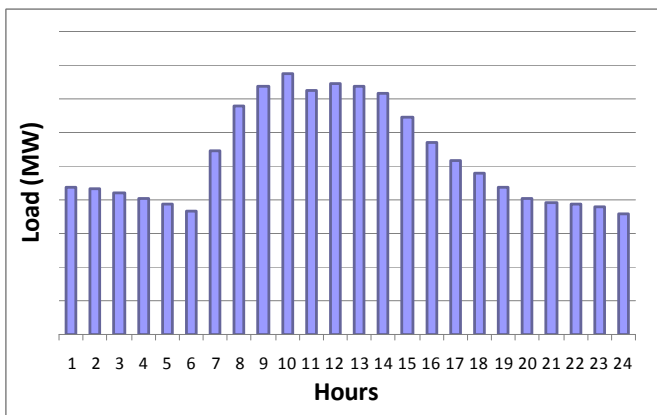


Fig. 4. Load diagram for Latvian Industry sector during working day.

Fig.3 and Fig.4 represent changes of ENS and interrupted load values in 24 hour period for Industry sector of Latvia during working day. Duration of power supply interruption for ENS calculation was assumed to be 7 hours.

From Fig.3 we can see that the biggest ENS values for Commerce and Services sector will be if power supply interruption starts within time period from 5:00 to 13:00. Time from 8:00 till 15:00 represents period of a day with the highest values of possible interrupted load.

Comparing high cost periods indicated in [1] – [3] with interrupted load and ENS of the two sectors, we can conclude that costs of Commerce and Services have good correlation with load values. In this case the average load can be used for identification of CCR.

In case of Industry sector we cannot see the same correlation between high costs and periods with the highest values of ENS and loads. Such situation can be explained by the effect of technological process in industry. In such case usage of average load value for calculation of CCR can lead to large scale errors, because even in Latvia, where Industry sector is assumed to be relatively small, it makes more than 25% of all electrical energy consumption [8].

To make calculation of CCR more precise, time-variable loads should be used in calculations.

The next section provides approach for evaluation of CCR, when power supply interruptions are caused by outages in distribution network.

III. APPROACH FOR EVALUATION OF CUSTOMER COSTS OF RELIABILITY

Proposed approach for evaluation of CCR is based on evaluation of effect of interruptions occurring at distribution network level. This can be based on the fact that according to statistical data [9], power supply interruptions are caused mainly by outages in distribution network.

Flowchart, developed by the authors of the paper, given in Fig.5 illustrates structure of the proposed approach. Before calculation starts, information about network that includes failure rates of network elements, load diagrams, protection devices, etc. is specified. As soon as the calculations can be carried out for different network configurations (states), e.g. different types of lines, number of reclosers, etc., information about networks' state number (indicated by n) is also given.

After network technical information for state n is known, calculations start. Taking into account that customer load diagrams, as well as failure rates of elements usually depend on time, different network operation regimes re should be assumed. Regimes re represent such network work regimes like working days in winter or other season, holidays in winter and other seasons, etc.

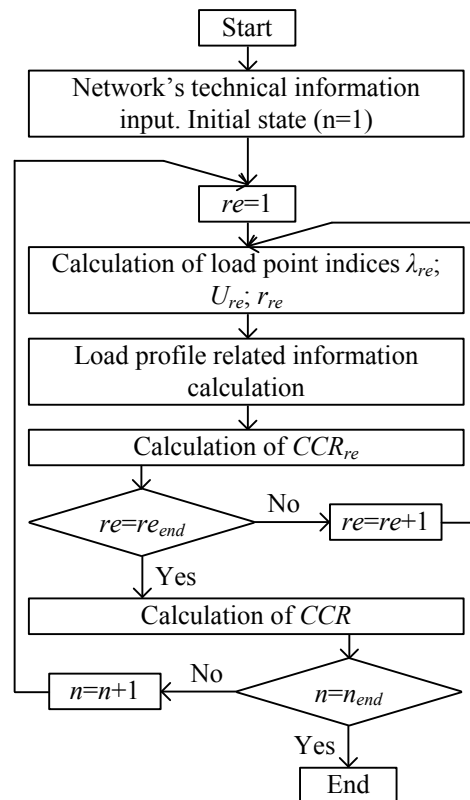


Fig. 5. CCR calculation flowchart.

When the number of regime is known calculation of load point indices starts. During this process, failure rate – λ_{re} ;

unavailability – U_{re} and average power supply restoration time – r_{re} values for each load point are calculated based on network configuration (state) n and regime re .

To calculate CCR for the regime re , ENS and interrupted load for each hour of a 24 hour (a day) period are calculated. CCR is calculated based on the information of each hour's ENS and interrupted load. CCR is formed by costs caused by short (< 3 min.) and long (> 3min.) power supply interruptions and can be calculated using (1):

$$CCR = CCR_s + CCR_l, \quad (1)$$

where

CCR_s – customer costs of reliability caused by short (< 3 min.) power supply interruptions [monetary units].

CCR_l – customer costs of reliability caused by long (> 3 min.) power supply interruptions [monetary units].

CCR caused by short power supply interruptions occur due to work of automatic reclosing devices that effectively operate in cases when line has no serious damages. For calculation of CCR caused by short power supply interruptions equation (2) is proposed by the authors of the paper. Using (2) the calculations are performed for all regimes re during a single year and for all feeders F of substation.

During such short faults whole feeder line is disconnected in respect to the feeder at the section of which the short outage occurred. This means that each load point of feeder is equally affected by whole feeder's short failures' rate – sum of short failure rates of each section. In (2), this failure rate is represented by the first item of sum in parentheses.

Short power supply interruptions also occur in cases when downstream sections have long power supply interruptions and automated reclosers are installed between sections. Effect of downstream sections' long power supply interruptions is taken into account by the second item of sum in parentheses of (2).

A days' load of load point lpf is divided into z loads – $P_{re,lpf,i}$ – according to time intervals with different load interruption costs during a day, like mentioned in "Formulation of problem". Each load of z loads is multiplexed with corresponding duration of load interruption costs and with respective costs of interrupted load. The result of this multiplexing is costs that would occur in case if interruption is in corresponding time interval of a day. Taking into account that short power supply interruptions not change in the frames of day, the probability to have short power supply interruption in other time interval is proportional only to the length of time interval. The sum of load interruption costs during different time intervals of a day is divided by number of hours in a day – 24. In such case we receive average costs of short interruptions for a load point.

The calculation process is repeated for all the load points lpf of feeder f until calculations for all load points LPf of all feeders F is made for respective network work regime re . Similar calculations repeat for each regime re and are taken

into consideration proportionally to duration of each regime h_{re} .

$$CCR_s = \sum_{re=1}^{re_{end}} \frac{h_{re}}{8760} \cdot \left[\sum_{f=1}^F \sum_{lpf=1}^{LPf} \left(\frac{\sum_{i=1}^z P_{re,lpf,i} \cdot h_{lpf,i} \cdot C_{s,re,lpf,i}}{24} \right) \cdot P_{max,lpf} \cdot \left(\sum_{L=1(L \in M_{L,f})}^{L=LPf} \lambda_{Ls,re} + \sum_{L=lpf+1(L \in M_{L,f})}^{L=LPf} \lambda_{Ll,re} \right) \right] \quad (2)$$

where

CCR_s – customer costs of reliability caused by short (< 3 min.) power supply interruptions [monetary units].

re – network regime that affects load diagrams of load points and failure rates of network elements.

re_{end} – total number of network working regime.

h_{re} – duration of working regime re during year [h].

f – number of feeder.

F – total number of feeders f connected to substation.

lpf – number of load point of the feeder f .

LPf – total number of load points on a feeder f .

i – number of time interval of a day that corresponds to specific costs of load interruption.

z – total amount of time intervals of a day.

$P_{re,lpf,i}$ – average active load in % of maximal active load, that corresponds time interval i of the load point lp on a feeder f during regime re [%].

$h_{lpf,i}$ – duration of interval i that corresponds to specific costs of power supply interruption in load point lp on a feeder f [h].

$C_{s,re,lpf,i}$ – costs of short power supply interruption (< 3 min.) in time interval i of the load point lp on a feeder f during regime re [monetary unit/kW].

$P_{max,lpf}$ – max. active load of load point lp of feeder f [kW].

L – number of feeder section.

$M_{L,f}$ – set of sections that form a feeder f .

$\lambda_{Ls,re}$ – failure rate (for short outages) for section L in regime re [short outage/km year].

$\lambda_{Ll,re}$ – failure rate (for long outages) for section L in regime re [long outage/km year].

CCR caused by long power supply interruptions occur due to serious network damages. For calculation of CCR caused by long power supply interruptions equation (3) is proposed by the authors of the paper.

$$CCR_l = \sum_{re=1}^{re_{end}} \frac{h_{re}}{8760} \cdot \left[\sum_{f=1}^F \sum_{lpf=1}^{LPf} \left(\frac{\sum_{x=1}^{24} ENS(t_{repair})_{re,lpf,x} \cdot C(t_{repair})_{l,re,lpf,x}}{24} \right) \cdot \left(\sum_{L=1(L \in M_{L,f})}^{L=lpf} \lambda_{Ll,re} + \frac{\sum_{x=1}^{24} ENS(t_{switch})_{re,lpf,x} \cdot C(t_{switch})_{l,re,lpf,x}}{24} \cdot \sum_{L=lpf+1(L \in M_{L,f})}^{L=LPf} \lambda_{Ll,re} \right) \right] \quad (3)$$

where

CCR_l – customer costs of reliability caused by long (> 3 min.) power supply interruptions [monetary units].

$ENS(t_{repair})_{re,lpf,x}$, $ENS(t_{switch})_{re,lpf,x}$ – energy not supplied to load point lpf in case if power supply interruption occur at time x of a day [kWh].

$C(t_{repair})_{l,re,lpf,x}$, $C(t_{switch})_{l,re,lpf,x}$ – costs of energy not supplied to load point in time of power supply interruption start hour x in regime re [monetary units/kWh].

CCR_l affected by long power supply interruptions are calculated by (3) in quite similar way as using (2) for CCR_s calculations.

CCR_l are affected by two types of interruptions: long interruptions in upstream sections represented by the first item of sum in parentheses of (3) and long interruptions in downstream section represented by the second item of sum in parentheses of (3). Long interruptions in downstream section affect CCR_l of a load point only in case if manual sectionalizing devices are installed at downstream load point with faulted section. Otherwise, faulted downstream section will be disconnected in 3 minutes and this will affect CCR_s .

According to (3), ENS for load points is calculated for 24 possible cases. It is assumed, that interruption could occur at any hour of a day. To evaluate ENS, load diagram should be used. In case if interruption starts at 01:00 and lasts for 7 hours, it will end at 08:00. In this case ENS will be formed of energy that would be consumed during 7 hours between 01:00 and 08:00. Fig. 6 gives an example of ENS evaluation for two power supply interruptions with duration of 7 hours and starting respectively at 01:00 and 12:00.

Each ENS value is multiplexed with corresponding costs of energy not supplied, that takes into account both regime and time of a day effect on costs.

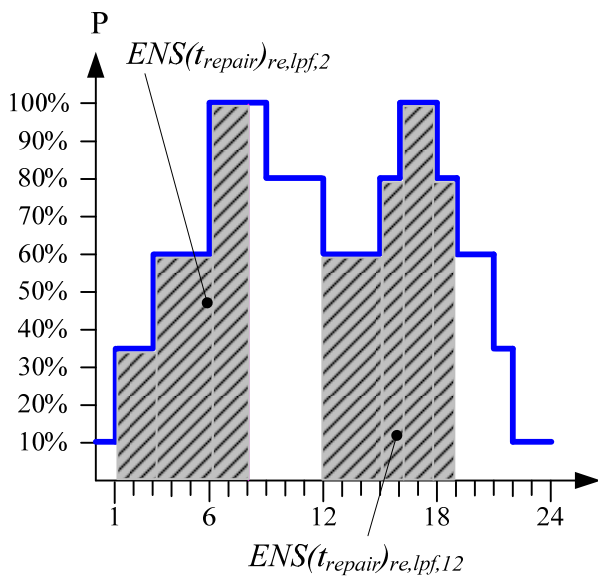


Fig. 6. Evaluation of ENS for power supply interruptions with different starting times.

Further paragraph gives numerical example of CCR calculations using average constant loads versus time-variable loads and power supply interruption costs.

IV. EXAMPLE OF CALCULATIONS

As example for CCR calculations, information about time-variable costs of power supply interruptions from real pellet producing factory (further in text – Factory) placed in Latvia was used. Factory’s load diagram was assumed to correspond to typical load diagram of “woodworking industry” working with 2 shifts (see Fig. 7.). Typical load diagram was taken from data base of Latvian DSO – AS “Sadales tikls” [10].

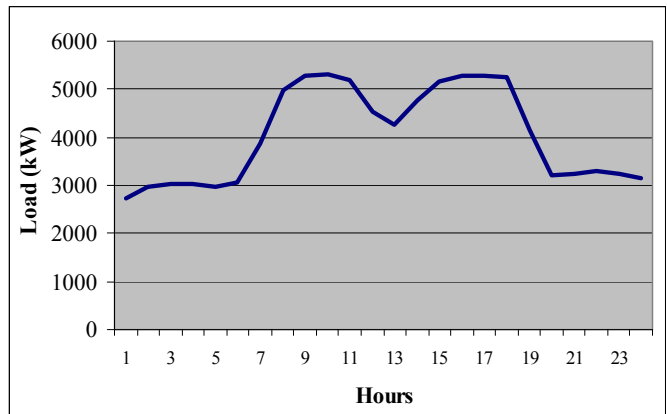


Fig. 7. Typical working day load diagram of “woodworking industry” working with 2 shifts.

According to information from the Factory, maximal allowed power consumption is 5300kW corresponding to winter maximum consumption.

Power supply interruption costs for unplanned interruptions that occur in autumn working day at 10:00 are given in Table I. Costs are given in Latvian lats per interruption.

TABLE I.
POWER SUPPLY INTERRUPTION COSTS

	Duration of interruption				
	1 min.	20 min.	1 hr.	4 hrs.	8hrs.
Costs [Ls/Interruption]	42	840	2520	10080	20160

Power supply interruption costs of the Factory also depend a lot on time, day and season of outage occurrence. Fig. 8, Fig. 9 and Fig. 10 illustrate interruption cost variation dependence on different factors.

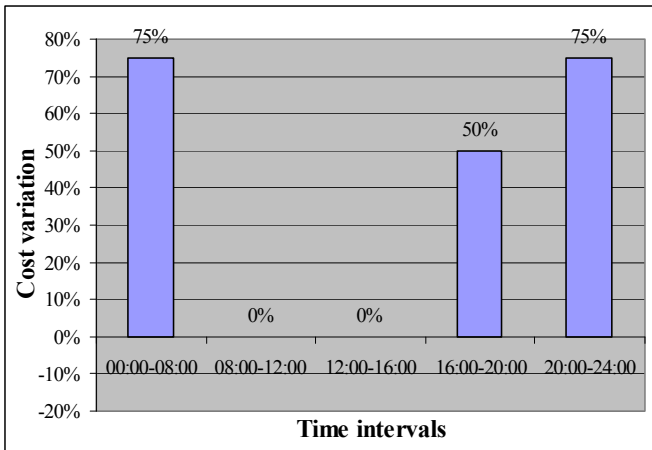


Fig. 8. Power supply interruption cost variation depending on time of a day.

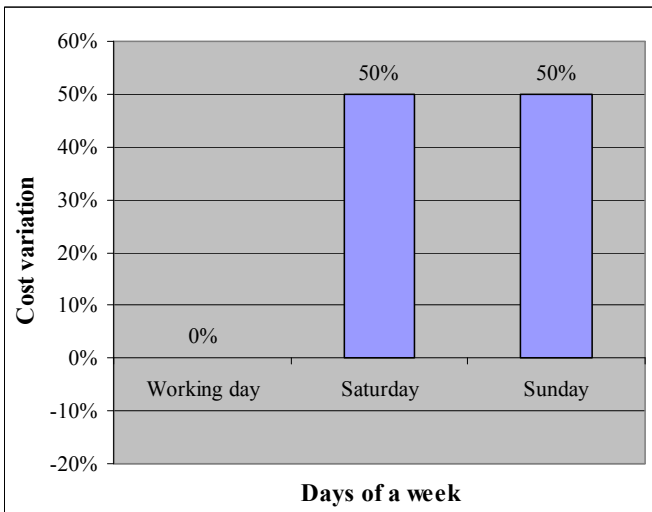


Fig. 9. Power supply interruption cost variation depending on day of a week.

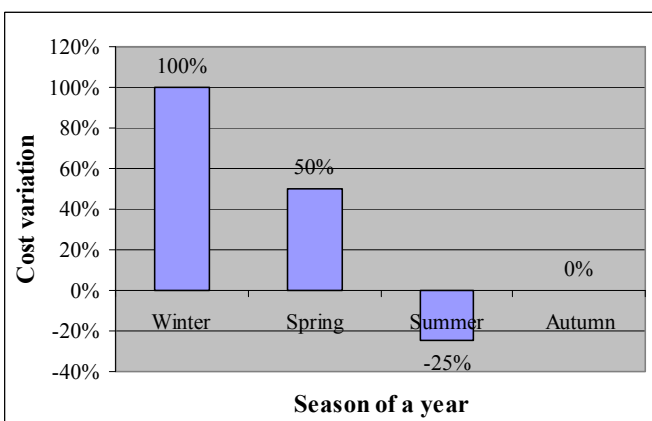


Fig. 10. Power supply interruption cost variation depending on season of a year.

Calculations of CCR for the Factory were made both for long and short power supply interruptions.

When estimating power supply interruption costs using constant average load values, average load values were

calculated for each season taking into account that autumn/spring load corresponds to 84% of winter load, but summer load corresponds to 74% of winter load. Seasonal power supply interruption cost variations for Factory were taken into account.

Performing calculations using time-variable load and cost, all types of cost and load variations were taken into account exactly in such way as it is given in equations (2) and (3).

Taking into account that variation of power supply interruption costs are given for 5 time intervals of a day (but not for all 24 hours of a day) and due to that some intervals had constant costs, the authors of the paper decided to perform calculations using the third approach. The 3rd approach is based on the approach proposed in the paper, but instead of using 24 time variable loads for a day, constant average loads for 5 time intervals for a day were used.

For calculations duration of long power supply interruption was assumed to be 7 hours [7] with occurrence of 2.18 times per year [11]. Short power supply interruptions were assumed to occur 5 times per year.

The results of the calculations are summarized in Table II. Fig.11. gives information about calculated customer costs by seasons.

TABLE II.
RESULTS OF CALCULATIONS

Nr.	Approach	CCR, [Ls/year]
1	Constant average seasonal loads and outage costs	1841
2	Proposed approach (time-variable outage costs and loads)	2203
3	Modified approach using constant seasonal loads	3085

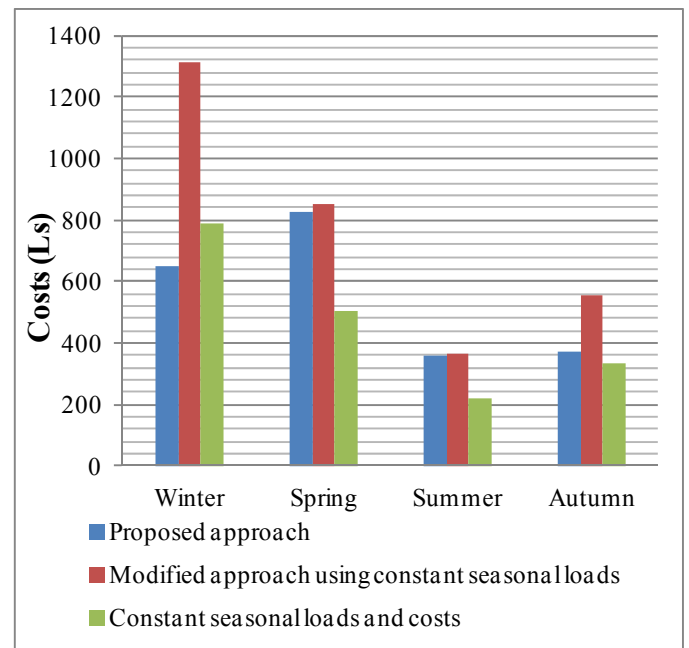


Fig. 11. Results of calculations by season.

As one can see from Table II and Fig.11 the results vary in a wide range. In all cases the usage of average loads and time-variable costs leads to cost overestimation. This can be explained by the fact, that for morning and evening periods, when the Factory has bigger outage costs, average load value is higher than actual load and this results in overestimation of ENS.

The proposed approach (with time-variable outage costs and loads) showed the second largest results in all seasons, except winter, where two other approaches indicated higher results. This also can be explained by higher average loads values comparing to actual load values in time periods with higher outage costs.

V. CONCLUSIONS

Approach for customer costs of reliability, that takes into account time-variable costs and loads was proposed.

Calculations, performed using outage cost data of real pellet producing factory, showed that the results of calculations extremely depend on the used approach. Depending on load type and cost variation in time, calculated CCR value can be both higher and lower comparing to actual CCR value.

In case when information about time variable costs is not available and only average cost value is known, usage of average loads and costs is allowable for approximate CCR calculation as such approach don't give extremely big error in calculations comparing with the results obtained with time-variable load and cost approach.

If information about outage cost variation in time and load diagrams of clients is known the proposed approach should be applied. Usage of average load values together with time-variable costs is not recommended as it could result in significant errors in results.

ACKNOWLEDGEMENT

This work has been supported by the European Social Fund within the project «Support for the implementation of doctoral studies at Riga Technical University».



REFERENCES

- [1] N. Kaur, S. Gurdip, M.S. Bedi and T. Bhatti, Evaluation of Customer Interruption Cost for Reliability Planning of Power Systems in Developing Economies. 8th International Conference on Probabilistic Methods Applied to Power Systems, September 12-16, 2004, Ames, Iowa, USA.
- [2] N.R. Karki, A.K.Verma, A.K. Mishra, J. Shrestha, M. Bhatkar, Industrial customers' survey for outage cost valuation in a developing country. North American Power Symposium (NAPS), October 4, 2009, Starkville, Mississippi, USA.
- [3] R.N. Allan, K.K. Kariuki, "Factors affecting customer outage costs due to electric service interruptions," IEE Proceedings Generation, Transmission & Distribution, Vol.153, Issue 6, pp.521-528, Nov. 1996.

- [4] J. Runčš, "Pilsētu elektrisko tīklu optimizācija," (in Latvian) PhD thesis, Riga Technical University, Riga, Latvia, 2007.
- [5] T. Solver, "Reliability in Performed-Based Regulation", Licentiate Thesis, Electrical Power Systems, Department of Electrical Systems, Royal Institute of Technology, KTH, Stockholm, Sweden, 2005.
- [6] I. Oļeinikova, Z. Krišāns, "Metodikas un datorprogrammas izstrādāšana Latvenergo augstsprieguma un sadales tīklu patērētāju elektroapgādes shēmas (tajā skaitā apakšstaciju primārās shēmas) drošuma novērtēšanai" (in Latvian), Latvian Academy of Sciences, Institute of Physical Energetics, Riga, Latvia, Report on results of the 2nd phase of the 1st stage, 2002.
- [7] "Energo Forums," (in Latvian), Nr.3 (31), 2011. [Online]. Available: http://www.latvenergo.lv/portal/page/portal/Latvian/EnergoForums1/EF_3_2011.pdf. [Accessed: February 15, 2012].
- [8] Statistics Database on Environment and Energy of Central Statistical Bureau of Latvia. [Online]. Available: <http://www.csb.gov.lv/dati/statistikas-datubazes-28270.html>. [Accessed: March 15, 2012].
- [9] A.A. Chowdhury and D.O. Koval, Power Distribution System Reliability: Practical Methods and Applications. New Jersey: John Wiley & Sons, Inc., 2009.
- [10] "Lietotāju tipveida slodžu grafiki" (in Latvian). Information about typical load diagrams of different customers. Database of Latvian DSO AS "Sadales tīkls". [Online]. Available: http://www.st.latvenergo.lv/portal/page/portal/Latvian/Sad_tikls/Tipveida+grafiki_jauns.htm. [Accessed: March 15, 2012].
- [11] "4th Benchmarking Report on Quality of Electricity Supply 2008". – Brussels: Council of European Energy Regulators ASBL. 2008. – 177 p.



Aleksandrs Lvovs was born in Riga in Latvia on April 20, 1985. He received the B.Sc. and Mg.Sc.ing. degrees in Riga Technical University (RTU) in 2007 and 2009 respectively. Currently he is a PhD student in RTU. His major field of study is power energetics.

His employment experience includes Ministry of Economics of the Republic of Latvia – Division of energy markets and projection division of Latvian TSO – JSC "Augstsprieguma tīkls". His special field of interests includes methods for reliability evaluation of electrical networks and systems and methods for development of power systems planning.

He is a Graduate student member of IEEE. He received „Werner von Siemens Excellence Award” in 2009 for his master's work. In 2007 he received paper of distinction form JSC "Latvenergo", LEEA and LIF for victory at the contest of scientific works in the field of power and electrical engineering with his bachelor work.

E-mail: Aleksandrs.Lvovs@rtu.lv, Riga, Kronvalda 1, LV-1010



Anna Mutule was born in St.Petersburg in Russia, in 1975. She received the BSc, MSc and Dr.sc.ing. degrees in Riga Technical University in 1999, 2002 and 2005 respectively. Her major field of study is power energetics.

She is a leading researcher in the Laboratory of Power System Mathematical Modeling at the Institute of Physical Energetics and also an assistant professor of RTU. Her main special field of interests includes methods for mathematical modeling of electrical networks and systems; methods for development of power systems planning; dynamic optimization methods and decision systems.

She received „Werner von Siemens Excellence Award” for her doctoral work in 2005. She also has papers of distinction form JSC "Latvenergo", LEEA and LIF for leading qualification works of students.

E-mail: a.mutule@edi.lv

Aleksandrs Ljovs, Anna Mutule. Patērētāju drošuma izmaksu novērtējums ar laikā mainīgo slodzes un pārtraukumu izmaksām

Elektroapgādes drošums ir viens no galvenajiem parametriem, kas raksturo energosistēmas darbību. Optimālais energoapgādes drošuma līmenis veicina ekonomiski efektīvu darbu energosistēmā, kas ietver sistēmas operatoru izdevumus un patērētāju izmaksas. Ir diezgan sarežģīti novērtēt patērētāju ar drošumu saistītus zaudējumus (CCR) un pieņemt lēmumu par attiecīgu investīciju daudzumu tīklam.

Lai novērtētu CCR, jābūt informācijai par elektroapgādes pārtraukumu radītajām izmaksām, kā arī par pārtrauktas jaudas un elektroenerģijas vērtībām.

Rakstā ir apspriesta CCR noteikšanas problēma, izmantojot laikā mainīgās patērētāju slodzes tradicionāli pielietoto vidējo slodžu vietā.

Vairumā gadījumu CCR un nepiegādātās enerģijas (ENS) novērtējums tiek veikts izmantojot vidējas slodzes vērtības. Šādā gadījumā enerģijas patēriņu aizstāj ar vidējo slodzi kādā laika intervālā - sezonā, gada, vai cita laika perioda. ENS aprēķināšanai vidējo slodzi gadam / sezonai / citam periodam sareizina ar vidējo elektroenerģijas pārtraukuma laiku patērētājiem.

Gadījumos, kad lietotāju zaudējumi no elektroapgādes pārtraukumiem ir proporcionāli nepiegādātajai elektroenerģijai, vidējo slodžu vērtību izmantošana ir pieļaujama. Taču dažos gadījumos ir novērojamas atšķirības starp elektroenerģijas patēriņa apjoma izmaiņas un lietotāju zaudējumu izmaiņu tendencēm.

Lai padarītu CCR aprēķinus precīzākus, aprēķinos jābūt izmantotām laikā mainīgām slodzēm. Raksta autori piedāvā pieeju CCR aprēķiniem izmantojot laikā mainīgas lietotāju slodzes un lietotāju pārtraukumu izmaksas.

Александр Львов, Анна Мутуле. Оценивание издержек потребителей на надежность с учётом временно – зависимых нагрузок и издержек отказа

Надёжность электрообеспечения является одним из главных параметров, который характеризует работу энергосистемы. Оптимальный уровень надёжности, который берёт во внимание затраты системных операторов и потери потребителей, способствует экономически эффективной работе энергосистемы. Оценить потери потребителей связанные с надёжностью (CCR) и принять соответствующее решение об объёме инвестиций в сеть.

Чтобы оценить CCR, необходима информация о потерях созданных перебоями, а также информация о прерванной мощности и энергии.

В статье рассматривается проблема определения CCR, используя переменные мощности потребителей вместо традиционно используемых постоянных (не меняющихся) мощностей.

В большинстве случаев CCR и недоотпущенная энергия (ENS) определяется, используя постоянные (не меняющиеся) мощности. В таком случае потребление принимается постоянным в какой-либо промежуток времени – сезон, год, или другой период. Для определения недоотпущенной энергии постоянную мощность умножают на длительность перебооя.

В случаях, когда потери потребителей от перебоев электроснабжения пропорциональны недоотпущенной электроэнергии, использование постоянных мощностей допустимо. Однако в некоторых случаях изменения потерь при перебоях электроснабжения не пропорциональны потребляемой мощности и энергии.

С целью сделать оценку CCR более точной, в расчётах должны учитываться изменения потребления. Авторы статьи предлагают подход для оценки CCR, используя переменное потребление и потери от перебоев.