ISSN 1330-3651
UDC/UDK 621.311.1:519.217

MODEL OF SUPPLY RESTORATION OF ENERGY CONSUMERS BY MARKOV STATE SPACE MODELS

Zoran Kovač, Vladimir Mikuličić, Damir Šljivac

Original scientific paper

The paper presents the determination of a density function of supply restoration duration for the application of Markov state space models. The study of supply restoration was performed in Croatian transmission system operator and transmission area of Osijek. An improved model of the supply restoration at the interface between the transmission and distribution system operator networks is given, based on the research of the supply restoration process and the determined supply restoration distribution density parameters. The use of the proposed model in a reliability analysis significantly contributes to the quality of electricity supply reliability indicators results.

Keywords: *supply restoration density function, Markov models, supply restoration model, supply restoration process, reliability indicators*

Model uspostave napajanja korisnika električnom energijom Markovljevim modelom prostora stanja

Izvorni znanstveni članak

Rad prikazuje utvrđivanje funkcije gustoće trajanja uspostave napajanja za primjenu Markovljevih modela prostora stanja. Istraživanje uspostave napajanja je provedeno u mreži pod nadležnošću hrvatskog Operatora prijenosnog sustava i Prijenosnog područja Osijek. Na temelju istraživanja procesa uspostave napajanja i utvrđenih parametara distribucije gustoće dan je prijedlog poboljšanog modela uspostave napajanja na sučelju između operatora prijenosa i distribucije. Primjenom ovog modela uspostave napajanja u analizi pouzdanosti značajno se doprinosi kvaliteti rezultata pokazatelja pouzdanosti napajanja korisnika električne energije.

Ključne riječi: *funkcija gustoće trajanja uspostave napajanja, Markovljevi modeli, model uspostave napajanja, proces uspostave napajanja, pokazatelji pouzdanosti*

1 Introduction

For the application of Markov state space models in modelling substations and switching procedures, i.e. a supply restoration procedure, it is crucial to determine all parameters that influence the supply interruption duration. The Markov model is chosen due to a possibility to clearly model all procedures and states during disturbances, which result in the supply interruption, according to [1, 2, 3]. In order to determine all the relevant parameters, the transmission network supply interruption reports from the year 2006 until the year 2010, as well as the supply interruption data in the transmission area Osijek from the year 2000 until the year 2010, were analysed. Based on this analysis, the supply restoration processes in the Croatian Transmission System Operator (TSO) and transmission area Osijek were determined.

The Markov state space models application is possible only if probability density of failure and restoration is exponentially distributed [1-5]. Use of the Markov models for the power system networks reliability analysis is appropriate due to the possibility to keep track of all the processes that happen during the disturbances, which result in the supply interruption of final customers. The TSO collects the data about the network under its jurisdiction and makes the reports about the supply interruptions annually. In order to be able to model the power network by using the Markov models, the density function of the supply restoration duration has to be determined. An initial assumption is that the supply interruption frequency, as a random variable, has is the exponential density function, so it would not be considered in this paper [3, 7]. If the supply interruption and the duration do not have the exponential density function, then fake states should be introduced in the model, which are combined to form the exponential density function [3-5]. Based on analyses of the data from [6] and [7], determination of the reliability density function was carried out [8, 9]. After it is determined that the supply restoration duration is exponentially distributed, a direct application of the Markov models is possible. The supply restoration was analysed and a flow diagram was build, based on the author's experience (dispatcher), as well as on the interviews with other transmission and distribution system dispatchers. Then all the assumptions for development of the supply restoration model, during different disturbances and relationships between all participants, taking into account availability of observed components and units on the interface between the transmission and distribution system, are set [10, 11], as it is determined that in most cases the supply interruption happens in such nodes [12-14]. Finally, a general model is given, with the determined supply restoration parameters, which depend on the supply restoration process and should be reduced to a reasonable number when modelling the substation, the node or the interface, in order to determine the quality supply reliability indicators [15]. Results of such reliability analysis could be used for the network development planning, optimisation, determination of the TSO's organizational structure quality, determination of necessity for more quality of the supply restoration participants education as well as for more quality of the power system overall control.

2 The electric energy supply interruptions annual reports

The TSO publishes the supply interruption reports annually. The supply interruptions have origin either in an observed or an unobserved network. The observed network is operated by the TSO, regardless of ownership. The report comprises the supply interruption description with the basic data such as date, the supply interruption start and end times, the undelivered energy estimation, name of the affected customer. The data about the disturbance start and end times are written down by the shift manager (dispatcher), while the undelivered energy estimation is calculated as [14, 16]:

$$W_{\text{est}} = P_{n-1} \cdot (t_{\text{end}} - t_{\text{start}}), \quad (1)$$

where:

W_{est} – the estimated undelivered energy, MWh/h
P_{n-1} – load of a previously recorded hour in MWh/h (average hour power).
t_{end} – the supply restoration time, h
t_{start} – the supply interruption start time, h.

Fig. 1 gives the disturbance model with the supply interruption at the revenue metering point, i.e. the customer connection point.

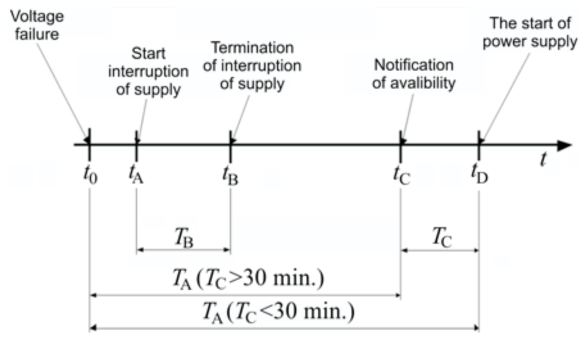

Figure 1 Diagram of disturbance with the interruption of supply [14]

Tab. 1 gives the total number of the supply interruptions, the total duration of the supply interruptions and the total estimated amount of the undelivered energy in the network that is under the Croatian TSO jurisdiction, according to the data from [6].

Table 1 The supply interruptions in the period 2007 ÷ 2010 for the transmission network under the Croatian TSO jurisdiction

Year	Number of the supply interruptions	Estimated amount of the undelivered energy	Duration of the supply interruptions
		kWh	h:min
2007	152	398109	75:25
2008	146	543712	94:24
2009	143	1587033	109:37
2010	128	702459	289:42
Total	569	3231313	569:08
Average value	17,25	807823	142:17

The supply interruptions data for the transmission area Osijek were collected and analysed in order to investigate the supply interruption causes. The supply interruptions data were given regardless of the cause from aspects of the network observability as well as responsibility for the disturbance with the supply interruption. Tab. 2 gives the total number of the supply interruptions, the total duration of the supply interruption and the total estimated amount of the undelivered energy in the Transmission area Osijek, in the period 2000 ÷ 2010.

Table 2 The supply interruptions in the period 2007 ÷ 2010 for the transmission network in the transmission area Osijek

Year	Number of the supply interruptions	Estimated amount of the undelivered energy	Duration of the supply interruptions
		kWh	h:min
2000	27	293417	15:28
2001	13	151174	10:12
2002	23	170549	11:03
2003	18	115210	12:18
2004	11	62350	4:29
2005	13	99156	4:01
2006	10	39560	2:43
2007	8	16950	1:46
2008	9	28200	2:04
2009	7	28837	3:25
2010	13	17100	1:59
Total	112	577912	68:58
Average value	12,44	64212,4	6:16

3 Probability density functions

Probability density functions that are often used for durations of the components failures and restoration are exponential [9]:

$$f(t) = \lambda \cdot e^{-\lambda \cdot t}, \lambda > 0 \quad (2)$$

and lognormal:

$$f(t) = \frac{1}{t \cdot \sigma \cdot \sqrt{2 \cdot \pi}} e^{\left(-\frac{(\ln t - \mu)^2}{2 \cdot \sigma^2}\right)}. \quad (3)$$

3.1 Determination of the supply restoration density function

By analyzing every disturbance with the supply interruption, it is determined that the supply restoration duration depends on the component and observed unit availability, as well as abilities, knowledge and experience of the dispatcher. The dispatchers have to act according to the Grid Code and laws of the country in which the transmission network in question is, [10, 11]. If it is assumed that the components necessary for the restoration process are available, meaning valid and switched on, which is almost always true, then the supply restoration duration depends on prescribed procedures and correct recognition, acceptation of the delivered data as well as a correct action of the dispatcher [12, 20]. Therefore it could be concluded that the supply restoration duration is directly correlated to the dispatcher and other operating personnel activities, according to the prescribed procedures. The analysis of the disturbances from the supply interruptions data, collected for the transmission area Osijek and the transmission network under the Croatian TSO, show that in most cases the supply interruptions occur at the energy delivery point, at the substations between the TSO and the 35 kV, 20 kV and 10 kV level networks users [14].

Fig. 2 gives relative frequencies of the supply interruptions duration, i.e. the empirical data were used to determine the supply restoration duration and the theoretical probability density functions.

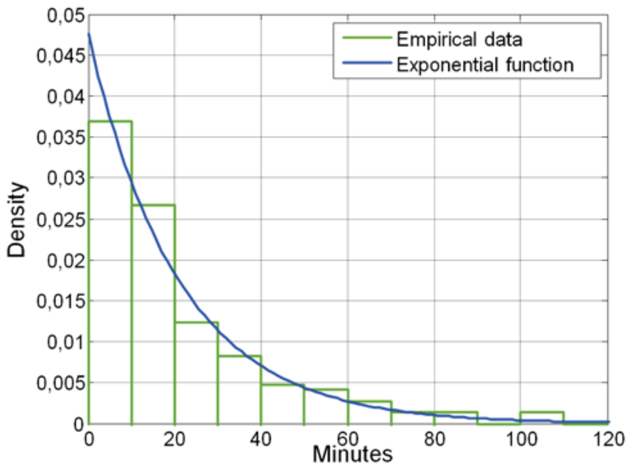

Figure 2 Probability density function based on empirical data

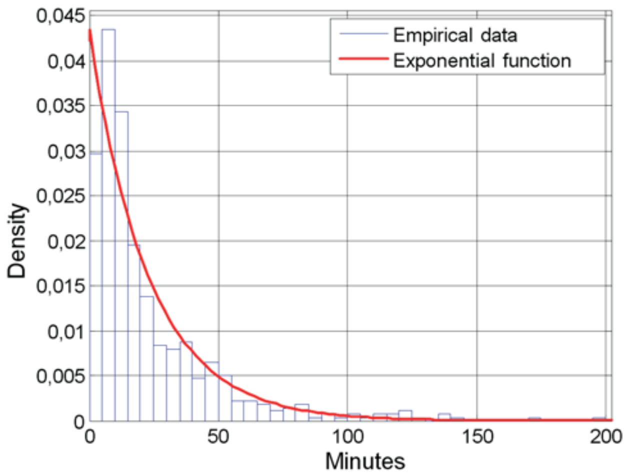

Figure 3 Probability density of the supply interruption duration based on the empirical data

Also, the theoretical probability density function for the transmission network under the Croatian TSO jurisdiction was determined, based on the supply interruptions empirical data, Fig. 3.

Fig. 4 gives the empirical data and the belonging theoretical probability density functions for the whole TSO and for the transmission area Osijek (TAOS) transmission networks.

It can be concluded that the theoretical probability density functions, for longer and shorter observation periods as well as for different data amounts, are matching.

The class width was determined according to Freedman-Diaconis rule, [9]:

$$d = 2 \cdot IQR(x) n^{-1/3} \tag{4}$$

where:
d – the class width,
$IQR(x)$ – interquartile range of data,
n – number of observations,
x – sample.

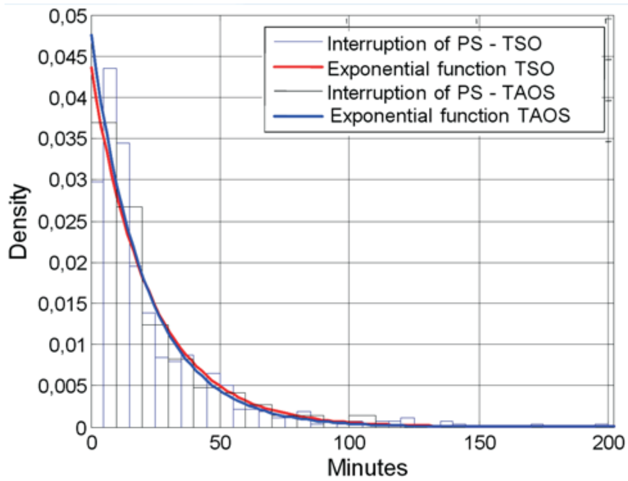

Figure 4 Probability density function of the supply interruption duration for the whole TSO and for the transmission area Osijek transmission networks based on the empirical data

Based on the empirical data, the class width for the supply restoration duration data for the transmission area Osijek customers is 10 minutes, while for the TSO customers is 5 minutes.

A Chi square test with a confidence interval of 95 % was used to test whether the random variables are exponentially distributed. It was proven that the random variable of the supply restoration duration for the consumers connected to the Croatian transmission network has the exponential density function. Parameters of the exponential density function were determined, based on the confirmed assumption, Tab. 3.

Table 3 The density duration exponential function parameters of the supply restoration

	Average duration of the supply interruption, minutes	Frequency of the supply restoration, 1/y
TSO	22,9402	0,0436
Transmission area Osijek	21,0068	0,0476

According to the determined parameters, the exponential density function is:

$$f(t) = \mu \cdot \mathrm{e}^{-\mu \cdot t}, \tag{5}$$

$$f(t)_{\mathrm{TSO}} = 0{,}0436 \cdot \mathrm{e}^{-0{,}0436 \cdot t} \tag{6}$$

and

$$f(t)_{\mathrm{TAOS}} = 0{,}0476 \cdot \mathrm{e}^{-0{,}0476 \cdot t}. \tag{7}$$

4
The supply restoration model

Obviously the supply restoration duration is exponentially distributed, i.e. it has the exponential probability density. Therefore, a basic condition for direct application of the Markov models to describe the processes during failure and restoration of the supply is fulfilled. The supply restoration duration is actually the duration of certain actions of the personnel that operate the transmission network under their jurisdiction, depending on the components availability, and actions of the personnel that operate the network at the interface, as well as the availability of normally open components.

There are a lot of parameters affecting the undelivered electrical energy that can be either uncontrollable (they cannot be influenced) or controllable (they can be indirectly influenced).

The uncontrollable parameters are:

– the unobserved network,
– the disturbance starting time,
– load at the affected node.

The parameters that can be defined as controllable:

– maintenance of the existing network,
– development and planning of the network,
– the network automation,
– the dispatchers and intervening operating personnel training,
– the operator training,
– the shift manager training,
– organization of the company dealing with the transmission and delivery of the electric energy.

For certain types of forced outages there are prescribed procedures that should be consistently followed. All the participants in the supply restoration process are obligated to carry out orders from the dispatcher in regional or national dispatching centre. In literature this process is called switching duration, speed of the supply restoration, or in case of a fault it is called procurement speed of the components to be replaced, speed of the component repair or replacement, turning on after the repair or replacement [16]. The supply restoration process is described by Markov model, with either serial or parallel states combination. The actions are usually preformed hierarchically so they can be described by the serial combination. In some cases when there are several operations or replacements of two or more components carried out simultaneously, then the parallel combination is used. First of all, it is necessary to determine the parameters that affect the supply restoration process duration.

Modelling of the supply restoration process was based on the prescribed procedures and recognized outages.

For documented events and analysis a classification according to mutual characteristics was carried out. It is recognized that the switching duration is affected by the following parameters:

– Gathering data about the event and information creation,
– Substation in remote monitoring and control system (high voltage and medium voltage),
– availability of communication links and the remote monitoring and control system,
– occupation by the constant operating personnel service,
– vicinity of the intervening operating personnel centre,
– necessity of the operating personnel arrival to the affected substation regardless of the remote monitoring and control system,
– possibility of taking over the load from other substations.

Speed of the dispatching centre manager decisions depends on the collected data about the event and a possibility to form quality information. Knowledge of the prescribed procedures and recognition of the events accelerates and verifies correctness of the decision. Speed

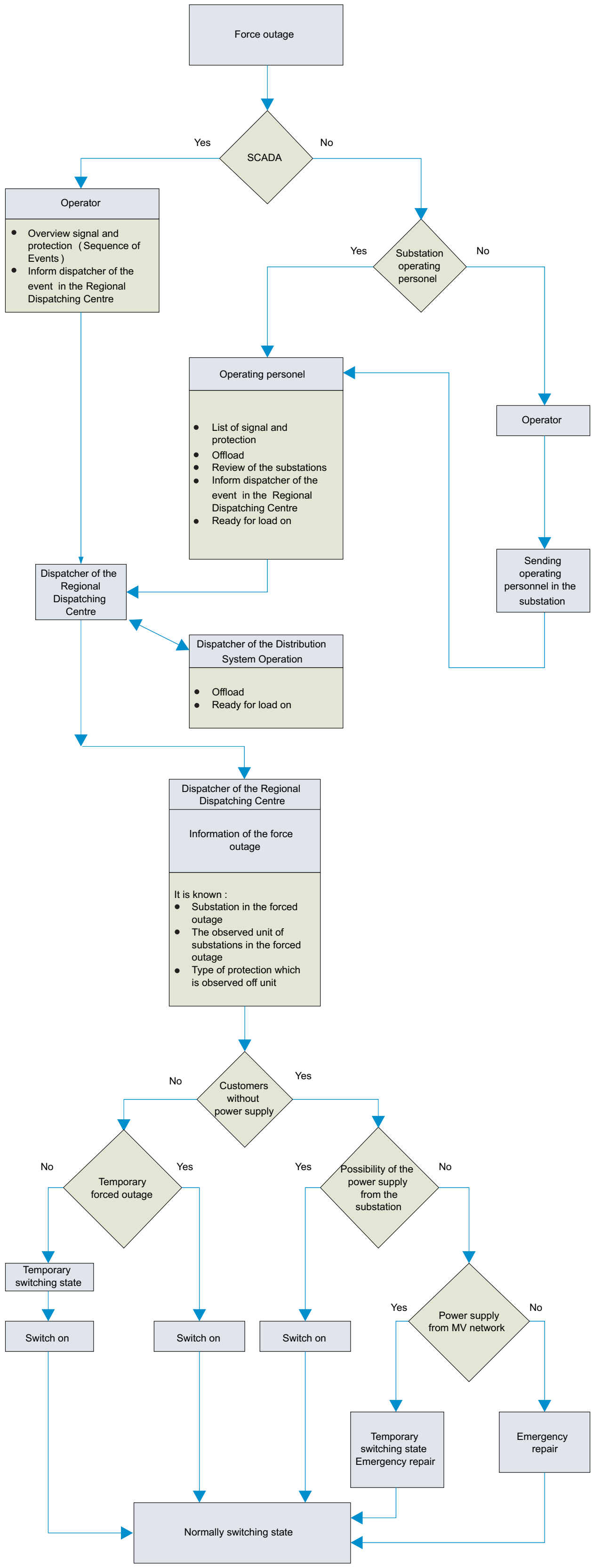

Figure 5 Flow diagram for the procedures in the disturbance cases

of the operating personnel arrival to the substation depends on the available number of the operating personnel, time of day (night/day, during or after working hours) as well as on the intervening centre vicinity. Speed of the necessary actions in the substation is affected by knowledge about the substation and deployed equipment, size of the substation, training and the possibilities of each operating personnel. Fig. 5 gives flow diagrams in case of the disturbance with or without the supply interruption with all relevant characteristics, whose development is based on the author's long time experience as the shift manager (dispatcher). These diagrams could be used to build a mathematical model of the switching process, based on the Markov state space models.

According to the previously determined parameters that influence the supply restoration process, i.e. necessary switching, it is possible to develop several models described by the Markov state space model [16-19].

All the models use the duration, i.e. the speed of data collection about an event, as well as the speed of the information formation by the dispatcher, inputs in order to start the supply restoration process [17]. The duration, i.e. the speed of data collection about an event and the information formation until a first command ordered to the operator or the operating personnel is labelled as λ_0, which is reciprocal value of the duration. The models could also include the speed of the operating personnel arrival to the substation, load shedding speed in the substation, with or without the remote monitoring and control system, speed of the fault isolation, speed of the supply restoration from the middle voltage network. The distribution network, which usually connects at least two 110/x kV substations at the middle voltage level, is often neglected in the reliability analysis. Therefore, the switching model could comprise the following parameters:

λ_0 – reciprocal value of the data gathering duration until the first decision,

t_U – duration of the operating personnel arrival to the substation,

t_R – duration of the substation load shedding,

t_I – duration of isolating the faulted component or observed unit and the plant overview,

t_O – duration of the substation load,

t_D – duration of the distribution network preparation for acceptance of the load.

Every switching, i.e. supply restoration model has different parameters, which depend on the supply restoration process.

Generally for the supply restoration (repair) frequency in j-th model stands:

$$\mu_{\text{swt},j} = \frac{1}{\sum_{i=1}^{n} t_i}. \qquad (8)$$

Fig. 6 gives the replacement switching model that includes all the parameters according to (8), with an assumption of sequential execution of each operation during the supply restoration process.

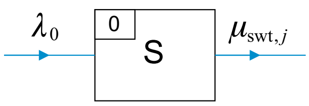

Figure 6 The replacement switching model

The data collection speed depends on availability of communications, the remote monitoring and control system, as well as the correct protection actions. Quality of the dispatcher's decisions depends on representation, i.e. SCADA (Supervisory Control And Data Acquisition) system, representation accuracy according to technical documentation of the substations, devices states and alarms signalization, dynamic colouring, electrical and nonelectrical quantities, as well as his training and experience.

5 Conclusion

For quality reliability analysis of the observed power system or subsystem, based on the Markov state space models, it is necessary to determine the probability density functions from the available data. Also, it is necessary to have the knowledge about the supply restoration processes, because the restoration duration is often added to the component repair duration, which certainly leads to bad results and wrong conclusions about certain node reliability; or the switching duration is linked only to acting components such as breakers. This paper gives the general model of the supply restoration, based on the research of the supply restoration process in the observed system, at the interface between the transmission and distribution system operator, as well as on implementation into standard models. Future research will comprise comparison of the proposed model to the supply interruption data, according to the data collected from the Croatian TSO and transmission area Osijek, which will confirm the assumptions. The reliability analysis results, which take into account the given switching, i.e. supply restoration model, could be used for the network planning, optimisation, determination of the TSO's organizational structure quality, determination of necessity of the more quality supply restoration participants training, as well as for the more quality power system control [20, 21].

6 References

[1] Billinton, R.; Allan, R. N. Reliability Evaluation of Engineering Systems, PlenumPublishing, New York, 1992.
[2] Billinton, R.; Allan, R. N. Reliability Evaluation of Power System, Plenum Publishing, New York, 1984.
[3] Mikuličić, V.; Šimić, Z. Electric Power System Reliability, Availability and Risk Models, Kigen, Zagreb, svibanj 2008.
[4] Nahman, J. M. Metode analize pouzdanosti elektroenergetskih sistema, Naučna knjiga, Beograd, 1992.
[5] Nahman, J. M. Dependability of Engineering Systems, Springer-Verlag, Berlin Heidelberg, 2002.
[6] HEP-Operator prijenosnog sustava d.o.o., Izvješće o prekidima napajanja u prijenosnoj mreži, Zagreb, 2007.÷2010.
[7] ETF Osijek, Analiza pouzdanosti elektroenergetskog sustava Hrvatske, studija, srpanj 2005.
[8] Pavlić, I. Statistička teorija i primjena, Tehnička knjiga, Zagreb, 1988.
[9] Scott, D. W. Multivariate Density Estimation: Theory, Practice and Visualization, Pages: 47–94, 2008, Published Online : 27 MAY 2008, DOI: 10.1002/9780470316849.ch3
[10] Mrežna pravila elektroenergetskog sustava, NN 36/2006.
[11] HEP-Operator prijenosnog sustava d.o.o., Zbirka uputa za vođenje pogona, Zagreb, svibanj 2007.
[12] Šljivac, D.; Nikolovski, S.; Kovač, Z. Distribution Network Restoration Using Sequential Monte Carlo Approach. // Proceedings of the 9th International Conference on Probabilistic Methods Applied to Power Systems, Stockholm, Sweden, 2006.
[13] Kovač, Z.; Nikolovski, S.; Štefić, B.; Kramar, Z. Proračun pokazatelja pouzdanosti prijenosne mreže metodom pobrojavanja stanja, 7. simpozij o sustavu vođenja EES-a, Cavtat, 5.-8. studenoga, 2006.

[14] Kovač, Z.; Šljivac, D.; Kramar, Z. Utjecaj trajanja sklapanja na neisporučenu električnu energiju. // Zbornik radova 8. savjetovanje HRO CIGRÉ / Irena Tomiša (ur.). Zagreb : Sveučilišna tiskara d.o.o. Zagreb, 2007. C2 1-10.
[15] Dillon, T. S.; Niebur, D. Neural Networks Applications in Power Systems, CRL Publishing Ltd, 1996.
[16] Bilinton, R.; Chen, H.; Zhou, J. General n+2 State System Markov Model for Station-Oriented Reliability Evaluation. // IEEE Transaction on Power System, Vol 12, November, 1997.
[17] Li, W. Risk Assessment Of Power Systems (models, methods and aplications), Institute of Electrical and Electronics Engineers, Canada, 2005.
[18] Šljivac, D. Probabilistic Cost Analysis of Electric Energy Supply Interruptions // PhD thesis, Faculty of Electrical Engineering and Computing, Zagreb, Croatia, June 2005 // Kigen, Zagreb, 2008.
[19] Stojkov, M.; Komen, V.; Šljivac, D. Improved Procedures of Distribution Power Network Failure Data Collection for Supply Availability Index Evaluation. // Strojarstvo, 51, 2 (2009), pp. 127-138.
[20] Vrbanić, I.; Šimić, Z.; Šljivac, D. Prediction of the time-dependent failure rate for normally operating components taking into account the operational history. // Kerntechnik, 73, 4(2008), pp. 190-196.
[21] Šljivac, D.; Šimić, Z.; Stojkov, M. Survey on Customer Power Supply Interruption Costs and Calculation of Expected Customer Damages. // Tehnički vjesnik : znanstveno-stručni časopis tehničkih fakulteta Sveučilišta u Osijeku, 16, 4(2009), pp. 47-53.

Authors' addresses

Zoran Kovač, MSc
HEP – OPS
Croatian Power Company – Transmission System Operator
Transmission area Osijek - Prijenosno područje Osijek
Šetalište k.F.Šepera 1a, 31000 Osijek, Croatia
Phone: 385 31 224 110,
e-mail: zoran.kovac@hep.hr

Prof. Vladimir Mikuličić, PhD
University of Zagreb,
Faculty of Electrical Engineering and Computing
Unska 3, 10000 Zagreb, Croatia
Phone: 385 1 6129 993
e-mail:vladimir.mikulicic@fer.hr

Prof. Damir Šljivac, PhD
Josip Juraj Strossmayer University of Osijek
Faculty of Electrical Engineering
Kneza Trpimira 2b, 31000 Osijek, Croatia
Phone: 385 31 224 651
e-mail:damir.sljivac@etfos.hr