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Multi-objective power-generation scheduling: Slovenian power system case study

Blaže Gjorgiev[1], Marko Čepin[2], Andrija Volkanovski[1], Duško Kančev[1]

[1] Reactor Engineering Division, Jožef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
[2] Faculty of Electrical Engineering, University of Ljubljana, Tržaška 25, SI-1000 Ljubljana, Slovenia
E-mail: blaze.gjorgiev@ijs.si, marko.cepin@fe.uni-lj.si, andrija.volkanovski@ijs.si, dusko.kancev@ijs.si

Abstract The multi-objective generation scheduling is a multidimensional, non-linear, non-convex and highly constrained problem. The problem comprises multiple and often conflicting optimization criteria for which no unique optimal solution can be determined with respect to all criteria. In this paper the generation scheduling is developed with regard to three objective functions: fuel cost, emissions of gaseous pollutants and unavailability of power generation. To solve the problem, an improved genetic algorithm is applied. First, the conventional generation scheduling is solved taking into consideration only the fuel cost. Second, the generation scheduling is solved as a combined risk-economic-environmental optimization problem that takes into consideration all of the above mentioned objectives. The Slovenian power system is used as a test power system. The results show that smart scheduling of power generation may decrease the emissions and increase the availability of power generation.

Keywords: multi-objective optimization, power-generation scheduling, power system, genetic algorithm, unavailability

Večkriterijska razporeditev obratovanja elektrarn: Elektroenergetski sistem Slovenije

Problem optimalne razporeditve obratovanja elektrarn je večdimenzionalen, nelinearen in nekonveksen problem z velikim številom omejitev. Obsega optimizacijske kriterije, ki so lahko medsebojno v konfliktu in za katere ne obstaja le ena sama rešitev, ki bi bila optimalna glede na vsa merila. Razviti model optimalne razporeditve obratovanja upošteva: stroške goriva, količine izpustov snovi v okolje in nerazpoložljivost enot v elektrarnah. Za namen optimizacije je bil razvit izboljšan genetski algoritem. Problem optimalne razporeditve obratovanja je bil najprej rešen kot enokriterijski problem z upoštevanjem stroškov goriva. Nato je bil rešen kot večkriterijski problem z upoštevanjem vseh treh prej omenjenih kriterijev. Elektroenergetski sistem Slovenije je bil uporabljen kot testni sistem. Rezultati kažejo, da lahko z uporabo pametne razporeditve obratovanja zmanjšamo količino izpustov v okolje in izboljšamo razpoložljivost elektroenergetskega sistema.

1 INTRODUCTION

The optimal generation scheduling plays an important role in power system operation and control. Thus, the short-term daily generation scheduling of hydrothermal power systems has been one of the most important and challenging optimization problems in the economic operation and control of power systems.

The objective of solving the classical generation scheduling problem is minimization of the total generation cost over the scheduling period while meeting the load demands and satisfying all unit constraints. The generation scheduling problem comprises two different problems, i.e. the unit commitment and the generation dispatch problem. The term unit commitment is associated with the strategic choice to be performed in order to identify the generating capacities of a given power system which are to be considered to supply electricity [1, 2]. The action of dispatching is associated with the fitting a given set of generation outputs into a specific demand. The unit commitment can be basically seen as a prerequisite for the dispatching problem, i.e. appointing a set of generating capacities from which the dispatching can choose.

Both the unit commitment and the generation dispatch problem have been solved using algorithms based on modern optimization techniques such as evolutionary algorithms [3, 4], swarm optimization [5, 6] and artificial neural networks [7]. In some studies [4, 8] a comparison has been made with classical optimization techniques such as dynamic programming (DP) and Lagrange relaxation (LR). The results of these studies verify the capability of the modern optimization techniques to find better optimal solutions compared to the classical ones.

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Some important parameters and constraints have been neglected in most of the studies and rarely solving the issue for a real power system has been presented in the published literature.

The objective of this paper is to solve the generation scheduling problem for the Slovenian power system taking in consideration all the thermal and hydro power plants connected to the transmission system. A multi-objective optimization method for solving the risk-economic-environmental optimization problem is developed. The fuel cost, emissions of gaseous pollutants and unavailability of power generation are considered. Two case studies are performed. The conventional generation scheduling problem is solved in the first case study considering only the fuel cost. The combined risk-economic-environmental optimization problem is solved in the second case study. The results are compared and analyzed.

2 GENERATION DISPATCH MODEL

The main focus of this paper is placed on the formulation of the generation dispatch problem as a critical part of the generation scheduling problem even though both the generation dispatch and the unit commitment problem are being solved for the test power system. Here, the generation dispatch model developed and presented in [9] is used for the analyzed power system. A short description of the model is presented.

2.1 Fuel cost objective

The fuel cost for each thermal generating unit in the system is usually determined by a second order function of the active power generation. During opening of each admission valve in a steam turbine, the so called drawing effect occurs [10, 11]. This rippling effect is a modeled as sinusoidal function of the active power generation. Therefore, the fuel cost function is written as a non-linear and non-convex function [12, 13] as follows:

$$FC_i(P_{T_i}) = t_m[a_i + b_i P_{T_i} + c_i {P_{G_i}}^2 + |d_i \sin[e_i(P_{T_i}^{min} - P_{T_i})]|] \quad (1)$$

where a_i(\$/h), b_i(\$/MWh), c_i(\$/MW^{2}h), d_i(\$/h) and e_i(rad/MW) are constants unique for each generating unit, P_{T_i} is the power output of the ith thermal unit, P_T^{min} is the minimum power output of the ith thermal unit, and t_m is the duration of the time interval in hours.

2.2 Environmental objective

The total emissions of sulfur oxides (SO_X) and nitrogen oxides (NO_X), emitted by thermal units can be modelled together and described by one function [12-15] as follows:

$$FE_i(P_{T_i}) = t_m[10^{-2}(\alpha_i + \beta_i P_T + \gamma_i {P_{T_i}}^2) + \eta_i exp(\lambda_i P_{T_i})] \quad (2)$$

where α_i, β_i, γ_i, η_i, and λ_i are constants unique for each thermal unit. The coefficient 10^{-2} is used only in the case when metric units are used for the input parameters [15].

2.3 Unavailability of the power generation objective

Here, the unavailability of power generation is defined as a risk index. The unavailability of power generation is calculated as a function of the power output of each generating unit and consideration of the probability of failure of any of the generating units, Q_{GEN} as follows [9]:

$$F_{U_t} = \sum_{i=1}^{I} {Q_{GEN}}_i^{TU} \frac{P_{T_i}}{\sum_{i=1}^{I} P_{T_i} + \sum_{j=1}^{J} P_{H_j}} + \sum_{j=1}^{J} {Q_{GEN}}_j^{HU} \frac{P_{H_j}}{\sum_{i=1}^{I} P_{T_i} + \sum_{j=1}^{J} P_{H_j}} \quad (3)$$

where $F_{U_t}$is unavailability of power generation at time interval t, ${Q_{GEN}}_i^{TU}$ and ${Q_{GEN}}_i^{HU}$are the probabilities of failure for thermal and hydro power units, respectively. The indices TU and HU denote the thermal and hydro units, respectively. Each generating unit participates at each time interval with its power output share in order to meet the load demand in that time interval. Since these shares are not the same and they differ over the different units, and as discussed above, the most reliable unit should be operated at a maximum power level, normalization is being applied as apparent in Eq. (3), i.e. $\frac{P_{T_i}}{\sum_{i=1}^{I} P_{T_i} + \sum_{j=1}^{J} P_{H_j}}$ and $\frac{P_{H_j}}{\sum_{i=1}^{I} P_{T_i} + \sum_{j=1}^{J} P_{H_j}}$.

Since the load demand changes at each time interval, also the unavailability of power generation will vary from interval to interval. A simple arithmetic average is used to estimate the average unavailability of power generation during the analyzed time period:

$$F_U = \frac{(\sum_{i=1}^{T} F_{U_t})}{T} \quad (4)$$

This is a novel approach to modeling the availability of the power system generation capacity. It is originally developed and introduced in [9]. Unlike some of the known methods and techniques for generation scheduling within a power system, this novel approach takes into account and incorporates the probability of failure of each of the generating units considered. In such a way, the unit unavailability/availability is being treated concurrently alongside the associated generation cost and emission as a realistically existing issue [9].

2.4 Mathematical formulation

The combined economic-environmental dispatch problem of reliability of generating units is mathematically formulated as a nonlinear, constrained multi-objective optimization problem as follows:

$$Minimize\ [F_C(P_S),\ F_E(P_S),\ F_U(P_S)] \tag{5}$$

subject to:

$$g(P_S) = 0 \tag{6}$$
$$h(P_S) \leq 0 \tag{7}$$

where $g(P_S)$ and $h(P_S)$ are the equality and inequality problem constraints, respectively, and P_S is a decision vector that represents a potential solution [16] as follows:

$$P_S = \begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,T} \\ \vdots & & \ddots & \vdots \\ P_{I,1} & P_{I,2} & \cdots & P_{I,T} \\ X_{1,1} & X_{1,2} & \cdots & X_{1,T} \\ \vdots & & \ddots & \vdots \\ X_{J,1} & X_{J,2} & \cdots & X_{J,T} \end{bmatrix} \tag{8}$$

The number of rows, $I + J$, is equal to the number of generating units; the number of columns, T, is equal to the number of time intervals [1].

2.5 Constraints

The following external constraints were considered in the generation dispatch problem: the power balance constraint, the water balance at each time interval constraint, the water balance at the end of the time period constraint, the pumped-storage hydro plant (PSHP) water conservation constraint and the ramp rate constraint [1].

Each type of constraint is applied several times depending on the impact that the constraint has on the power system. Thus, the sum of external constraints for the Slovenian power system is 835.

To simplify the calculations the transmission system was not considered in our analyses. Thus the transmission system constraints, i.e. the security constraints do not figure in our calculation. However, the power losses in the transmission system were considered. They were modeled as a percentage of the load demand. The losses of the Slovenian power system were assessed of 4.5 % of the total load demand including the export.

3 PROBLEM SOLUTION

A multi-objective improved genetic algorithm (IGA) is employed in order to solve the optimization problem developed above and represented with Eq. (5). The weighted sum method is used for multi-objective purposes [17]. The fuzzy penalization method and the dynamic normalization method are utilized to deal with the constraints [16]. The algorithm structure is presented in details in [16]. A brief discussion of GA is given.

3.1 GA structure

GA is a probabilistic search approach based on the principle of natural selection and genetic recombination. It provides a very powerful method that efficiently utilizing historical data to evaluate new search points with the expected better performance [1, 18, 19].

3.1.1 Initial population

GA begins with an initial population of chromosome, i.e. potential solutions. All variables from each chromosome in the initial population are randomly determined using a uniform probability distribution covering the entire search space uniformly.

3.1.2 Selection

After the fitness function is evaluated for each possible solution form the initial population, the linear rank selection operator is used. The chromosomes are being sorted with regard to their fitness. Each get a different selection probability since the selection probability is linearly assigned to it according to its rank. Thus, the best chromosome is assigned with the greater probability and the worst chromosome with the lowest probability. The probability is based on the chromosome rank and not on its fitness value [1].

4 THE SLOVENIAN POWER SYSTEM DESCRIPTION

The Slovenian power system consists of nuclear, fossil-fired and hydro generating units. The Krško nuclear power plant (NPP) participates with some 40% of the total power generation annually and the fossil-fired and hydro power plants with some 30% each. The Krško NPP is co-owned by the Slovenian state-owned company “Gen-Energija” (GEN) and the Croatian state-owned company “Hrvatska elektroprivreda” (HEP). The Krško NPP generates and supplies electricity exclusively for the two owners each entitled to 50% of the plant total output [20]. Thus, half of the energy generated by the Krško NPP is delivered to Croatia.

Each of the hydro and thermal power generating units connected to the Slovenian power transmission system was considered in our analyses. The fuel cost and pollutant emission characteristics of all the thermal units are generic and can be found in the technical literature. The unit data are presented in [1].

Table 1: Hourly generation scheduling (MW) of all the thermal units operating in the Slovenian power system for the first case study

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	13	14	15	16	17	18	19	20	21	22	23	24
Šoštanj TPP:																								
TEŠ PE1	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	0	0	29	28	0	0
TEŠ PE2	0	0	0	0	0	0	30	0	0	0	0	0	0	0	0	0	0	0	29	30	29	29	0	0
TEŠ B3	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75	75
TEŠ B4	248	248	247	248	245	248	248	248	248	248	248	248	248	248	248	248	248	248	248	248	248	248	248	248
TEŠ B5	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305
Trbovlje TPP:																								
TET B4	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110	110
Brestanica TPP:																								
PB 1	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	21	21	21	21	21	0	0
PB 2	0	0	0	0	0	0	31	0	0	0	0	0	0	31	0	0	0	31	31	31	31	31	31	0
PB 3	0	0	0	0	0	0	32	0	32	32	32	32	32	32	0	0	0	32	32	32	32	32	32	0
PE 4	66	56	47	0	0	85	87	88	89	87	87	88	87	87	87	87	87	87	87	87	87	86	66	55
PE 5	69	58	0	0	0	0	87	90	91	88	87	90	87	89	87	87	87	87	87	87	87	87	68	56
CHPP Ljubljana:																								
B1 coal	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39	39
B2 coal	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29	29
B3 coal	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45	45
Krško NPP	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696	696
Import:	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cost=169251 ($)								Emission=210 (ton)								Unavailability=0.0627 (/)							

5 Analyses and results

The load demand considered in our analyses was the one of January 17, 2013. [21]. To account for the power export from Slovenia to Croatia, as a result of the Krško NPP co-ownership, a consumer constantly consuming 348 MW at each time interval was modeled. Besides, 100 MW of the power were foreseen for export. This allowed us to test the capability of the Slovenian power system to meet the load demand even in cases requiring and additional amount of the peak power.

To account for the possible import of energy, a unit of specific fuel cost and pollutant emission characteristics was modeled. A certain forced outage rate, more or less depending on the connection and the reliability state, of the interconnected neighboring systems was also accounted for. The characteristics were designed so that both, the fuel cost and the pollutant emissions were higher than that of the most inefficient unit.

Two case studies were performed. In the first one, the optimization problem was solved as a single-objective, i.e. the fuel cost objective was the only one considered. In the second one, the problem was solved as a multi objective one considering all the three objectives given above: the cost objective, the emission objective and the risk objective.

5.1 The first case study

In the first case study, the economic dispatch was solved, i.e. the fuel cost objective was considered as a single-objective in the optimization process. Since there is a significant number of the peak-load units in the Slovenian power system, the unit commitment problem was solved first. The unit commitment solution provided the on-off status of each generating unit at each time interval. The mathematical formulation of the unit commitment problem is given in [1]. Also the spinning reserve in the power system was scheduled when the unit commitment was solved. The margin selected for the spinning reserve from the load demand at each hour was set to 10%. The obtained unit commitment schedule was used as a reference point for the generation dispatch. The hourly generation scheduling of each thermal unit is given in Table 1 including the calculated cost, pollutants emission and unavailability. The generation scheduling of all hydro units is shown in Table 2.

As seen from Table 1, the Krško NPP operates at its full scale during the scheduled time period, simultaneously with the largest thermal units, such as Šoštanj B4 and B5 and Trbovlje B4 operating as base-load units. The coal fired units at combined heat and power plant (CHPP) of Ljubljana are also operated at their maximum. Though not being as efficient as the largest coal-fired units, the result is not surprising because these units are being operated as a heating source for the Ljubljana area; this is the main reason for their efficiency during the winter days. All the gas-fired units operate as peak-load units during the scheduled time period.

Table 2: Hourly generation scheduling (MW) of all hydro units operating in the Slovenian power system for the first case study

Hour	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Moste	2	2	2	2	2	5	13	13	13	13	10	13	3	13	2	2	4	13	2	12	13	9	2	2
Mavčiče	3	3	3	3	3	3	4	19	13	34	3	9	3	13	3	3	17	8	3	5	13	5	3	3
Medvode	3	3	8	3	3	6	10	12	20	5	4	5	16	13	13	8	7	8	16	7	16	18	3	3
Vrhovo	7	12	12	14	6	8	15	10	13	26	12	10	20	10	15	15	11	12	15	8	17	11	6	16
Boštanj	6	6	14	10	12	13	21	22	10	9	16	10	11	8	15	23	13	9	17	7	11	7	7	26
Blanca	8	7	21	7	18	13	17	16	19	17	17	9	23	8	25	33	12	8	27	9	22	17	12	12
Krško	13	14	15	12	11	17	25	9	34	12	9	16	23	16	22	25	13	18	14	17	10	14	14	29
Solkan	6	6	6	12	6	17	14	11	9	16	12	10	19	20	25	26	13	7	26	17	9	18	9	10
Doblar 1+2	16	16	16	16	16	21	21	73	73	73	16	28	16	33	54	51	53	29	16	64	48	23	16	16
Plave 1	16	12	19	14	17	22	19	11	23	13	23	18	19	22	22	24	20	37	32	15	15	14	21	24
Dravograd	17	10	24	16	14	14	16	28	11	12	20	20	19	10	19	25	17	8	22	24	13	13	22	20
Vuzenica	18	16	15	28	26	35	23	38	20	53	30	23	59	18	23	39	35	18	37	23	35	24	27	12
Vuhred	31	14	14	14	26	39	35	41	41	44	34	25	53	23	70	71	29	30	46	32	29	46	35	19
Ožbalt	45	14	14	44	14	54	29	36	74	47	32	21	54	31	38	26	48	35	24	23	55	45	34	20
Fala	13	32	35	28	31	26	33	35	38	31	42	28	18	28	37	39	20	46	37	32	18	20	35	41
M. Otok	34	12	12	31	12	31	33	60	43	56	29	16	44	23	26	12	50	19	51	13	30	51	24	12
Zlatoličje	26	51	39	68	119	64	33	38	29	29	70	54	139	37	96	139	71	31	112	60	28	30	139	120
Formin	24	24	24	24	24	24	80	120	120	119	50	120	24	120	24	24	75	101	24	56	118	111	49	64
Avče	-143	-143	-143	-143	-143	-143	-143	0	0	0	172	172	39	172	69	14	105	172	94	172	-66	-143	-143	-143

Fig. 1 shows the total of the thermal and the hydro generation compared to the total load demand, including consumption of the Avče PSHP, as well as the power export and power losses in the transmission system. The regular load demand is shown, too.

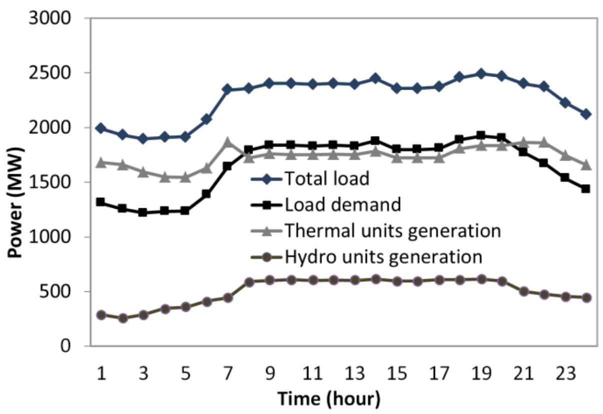

Figure 1. Load demand and power generation for the first case study.

As seen from Fig. 1, the hydro power generation mostly meets the peak-load demand. This is so mainly because of the Avče PSHP, which is operating during the observed period of the day. Also to be seen is that hydro generation is considerable during the early hours of the day when the load demand is lower. This is strongly related to the type of the hydro power plants operating in the Slovenian power system; practically all of them are a combination of the run-of-the-river type and the accumulation type of the hydro power plants. Characteristic for almost all of them are a small net head and large water discharge through the turbine is a specific for almost all of them. Also there is a constraint regarding the required minimum amount of water that has to be discharged into the river. These characteristics do not allow large power storage for a longer period of time. Most of the plants must therefore to operate uninterruptedly during the entire day.

5.2 The second case study

In the second case study, the combined risk-economic-environmental power dispatch was solved. Unlike in the first case study, the unit commitment had not been solved in advance, because of simple reason concerning the risk and emission objectives; each of the intermediate and peak load units needs to operate because of its higher reliability and higher emission efficiency compared to the base-load units.

Since the optimization problem we are dealing with is a multi-objective optimization problem, there is not just one optimal solution to be found but a set of them, none being better than the other considering all objectives. Such solutions are known as the Pareto optimal solutions and the front they describe is the so called Pareto optimal front. The Pareto optimal front for the Slovenian power system obtained in the second case study, by using the proposed multi-objective optimization approach is shown in Fig. 2. The figure also illustrates projections of each solution on each of the three planes. A set of 43 user-supplied weights were applied in order to explore the Pareto front.

Usually when the Pareto optimal front is defined, there is one solution which prioritizes all the objectives equally. This solution is known as the best compromise solution (BCS).

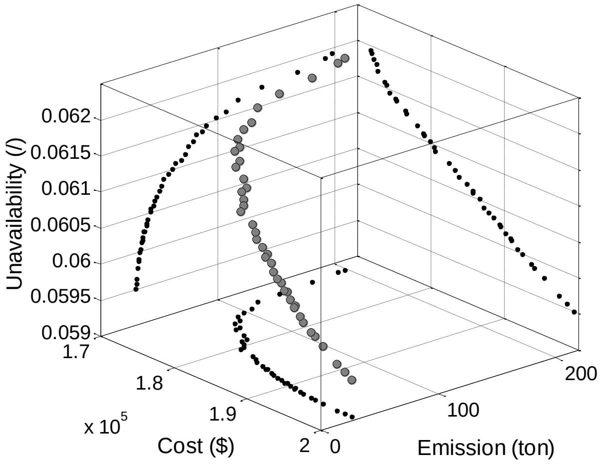

Figure 2. Pareto optimal front obtained in the second case study

Here a comparison is made between the optimal solutions obtained in the first case study, when only the fuel cost objective is considered, and the BCS from the second case study, when all the three objectives are considered. The comparison is shown in Table 3.

Table 3: Comparison of the results

	Cost objective	All objectives	Rel. difference [%]
Total fuel cost ($)	169251	177457	**4.62**
Emission (ton)	210	45	**-78.57**
Unavailability (/)	0.0627	0.0599	**-4.47**

As seen from the last column, a small increase in the cost will significantly decrease the emissions of gaseous pollutants including the generation risk.

In the second case study, most of the units, considered as the peak-load units operate and generate during the hours of the scheduled time period. Most of the thermal units operate as intermediate units, thus performing the load following maneuvers during the day. This is the result of the emission and reliability competitiveness between the peak-load units and the largest coal-fired units.

6 Conclusions

A multi-objective optimization generation scheduling model is presented. Three objective functions are taken into account: fuel cost, emission of gaseous pollutants and unavailability of power generation. Each of the significant types of the unit constraints is considered. A sophisticated generation scheduling model for the generation scheduling problem solving for a practical application case is therefore developed.

The Slovenian power system is used as a case study power system. A comparison is made between the optimal solution obtained with a single-objective optimization, considering only the fuel costs, and the BCS obtained with a multi-objective optimization. The results show that smart scheduling of power generation in the power system improves the pollutant emission efficiency of the system and decreases the unavailability of power generation.

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Blaže Gjorgiev received his B.Sc. and M.Sc. degrees in 2007 and 2010, respectively, both in Electrical Engineering from the University Ss. Cyril and Methodius, Skopje, Macedonia. In 2013 he obtained his Ph.D. degree in Nuclear Engineering from the Faculty of Mathematics and Physics, University of Ljubljana, Slovenia. Since 2009 he has been employed as research assistant with the Reactor Engineering Division, Jožef Stefan Institute of Ljubljana. His research interests include Power System Optimization, Management and Reliability and Probabilistic Safety Analysis of Nuclear Installations.

Marko Čepin received his B.Sc., M.Sc. and Ph.D. degrees from the University of Ljubljana, Slovenia, in 1992, 1995 and 1999, respectively. From 1992 to 2009 he was employed with the Jožef Stefan Institute of Ljubljana. Currently, he is an associate professor at the Faculty of Electrical Engineering, University of Ljubljana. In 2001 he was invited to Polytechnic University of Valencia, Spain. He is a president of the Nuclear Society of Slovenia. His research interests include Energy Engineering, Power Plants and Reliability of Power Systems.

Andrija Volkanovski received his B.Sc. and M.Sc. degrees in 1999 and 2005, respectively, from the Faculty of Electrical Engineering, University Ss. Cyril and Methodius, Skopje, Macedonia. In 2008 he obtained his Ph.D. degree in Nuclear Engineering from the Faculty of Mathematics and Physics, University of Ljubljana, Slovenia. Currently, he is a research associate at the Reactor Engineering Division, Jožef Stefan Institute of Ljublkana. His research interests include Power and Nuclear Engineering, Reliability and Safety studies and Optimization Techniques.

Duško Kančev received his B.Sc. degree in 2007 from the Faculty of Electrical Engineering and Information Technologies - University Ss. Cyril and Methodius, Skopje, Macedonia. In 2012 he obtained his Ph.D. in Nuclear Engineering from the Faculty of Mathematics and Physics, University of Ljubljana, Slovenia. Since 2008 he has been employed as research assistant with the Reactor Engineering Division, Jožef Stefan Institute of Ljubljana. His research interests include Probabilistic Safety Analysis (PSA) of Nuclear Installations, Surveillance Testing and Maintenance Schedules Optimization and Ageing PSA.