Reliability Evaluation of Balkan Generation Systems Considering Planning Exercise of Wind Power Integration

Milenko Tomić [1], Tatjana Konjić [2], Mauro da Rosa [#3], and Vladimiro Miranda [#4]

[1] *The State Electricity Regulatory Commission*
Miška Jovanovića 4/II, 75000 Tuzla, Bosnia and Herzegovina
[1] mtomic@derk.ba

[2] *University of Tuzla, Faculty of Electrical Engineering*
Franjevačka 2, 75000 Tuzla, Bosnia and Herzegovina
[2] tkonjic@inescporto.pt

[#] *INESC Porto - FEUP - Faculty of Engineering of Porto*
Campus da FEUP, Rua Dr. Roberto Frias 378, Porto, Portugal
[3] marosa@inescporto.pt , [4] vmiranda@inescporto.pt

Abstract— **In order to deal with the power fluctuations that come from wind uncertainties, this paper presents a generating reliability assessment of the real generation system of Bosnia and Herzegovina (BH) including wind power as an planning exercise for a given horizon. For this purposes, the sequential Monte Carlo simulation is used not only to assess conventional reliability indices as loss of load probability, loss of load expectation, loss of load frequency, and loss of load duration, but also to discuss an alternative measure of risk-based level called Well-being Analysis.**

I. Introduction

Discussions on innovative planning criteria and assessment tools are major concerns for Balkans countries in order to monitoring the security of supply considering renewable power sources as an important option for sharing the total conventional production for the years to come. Nowadays, market forces provides one of the main guidelines for planning exercises into utilities, where usually, relatively low costs of electricity and high levels of reliability are often requirements for determining appropriate boundaries for the reserve generation.

In terms of open electricity market, the use of probabilistic methods in planning the development of production capacity and transmission network is expected to be frequent. The advantage of these methods is the flexibility due to it is possible to capture uncertainties that usually occur in planning exercises, and the ability to support decisions to determine the economic benefits (legitimacy) of certain investments for the development of the electric system.

It is possible to apply deterministic methods to estimate reliability. However, these methods cannot be directly applied to determine the capacity required, if the system encompasses renewable sources as well. The reason being the fact that generation using renewable sources is not stable in a longer period, as it is the case with conventional units, but it is a time volatile variable depending, *inter alia*, on meteorological conditions. For this reason, planning of power system facilities in the future which are influenced by accidental parameters can be realized if probabilistic techniques are used. Probabilistic techniques, however, do not indicate the marginal reserve in the system, because the system can also operate successfully in the marginal state from the aspect of safety, however, it is a signal to planners and operational stuff that it is necessary to react in order to avoid putting the system under risk. Lack of information on the operation of the system with regard to risk indicators and different views in the interpretation of the risk as a measure of the system adequacy make planners unsatisfied when using this method.

A new concept, called “well-being” analysis, is hybrid approach that has been applied on power systems reliability evaluation to combine deterministic perceptions with probability concepts. This framework reduces the gap between deterministic and probabilistic approaches by providing the ability to measure the degree of success of any operating system state. In a well-being analysis, success states are further split into healthy and marginal states, using the previously mentioned engineers' perception as criterion. This approach is shown in Fig. 1.

The system operates in normal condition if there is enough capacity reserve for satisfaction deterministic criteria. Measure of comfort associated with the activity of the system within the accepted deterministic criterion is given with the probability of staying in the normal state (Healthy State Probability - P(H)). In the marginal (successfully admissible) state, the system is not in any difficulty, but there is not enough to plug the security (no excess reserve capacity) satisfaction of specified deterministic criteria. Marginal probability of state (Marginal Probability State - P(M)) is the probability of staying in a state in which deterministic criterion has been violated. Staying the system in normal and marginal state is called the concept of a successful state. Consequently, the probability of successful state (Success Probability State – P(S)), is defined as the sum of probabilities of normal and marginal conditions: P(S)=P(H)+P(M).

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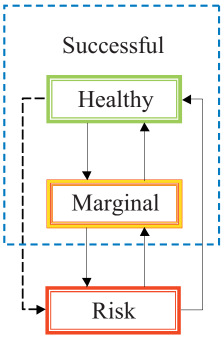

Fig. 1. Well-being framework

Beside these basic well-being indicators performed, there are few more well-being indices such as: the expected hours of staying in the successful and the marginal condition (expected duration D(S) and D(M)), respectively, the expected frequency associated with successful and marginal states, F(S) and F(M), respectively, the expected number of hours per year during which the system will be in the normal condition (expected healthy hours – EH), the expected number of hours per year during which the system will be in marginal condition (expected marginal hours – EM).

In the risk state, load exceeds available capacity in the system. Deterministic criterion is the loss of the largest production unit. Respect deterministic criteria, which drives the probabilistic well-being indicators, these indicators makes it easy for the interpretation of planners who are more accustomed to a deterministic approach.

In the paper, idea is to study the behavior of reliability indices (conventional and well-being) when a major portion of the wind energy sources is integrated into the system with predominant thermal power plants. In order to deal with the power fluctuations that come from wind uncertainties, this paper presents a generating reliability assessment of the real generation system of Bosnia and Herzegovina including wind power as an planning exercise for a given horizon. For this purposes, the sequential Monte Carlo simulation is used not only to assess conventional reliability indices as loss of load probability (LOLP), loss of load expectation (LOLE), loss of load frequency (LOLF), loss of load duration (LOLD), expected power not supplied (EPNS) and expected energy not supplied (EENS) but also to discuss an alternative measure of risk-based level called "Well-being Analysis".

II. Proposed Methodology

The term sequential simulation means that the history of a system is simulated in fixed discrete time steps [1]. The sequential approach is based on sampling the probability distribution of the component state duration. It is used to simulate the stochastic process of the system operation through the use of its probabilities distributions, associated with mean-time-to-failure (MTTF) and mean-time-to-repair (MTTR) of each system component. Considering the two-state Markov Model, these are the operating and repair state duration distribution functions that are usually assumed to be exponential. Other distributions, such as Weibull, Normal, etc., can also be used to represent different behaviors. The problem of estimating reliability indices can be written as follows:

$$\tilde{E}[F] = \frac{1}{NY}\sum_{n=1}^{NY} F(y_n) \tag{1}$$

where: NY is the number of simulated years; y_n is the sequence of system states x^k, in the year n; and $F(y_n)$ is the function to calculate yearly reliability indices over the sequence y_n. The sequential approach can be summarized in the following steps:

i. Generate a yearly synthetic sequence of system states y_n by sequentially applying the failure/repair stochastic models of equipment and the chronological load model. Thus, the initial state of each component is sampled. Usually, in the first sample, it is assumed that all components are initially in the success or up state, even though other approaches may be used. The duration of each component residing in its present state is sampled from its probability distribution. Assuming an exponential probability distribution and using the inverse transform method [2], the duration of each component will follow:

$$T = -\frac{1}{\lambda}\ln(U) \tag{2}$$

where: T is the time residence of each equipment; λ is the failure rate of the component if the present state is the up state or λ is the repair rate of the component if the present state is the down state; and U is a uniformly distributed random number sampled in the interval between [0,1];

ii. Chronologically evaluate each system state x_k in the sequence y_n and accumulate the values;

iii. In order to obtain yearly reliability indices, calculate the test function $F(y_n)$ over the accumulated values;

iv. Estimate the expected mean values of the yearly indices as the average over the yearly results for each simulated sequence y_n;

v. The stop criterion is also based on the relative uncertainty of the estimates. Therefore, calculate β (coefficient of variation) [3];

vi. Verify if the degree of accuracy or confidence interval is acceptable. If the answer is yes, stop the simulation; otherwise, go back to step *i*.

In the sequential approach, the system evaluation is conducted for each different system state in order to achieve the reliability index function. For instance, considering the *LOLE* index: $F(y_n)$=sum of the sampled duration of all failure states in y_n. In turn, if the $F(y_n)$ is the sum of energy not supplied associated with all failure states in y_n, $\tilde{E}[F]$ will represent the expected energy not supplied (EENS) index. Several other reliability indices can be easily achieved using the sequential approach.

III. Proposed Models

In order to obtain indices of risk with simulation program, as the first are established production models as:

A. Hydro model:

In this model beside a number of generators and their installed power, the average volume of river/lake (hm^3) in the form of hydrologic series is used. Also, the model uses the stochastic parameters such as failure rate - *FRATE* and mean time to repair - *MTTR*, which is related to the production units [1]. A basic configuration (year 2006) includes 34 generating units with a total power of 1980.70 MW. It is assumed that all existing hydropower plants will be in operation by the end of the observed simulation period (2006 – 2013). Some smaller deadlocks in productions are possible but it is taken into account through the stochastic parameters (*FRATE* and *MTTR*).

B. Thermal model:

Beside a number of generators and their installed power, stochastic parameters such as failure rate and mean time to repair were used in the thermal model. Total power of engaged generators in thermal power plans is 1606 MW. Outgoing of some generating units from operation (i.e. due to the expiration of designed life-span) as well as dynamics of the revitalization of existing thermal power plants [4] is taking into account in simulations for different scenarios.

C. Wind model:

Wind model is characterized by the number and nominal power generators, failure rate and mean time to repair and time series of wind. Time series of wind enables conversion of wind speed into a useful power of wind generators. Since the moment of preparing simulations for the scenarios, the wind atlas of Bosnia and Herzegovina was not available. Due to a lack of data about wind speeds at potential locations for future wind parks, wind time series is based primarily on the spatial distribution mean annual wind speed and wind power taken from the World Wind Atlas.

D. Small hydro power plants model:

Small hydro power plants are considered in accordance to data about the possible potential of such energy sources [4], [5]. Due to unavailability of data (especially those related to future investments in building new sources), as well as the lack of hydrological series of rivers and rivulets where the new sources would be built, all small hydro power plants are represented by appropriate equivalent generators.

E. Model of electricity export and import:

Electricity exchange (export/import) with neighboring systems is modeled by equivalent power plants/generators with maximum power equal to the power exchange. In that case, it is necessary to take in account the availability of cross-border capacities (net transfer capacity values – NTC), with neighboring countries (Croatia, Serbia and Montenegro) through interconnected lines at 110 kV, 220 kV and 400 kV voltage level [6].

F. Load model:

Annual peak load of 2.034 GW in basic scenario for 2006 is estimated in accordance to linear increase of hourly load and peak load in period 2001-2005 at the level of entire power system of BH. Real annual peak load was 2.019 GW in 2006. A chronological load model consists of 8736 load points that correspond to each hour in the year is shown in Fig. 2. During the simulation, the load steps of a year are sequentially performed due to the chronological representation promoted by Sequential Monte Carlo Simulation. Predicted power data given by ISO BH [4] is used for the simulations period (2008-2013).

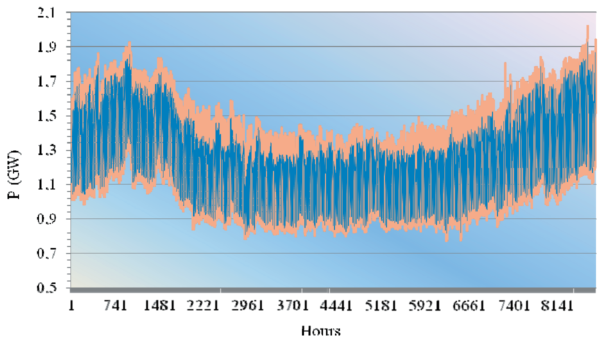

Fig. 2. Chronological annual hourly load for 2006 year

IV. Description of Scenarios and Discussions

In order to calculate reliability indices of BH power system, chosen basic configuration for the simulation is power system configuration from 2006. The basic configuration does not take into account renewable energy sources.

The simulation period is carried out until 2013 year. Each simulation is done in accordance to the data available in two published documents of the Independent system operator ISO BH: Energy sector Study BH [4] and Production Development Indicative Plan 2007 – 2016 year [5].

The main characteristics of power system configuration (type of sources, installed power per type of sources, number of units per type of source, peak load, total power and total number of units) for different scenarios in period 2006-2013 are presented in Table I.

Annual hourly peak load of 2.019 GW is recorded on the day of December 12, 2006. Bearing in mind these values (the installed capacity and annual peak demand) corresponds to static reserves (generation capacity margin) of 43.7% of installed capacity. Total installed power at the threshold of small hydro power plants in the power system of Bosnia and Herzegovina amounted to 27 MW (total participation in the production of only about 1%). Since then, the power utility of Bosnia and Herzegovina (EP BH) has disposed of 15 units with total installed capacity of 12.9 MW, the power utility of the Republic of Srpska (EP RS) with 9 units of total installed capacity of 14.1 MW. All three power utilities in BH, including the power utility "Croatian Community of Herceg-Bosna" (EP HZHB) are planned in the foreseeable future construction a large number of small hydro power plants [4], [5].

TABLE I
CHARACTERISTICS OF DIFFERENT SCENARIOS

Scenario	Type	Power (MW)	No. of units	Peak load (MW)	Total Power (MW)	Total No. of units
2006	Hydro	1980,7	34	2034	3586,7	43
	Thermal	1606	9			
	Wind	0	0			
	Small hydro	0	0			
2008	Hydro	1980,7	34	2108	3723,7	97
	Thermal	1606	9			
	Wind	102	51			
	Small hydro	35	3			
2009	Hydro	2015,7	37	2154	3623,9	161
	Thermal	1132	7			
	Wind	230	115			
	Small hydro	246,2	2			
2009 A	Hydro	2261,9	39	2154	4097,9	163
	Thermal	1606	9			
	Wind	230	115			
	Small hydro	0	0			
2009 B	Hydro	2261,9	39	2154	3821,9	162
	Thermal	1330	8			
	Wind	230	115			
	Small hydro	0	0			
2010	Hydro	2261,9	39	2201	4307,9	230
	Thermal	1307	7			
	Wind	360	180			
	Small hydro	80	3			
	Interconnection	299	1			
2011	Hydro	2341,9	42	2247	4386,9	320
	Thermal	1330	8			
	Wind	528	264			
	Small hydro	187	6			
2011A	Hydro	2528,9	48	2247	4636,9	321
	Thermal	1330	8			
	Wind	528	264			
	Small hydro	0	0			
	Interconnection	250	1			
2012	Hydro	2528,9	48	2293	5343,9	366
	Thermal	2026	10			
	Wind	610	305			
	Small hydro	179	3			
2012A	Hydro	2707,9	51	2339	4923,9	365
	Thermal	1606	9			
	Wind	610	305			
	Small hydro	0	0			
2013	Hydro	2707,9	51	2339	6471,9	375
	Thermal	2660	12			
	Wind	610	305			
	Small hydro	494	7			
2013A	Hydro	3201,9	58	2339	5326,9	372
	Thermal	1515	9			
	Wind	610	305			
	Small hydro	0	0			

A. Results A – Conventional reliability indices

Based on the simulations performed, the values of conventional indices of reliability are summarized in Table II.

Usually there are several standards for LOLE index regarding Static Reserve Evaluation, for instance: in systems predominantly thermal, such as United States of America it is assumed 0,1 day/year. On the other hand, in systems with predominance on hydro units such as Brazil it is assumed 60 hours/year.

For a hybrid systems, such as BH system is, may be assumed 10 hours/year as a reference value. Therefore we can conclude that estimated LOLE for the basic scenario is acceptable.

During 2008, according to the plan, renewable are connected to the network with total power of 137 MW. A peak load is increase on 2108 MW and the estimated LOLE index is increased on 11.37 hours/year.

The scenario 2009 is characterized by contribution of renewable, mainly the wind generations. However, the production from these sources is insufficient to meet the needs of the total load in the system due to the stochastic nature of these sources and the fact that two large conventional units in thermal power plans are unavailable (due to the revitalization). Therefore, the loss of load expectation is very high (176.5 hours/year) and it presents the worst value of all analyzed scenarios. To meet the needs in the system it is necessary to import electricity but it is not a "popular" action in market operating conditions.

The scenario 2009 A is very similar to scenario 2009 except the only one large conventional unit in thermal power plan is on revitalization. LOLE index is decreased from previous case on 12,37 hours/year.

Following the description of the power system in Table I, it is easy to understand reliability indices presented in Table II.

TABLE II
CONVENTIONAL RELIABILITY INDICES

Indicators / Scenarios	LOLP	LOLE (hours/ year)	EPNS (MW)	EENS (MWh/ year)	LOLF (occ./ year)	LOLD (hours)
2006	9.523E-04 (3.63%)	8.342 (3.63%)	8.658E-02 (4.99%)	758.4 (4.99%)	3.102 (2.77%)	2.690 (4.24%)
2008	1.298E-03 (3.50%)	11.37 (3.50%)	0.1227 (5.00%)	1075.2 (5.00%)	4.285 (2.73%)	2.653 (4.14%)
2009	2.015E-02 (3.29%)	176.5 (3.29%)	2.3780 (4.99%)	0.2083E+05 (4.99%)	47.37 (2.44%)	3.726 (3.92%)
2009 A	1.412E-03 (3.49%)	12.37 (3.49%)	0.1392 (5.00%)	1219.1 (5.00%)	4.485 (2.54%)	2.757 (4.07%)
2009 B	6.158E-03 (3.50%)	53.94 (3.50%)	0.6128 (5.00%)	5368.2 (5.00%)	17.70 (2.52%)	3.048 (4.12%)
2010	9.483E-04 (3.43%)	8.308 (3.43%)	8.932E-02 (4.99%)	782.4 (4.99%)	3.088 (2.71%)	2.690 (4.04%)
2011	6.730E-03 (3.29%)	58.96 (3.29%)	0.7477 (4.99%)	6550.1 (4.99%)	18.67 (2.41%)	3.158 (3.86%)
2011 A	7.424E-04 (3.36%)	6.504 (3.36%)	6.900E-02 (4.99%)	604.5 (4.99%)	2.576 (2.47%)	2.524 (3.85%)
2012	1.622E-04 (3.58%)	1.421 (3.58%)	1.533E-02 (5.00%)	134.3 (5.00%)	0.6162 (2.82%)	2.306 (4.09%)
2012 A	1.749E-03 (3.53%)	15.32 (3.53%)	0.1846 (4.99%)	1617.2 (4.99%)	5.616 (2.67%)	2.729 (4.13%)
2013	3.322E-07 (49.40%)	2.910E-03 (49.40%)	1.835E-05 (54.48%)	0.1607 (54.48%)	1.000E-03 (44.70%)	2.910 (48.41%)
2013 A	4.455E-03 (3.64%)	39.03 (3.64%)	0.5098 (4.98%)	4466.1 (4.98%)	12.95 (2.85%)	3.014 (4.37%)

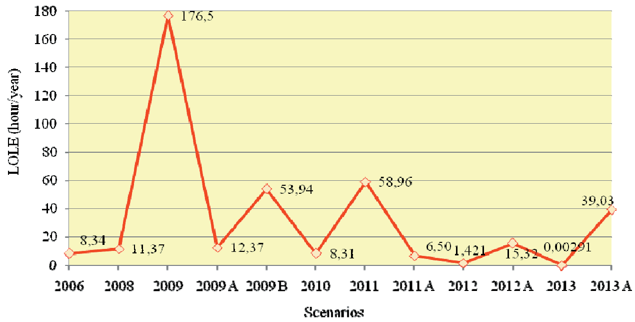

Fig. 3. LOLE index through all the scenarios

Loss of load probability, LOLP, is an indicator of the likelihood that production will be insufficient to settle the load observed for a period of time. At the same time, it is a measure that expresses the level of security of consumers supply, or the amount of undelivered energy in the power system. It should be noted that LOLP can be measured by hourly, daily, weekly, monthly or seasonal reliability. In this case, it is an annual loss of load probability. The largest estimated value is 2.015% for the scenario 2009. This means that the load cannot be satisfied in 2.015% of the total number of hours. The smallest estimated LOLP is $0.3322 \cdot 10^{-6}$ for the scenario 2013. Although this indicator does not indicate the size of the problem, low value of LOLP indicate reliable operation of the system in different scenarios (Fig.4).

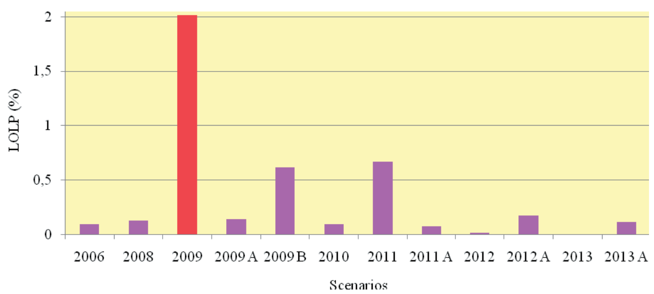

Fig. 4. LOLP indices through all the scenarios

B. *Results B – Well-being indices*

Well-being indices are estimated and analyzed for the same scenarios from the previous case. The well-being indices are presented in the Table III.

The scenario 2009 is identified as a scenario with the worst LOLE and LOLP indices in previous analyze. If we analyze well-being indices for the same scenario, we can say that: the probability of a successful state, P(S), is 90.41%; the expected frequency of occurrences in a successful state, F(S), is 169.2 occ./year; the average duration of stay in a successful state, D(S), is 46.82 hours; the probability that the system is in marginal state, P(M), is 7.598%; the frequency of occurrences in a marginal state, F(M), is 215.2 occ./year and the expected duration of stay in a marginal state, D(M), is 3.092 hours. Expected number of hours in which the system will be in normal state, an indicator of EH, is 7896.2 hours/year, while the expected number of hours in which the system will be in marginal state, an indicator of EM, is 663.8 hours/year. Taking in account the conventional and well-being indices, we can conclude that the system is in a risk state.

TABLE III
WELL-BEING INDICES

Indicators / Scenarios	P(S)	P(M)	F(S) (occ./year)	F(M) (occ./year)	D(S) (hour)	D(M) (hour)	EH (hour/year)	EM (hour/year)	LOLE (hour/year)
2006	0,9908	8,282 E-02	23,70	26,80	366,3	2,707	8004,2	723,5	8,34
2008	0,9889	9,838 E-02	28,53	32,35	303,7	2,664	7865,2	859,4	11,37
2009	0,9041	7,598 E-02	169,2	215,2	46,82	3,092	7896,2	663,8	176,5
2009 A	0,9881	1,019 E-02	29,62	34,28	292,2	2,603	8634,6	89,0	12,37
2009 B	0,9597	3,37 E-02	86,66	105,5	97,01	2,799	8387,8	294,4	53,94
2010	0,9872	1,175 E-02	31,94	35,36	270,7	2,910	8625,1	102,6	8,31
2011	0,9612	3,143 E-02	84,58	103,5	99,55	2,660	8402,6	274,6	58,96
2011 A	0,9926	6,727 E-03	21,30	23,92	408,3	2,464	8670,7	58,8	6,5
2012	0,9949	4,964 E-03	14,46	15,32	602,6	2,839	8691,2	43,4	1,421
2012 A	0,9882	1,037 E-02	32,72	37,66	264,6	2,412	8630,1	90,6	15,32
2013	0,9999	2,192 E-05	9,68 E-02	9,78 E-02	9,049 E+04	1,964	8735,8	0,2	2,91 E-03
2013 A	0,9731	2,267 E-02	61,62	74,74	138,3	2,657	8499,0	198,0	39,03

Well-being indices EH and EM are interacted with conventional index LOLE in each analyzed scenario as it shown in the Fig. 5. The expected hours of staying in the normal state, an indicator EH, is marked in green, the expected hours of staying in a marginal state, an indicator EM, is highlighted yellow and loss of load expectation, LOLE indicator, is marked in red.

Scenarios 2009A, 2010, 2011A, 2012, 2012A and 2013 are the scenarios with high value of indicators EH and low value of LOLE. Therefore, the system is in a comfortable state. Scenarios 2006 and 2008 are scenarios with increased system operation risk, because the system operates with increased hours of stay in marginal condition. The system is unreliable in scenarios 2009, 2009B, 2011 and 2013A, if criteria adopted for the LOLE indicator is up to 10 hours/year. A critical aspect of the scenario 2009 is to satisfy the balance of electricity. Therefore the system will be 663.8 hours/year in a marginal state that is unfavorable for the system.

To reduce LOLE indicator from 175.6 hours/year to 10 hours/year additional 868 MW through the interconnection lines is required in scenario 2009. The estimated reliability indices are valid in the case if the real system operation is very close to the presented plans in [4], [5].

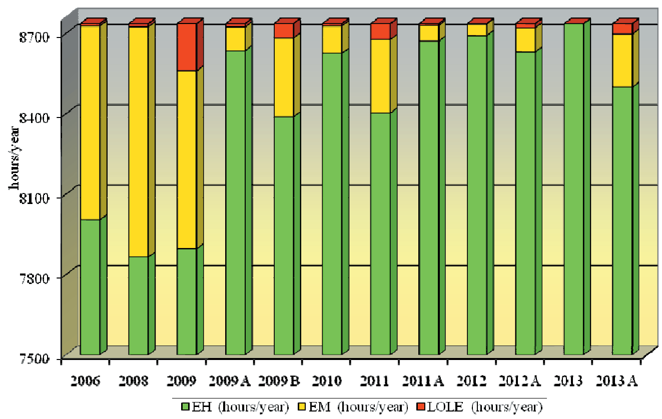

Fig. 5. Well-being indices EH and EM in interaction with LOLE

V. Conclusion

In accordance with the official documents [4], [5] used to get information about new production capacity in the future and to get inputs for the models of productions and load model, four (on the base of 13 scenarios) critical scenarios in BH power system were identified.

Obtained results for conventional and well-being indices signified on the scenario 2009 as one of the worst scenarios. Revitalization of two big generators units would cause imbalance in electricity and needs to import electricity to BH power system through interconnected lines with neighborhood systems regardless of some contributions of renewable energy sources. It was necessary to import 868 MW to reduce LOLE index from 175,6 hour/year to 10 hour/year.

Evan if the modeling and calculations was done with some hypothetical data (mainly related to the meteorological data and parameters FRATE as well as MTTR) obtained results do not deviate a lot from estimated needs for automated secondary regulation (ASR) made by the ISO BH and in accordance with ENTSO-E (former - UCTE) Operational Handbook. The estimated value for 2009 year was 610 MW.

The power system of BH is a part of ENTSO-E block SCB (Slovenia-Croatia-Bosnia and Herzegovina) that helps in own system balancing by neighboring power systems. However, the situation will be more complicate by introducing penalty at the level of ENTSO-E. Therefore, usage of available data and advanced analyses of conventional and "well-being" indices will be very important in market-oriented power system operation.

In general, we can conclude that power system operation in BH is acceptable because the system is in normal state in more than 90% of analyzed scenarios [7]. It can be explained by currently well availability of power sources, but until when?

Production capacities in BH are mainly at the end of life-span. Therefore it is necessary to start building new production capacities like hydro and thermo power plans as well as wind generators and small hydro (renewable). Start-up of the new capacities will influence on reliable operation of power system.

Only safe and reliable electric power system can be a basic condition for establishing the electricity market and a basic condition for safe and reliable supply of connected customers.

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