RELIABILITY MODELING AND SIMULATION OF THE HYBRID POWER SYSTEMS

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Abstract – Valorization wind and solar resources today are considered of special importance to satisfy all sustainable development targets from social and economic point of view. The reliability and availability analysis of the system that utilize that renewable resources has specific aspects, compared to conventional power systems. In this paper the authors present the specificities that must to be take in consideration when analyze a hybrid power system (HPS) in design phase and exemplifies three methods/instruments more suitable for HPS reliability assessments: events and fault tree, equivalent reliability diagram, and Markov chain with continuous parameter. To counter the limitations of traditional reliability analyses authors develop a fuzzy program in MATLAB environment, in the end presenting the conclusions.

Keywords: Previsional reliability, hybrid power system specificity, time safety modeling, fuzzy simulation

1. INTRODUCTION

Hybrid power generation systems (HPS) using wind and solar resources were born from double necessity: first to diminish the negative impact on environment of Diesel groups and second to electrify insulated areas far from national grids (continental or islander) [1, 2].

Due to the fact that the cost of renewable technologies has been reduced recently (especially solar and wind) and many countries provide subsidy for that systems, implementing of them make a very attractive alternative nowadays.

Systems reliability analysis using Monte Carlo simulation method allows adding the variation of intermittent energy sources such as wind speed and solar irradiation [3]. To a more precise assessment of the HPS previsional reliability it is necessary to be known both the nominal reliability indicators of its components and its operational strain conditions [4,5].

Also, there are some factors that affect its subsystem reliability such as:

- Wind speed which influences the reliability of power convertors [6];
- Using reliable components combined with the use of experienced PV designers boost the reliability of PV and INV subsystems [7];
- Infrastructure support is critical: using service technicians experienced with HPS different components (to install and repair HPS subsystems) provides a major boost in system reliability [7];
- Using a proper reliability estimation method may improve assessment accuracy of the reliability indicators of a HPS, which can be a vital help to a system designer [8]-[11].

2. SPECIFICITIES REGARDING HPS RELIABILITY ANALYSIS

Reliability analyses of the HPS are subordinated to the objectives of energy availability correlation with consumer load curve and maximization of the energy capitalization from renewable resources (RR).

Both within the text of this paper as well as in the figures have been used the following acronyms listed in table 1:

Table 1. Significance of the acronym used

Acronym	Significance
WGS	Wind generation subsystem
PVS	Photovoltaic subsystem
BSS	Battery storage subsystem
DS	Diesel subsystem
WT	Wind turbine
SG	Synchronous generator
CV	Converter
PV	Photovoltaic array
MPPT	Maximum power point tracker
DG	Diesel group
INV	Inverter
DAPS	Driving, automation and protection subsystem (system controller included)
B_i	Bus “i”
S	Switching subsystem
IC	Insulated power consumer
PE	Power equipment

Having in view structural and functional specifics of HPS, its related equipments are characterized by intermittent operating regime. Previsional reliability analysis relates to analysis interval T_A and begins with recalculating of failure intensity “λ” indicator values for concrete operating condition of the ”i” subsystem / equipment [12]:

$$\lambda_i = k_{Li} \cdot k_{CFi} \cdot k_{MFi} \, \lambda_{Ni} , \quad (1)$$

Where:

k_{Li} = Correction coefficient related to loading (strain) degree;

k_{CFi} = Correction coefficient determined by climate factors;

k_{MFi} = Correction coefficient determined by microclimate factors;

λ_{Ni} = Failure intensity guaranteed by supplier for nominal (standard) functioning condition.

In case of intermittent functioning mode the equipment strain is differentiated during the three regimes thus:

- Transient (starts-stops) → characterized by overstressing;
- Stabilized functioning in load → characterized by PE strain variation from nominal power to a part of nominal value (fixed by solar irradiance value and/or wind speed value);
- Stagnation → for irradiance / wind speed increases (waiting), case in which PE are under strained or completely unstrained.

For DAPS within HPS we neglect reliability indicators variations with strain level, considering K_{li} = 1 whatever mode and functioning regime. For PE the strain degree is differentiated during stabilized regimes.

To exemplify the reliability analysis methodology we consider a HPS wind – solar – Diesel type (HPS-WSD) having the functioning scheme represented in figure 1:

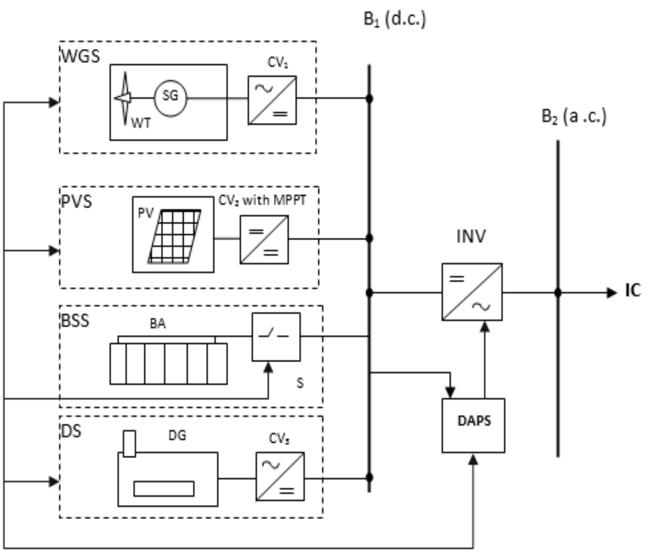


Fig. 1. HPS block diagram utilized in reliability modeling exemplification

For PE of HPS from figure1 the strain level is depending of the functioning regime which is synthesized in table 2.

For PE inscribed in table 2, "k_{Li}" coefficient is different in the two regimes, so we can proceed in two ways:

- On determine first the medium value of "k_{Li}" and then the medium value of "λ_i". In this case we work as in case of HPS with continuous operation;
- On determine the following two values of the "k_{li}" coefficient:
  - ➢ k_{Li}^{L} = The value of load factor in load;
  - ➢ k_{Li}^{WL} = The value of load factor in waiting regime.

Table 2. PE strain characteristic during stabilized regime of the HPS

HPS regime / PE	Load operation			Complete stagnation (waiting)	Power storage	
	With RS*	With BA	With BA and DG		From RR	From DG
WGS (WT+CV1)	Normal strain	Mechanical strain	Mechanical strain	Mechanical strain	Normal strain	Completely unstrained
PVS (PV+CV2)	Normal strain	Completely unstrained	Completely unstrained	Completely unstrained	Normal strain	Completely unstrained
DS (DG+CV3)	Completely unstrained	Completely unstrained	Normal strain	Strained in voltage	Completely unstrained	Normal strain
BSS (BA+S)	Strained in voltage	Normal strain	Normal strain	Strained in voltage	Normal strain	Normal strain
INV	Normal strain	Normal strain	Normal strain	Completely unstrained	Completely unstrained	Completely unstrained
B1	Normal strain	Normal strain	Normal strain	Strained in voltage	Normal strain	Normal strain
B2	Normal strain	Normal strain	Normal strain	Completely unstrained	Completely unstrained	Completely unstrained

* RS = renewable subsystems of the HPS (WGS and PVS)

Thus we obtain the values of "λ_i" indicator in two cases:

▪ For load operating:

$$\lambda_{Li}^{L} = k_{Li}^{L} \cdot k_{CFi} \cdot k_{MFi} \cdot \lambda_{Ni} \quad (2)$$

▪For waiting regime:

$$\lambda_{Li}^{WL} = k_{Li}^{WL} \cdot k_{CFi} \cdot k_{MFi} \cdot \lambda_{Ni} \quad (3)$$

The "i" elements from table 2 will be treated in this second case like two fictive series elements having the following failure intensities:

$$\lambda_i^{L} = \frac{T_L}{T_A} \lambda_{Li}^{L} \quad ; \quad \lambda_i^{WL} = \frac{T_{WL}}{T_A} \lambda_{Li}^{WL} \quad (4)$$

For PE of HPS which operates in intermittent regime *i*, it justifies utilizing a third value for fault intensity of equipment:

$$\lambda_i^{T} = k_{Li}^{T} \cdot k_{CFi} \cdot k_{MFi} \cdot \frac{T_T}{T_A} \cdot \lambda_{Ni} \quad (5)$$

Where:

T_T = Transient time interval;

k_{li}^{T} = Load factor (overstrained) in transient regime.

In reliability analysis the PE can be treated, depending on available calculus elements:

- As being composed from three fictive elements, having three fault intensities, corresponding the three operating regime: load, waiting and transient ($\lambda_i^{L}, \lambda_i^{WL}, \lambda_i^{T}$);
- As a one equivalent element having fault intensity "λ_i".

Considering the fact that often the microclimate factors affect HPS maintenance, it is justified to perform correction on "maintenance intensity" factor:

$$\mu_i = \frac{\mu_{Ni}}{k_{CFi} \cdot k_{MFi}} \quad (6)$$

The reliability of the auxiliary HPS components is not affected by its operating mode.

3. EXAMPLES OF MODELING TIME SAFETY OF THE HPS

For HPS time safety (R_T) assessment we take into consideration the technological scheme (shown in figure1) and the following widely accepted hypothesis [12,13]:

- It is known the functional level for which the modeling has to be done;
- It is known the reliability indicators for elements of HPS structure (λ_i, μ_i), adjusted for concrete operating conditions;
- HPS components and structural subsystems are considered independent from reliability point of view;
- Considering the relatively high reliability level of the components within HPS structure, in many applications are neglecting the probability of double faults;
- The reliability level of DAPS, BA charger, d.c. and a.c. buses is superior to reliability level of the HPS power sources and therefore these components are not highlighted in its structural details.

In these conditions, the most appropriate methods for HPS time safety modeling are: events and fault tree analysis (FTA), reliability block diagram (RBD) and Markov chain with continuous parameter. We take into account the values for mean time between failures (MTBF) and mean time of maintenance (MTM) of each equipment, which can be found in [13]-[17] and synthesized in table 3. Numerical values obtained for HPS subsystems are presented in table 4.

Table 3. MTBFand MTM sets of values

	PVS	INV	BSS	DS	WTG
MTBF	10 years	1,5 years	5 years	1000 h	2400 h
MTM	40 days	40 days	40 days	60 days	60 days

Table 4. Values obtained for HPS elements

HPS Subsystem	λ_i [x10^{-4} h^{-1}]	μ_i [x10^{-4} h^{-1}]	F_i
WGS	4,166	6,944	0,011
PVS	0,114	10,416	0,375
BSS	0,232	10,416	0,022
DS	10	6,944	0,590
INV	0,76	10,416	0,068

A. Events and fault tree analysis (FTA) method:

Making the HPS configuration with BSS and DS as backup subsystems, we consider two more hypotheses:

- This one's two categories of generating subsystems (RS=WGS+PVS) and (RZ=BSS+DS) are sized for 100% level, namely to cover the peak power requested by IC;
- Because in this frame we fallow the time safety assessment we consider only the intrinsic safety of the HPS components.

The FTA of the HPS is presented in figure 2.

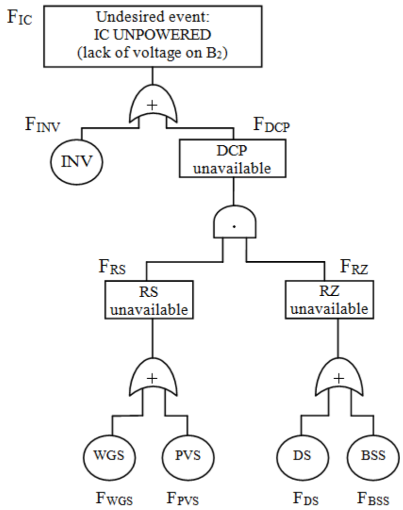
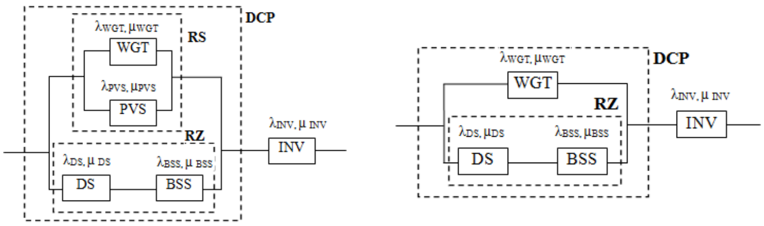


Fig. 3. Fault three of the HPS-WSD in RZ=DS+BSS configuration

With data from table 4 we obtained F_{IC} = 0,07. Other reliability indicators we can calculate, considering analysis period of T_A = 8760 hours, are: Reliability R_{IC} =1-F_{IC} = 0,93; Total time of good functioning $\alpha_{IC}(T_A) = R_{IC} \cdot T_A$ = 8146,8 hours; Total time of no functioning $\beta_{IC}(T_A) = T_A - \alpha_{IC}(T_A)$ = 613,2 hours.

B. HPS assessment based on reliability blocks diagram (RBD) method:

Due to the fact that PVS is not available during the night, HPS configuration changes, so there will be two reliability block diagram as shown in figure 4.



a) HPS_{day} b) HPS_{night}

Fig. 4. Day (a) and night (b) configuration of the HPS

The equivalent HPS consist from the two series elements corresponding the day and night time configuration. Solving these schemes is done easy. By successive reductions and supposing that λ and μ is constant, we can write the equivalent fault and ıaintenance intensities with consecrate formulas [12], umerical results being presented in table 5:

C. Markov chain with continuous parameter ИCC) method

For HPS structure considered in figure2 pplying MCC are done considering the well known ypothesis [12], [13], [19]. The HPS-WSD type is graphically reduced by RBD instrument, considering day time configuration as shown in figure 4 and analytically by applying relations from [12]. For DG from DS, fault intensity in "starting refusal" is calculated taking into account that repair intensity is the same when DG passes from "fail in operation" state or from "fail in starting" state. From [16] it is known that R_{DG} = 0,99 and considering MTM_{DG} = 60 days = 1440 h [16], results:

$$\mu_{SD} = \mu'_{SD} = \frac{1}{1440} = 6{,}99 \cdot 10^{-4} \;;$$

$$R_{SD} = \frac{\mu'_{SD}}{\lambda'_{SD} + \mu'_{SD}} = \frac{\mu_{SD}}{\lambda'_{SD} + \mu_{SD}} = 0{,}99 \quad \Rightarrow \quad \lambda'_{SD} = \frac{\mu_{SD} - 0{,}99\mu_{SD}}{0{,}99} \qquad (7)$$

Taking into account that HPS subsystems cam be in three states (normal operation-N, failure-F and reserve-RZ) and based on states graph, the matrix of transitions will be written taking into account the rules of their formations [13], [14]. By resolving the linear equation of the system [12], [13] we found the probability of each state (P_0, P1, P_2, P_3).

With the probability of each state we calculate the reliability indicators for DCP and having the reliability indicators for INV we can calculate reliability indicators of HPS using RBD instrument (as DCP and INV being two series elements), numerical results being presented in table 6:

Table 5. Values obtained applying RBD instrument

Reliability indicators	Units	Values obtained
λ_{HPSday}	$[h^{-1}]$	$8{,}189 \cdot 10^{-5}$
μ_{HPSday}	$[h^{-1}]$	$1{,}086 \cdot 10^{-3}$
$\lambda_{HPSnight}$	$[h^{-1}]$	$3{,}994 \cdot 10^{-4}$
$\mu_{HPSnight}$	$[h^{-1}]$	$1{,}323 \cdot 10^{-3}$
λ_{HPSe}	$[h^{-1}]$	$5{,}572 \cdot 10^{-4}$
μ_{HPSe}	$[h^{-1}]$	$1{,}282 \cdot 10^{-3}$
$MTBF_{HPSe}$	[h/y]	1795
MTM_{HPSe}	[h/y]	780,284
R_S	-	0,697
F_S	-	0,303
$\alpha_{HPS}(T_A)$	[h]	6105
$\beta_{HPS}(T_A)$	[h]	2655
$\nu_{HPS}(T_A)$	[in./y]	3,402

Table 6. Values obtained applying MCC method

Reliability indicators	Units	Values obtained
P_0	-	0,405
P_1	-	$1{,}650 \cdot 10^{-3}$
P_2	-	0,592
P_3	-	$2{,}772 \cdot 10^{-3}$
R_S	-	0,977
F_S	-	0,023
$MTBF_{HPS}$	[h/y]	$3{,}383 \cdot 10^{4}$
MTM_{HPS}	[h/y]	798,853
$\alpha_{HPS}(T_A)$	[h]	8558
$\beta_{HPS}(T_A)$	[h]	202
$\nu_{HPS}(T_A)$	[in./y]	0,253

4. RELIABILITY SIMULATION OF THE HPS BASED ON FUZZY MODEL

Analyze of the HPS operating behavior is difficult because comprise three factors of uncertainty: random characteristic of RR (solar and wind), random characteristic of load and random characteristic of time of good functioning and time of corrective maintenance.

Implementing fuzzy model for the HPS scheme from figure 2 imply covering three steps [20]: preparing fuzzy analysis, generating the source code of fuzzy program and analysis the data obtained by running the program.

S1) Preparing fuzzy analysis: consist in six phases synthesized in figure 5:

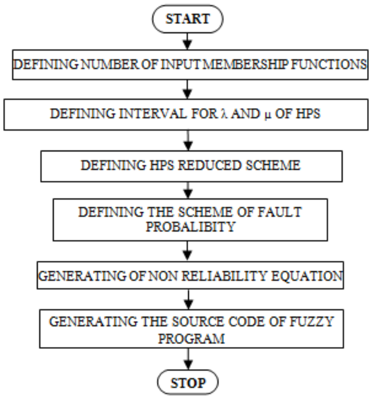


Fig. 5. Phases of fuzzy preparation

We consider it would be more appropriate to utilize Gauss membership functions instead trapezoidal or triangular (widely used for calculating and interpreting reliability data [21]). For this type of function must specify central value and standard deviation (σ). For each HPS component (WGS, PVS, BSS, DS, INV) have been defined seven linguistic degrees on a linear interval for the indicators intensity of fail and intensity of repair (λ_i, μ_i): from unsatisfactory (U), to very good (VG). To establish the variation interval for (λ_i, μ_i) was taken into account of MTBF and MTM values find in [14]-[18]. In results, the minimum and maximum values for (λ_i, μ_i) for the five HPS components are calculated. To reduce the HPS scheme we utilize the RBD instrument and to assess HPS probability of failure we utilized FTA method.

S2) Generating the source code: has been made in MATLAB programming environment, these featuring predefined functions in realize the different stage of fuzzy calculus: fuzification, inference, defuzyfication. The fuzzy simulation program has followed the steps contained in the logic scheme presented in figure 6. The center of input membership functions are computed for F_i, where i = 1 …7 is the number of membership function corresponding the linguistic degree previously defined. Standard deviation (σ) is computed for asymmetric Gauss function.

After computing membership functions characteristics of the HPS system, the program generates these functions and displayed in separate windows. In module "generating the rules sets", these rules are under the form of logic equations, having as variables the linguistic degree of the inputs and as operators the logic operators "and" and "or". In this case we choose the fallowing sets of fuzzy rules for every seven linguistic degree: "If (element_1 is VG) and (element_2 is VG) and (element_3 is VG) and (element_4 is VG) and (element_5 is VG) then (system is VG)".

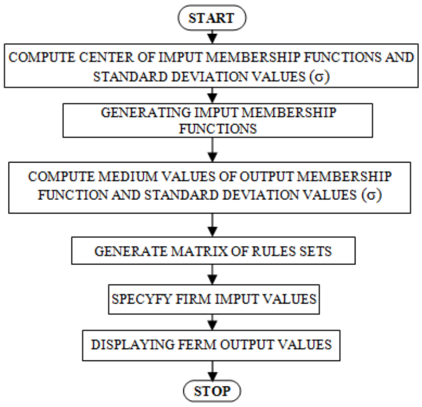


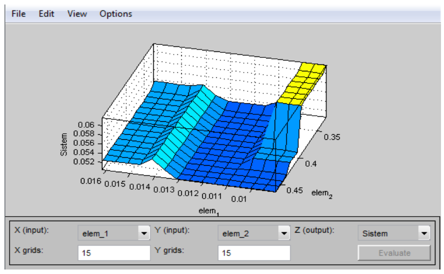
Fig.6. Logic scheme of fuzzy modeling program

S3) Analysis the data obtained by running the simulation program:

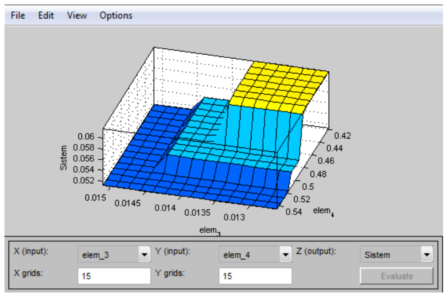
Launching the program from main module entitled "d_fuzzySH1.m" lead to a graphical window appearance, with virtual buttons as shown in figure 7.

Fig. 7. Snapshot of the main graphic interface

Pressing the "Specification domain λ and μ" button will appear an editing window in which is introduced the minim and maxim values of λ and μ from each HPS components, calculated in (P1). Pressing the "Specification inputs" button results a new window called "Specification of simulation data" in which the program computes non reliability values of each HPS component with the values of λ and μ previously entered. Result a non reliability interval [F_1, F_2] for each HPS component. In the "Inputs" column are computed the values of membership functions centers, this column being also an editing window in which we can introduce specific values for F, previously calculated for each HPS component. After introducing the new F values is pressed "Saving data" button, the data is saved in a separate MATLAB file which can be called whenever needed. Choosing "Fuzzy simulation" option the program generates input membership functions for each HPS component and computes the output membership function for the system. In a separate window is computed non reliability of the HPS. Choosing "Decision surfaces" option, the program generates inference surfaces based on the rules defined in "d_fuzzySH1.m" module. We obtained 3D representations in which are distinguished the dependency of HPS non reliability according to two of its subsystem non reliability from five considered elements. These surfaces is depending on two inputs, at choice, the other three inputs being considered constant. Exemplifications are presented in figures 8, 9. In case of HPS analyzed in this paper results non reliability of the system depending on two elements from a total of five.

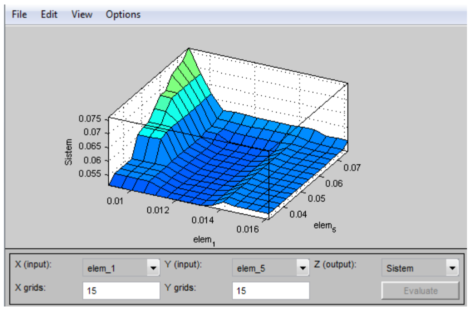


a) HPS non reliability depending on WGS and PVS

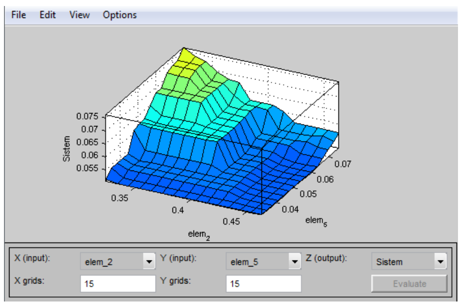


b) HPS non reliability depending on BSS and DS

Fig. 8. HPS non reliability simulations in case of both RR are available (a) and non available (b)



a) HPS non reliability depending on PVS and INV



b) HPS non reliability depending on WGS and INV

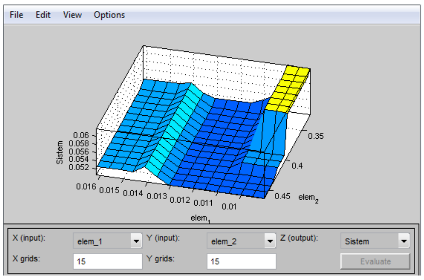
Fig. 9. HPS non reliability simulations in case of one of the RR are available: (a) solar (b) wind

In case of modification MTBF and MTM sets of values, the program need no modification, but the new values of λ and μ must be introduced and saved from the same graphic interface with virtual buttons (figure 7). For example we modified λ of the HPS components according to MTBF changes [13]-[17], the new values being presented in table 7.

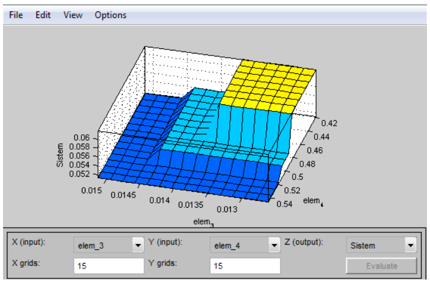
Table 7. New values of MTBF within HPS

	PVS	INV	BSS	DS	WTG
MTBF	15 years	5 years	7 years	1500 h	2400 h
MTM	40 days	40 days	40 days	60 days	60 days

Non reliability of the system depending on two elements from a total of five is obtained by running the simulation program, the 3D graphic results being presented in figure 10 and 11.

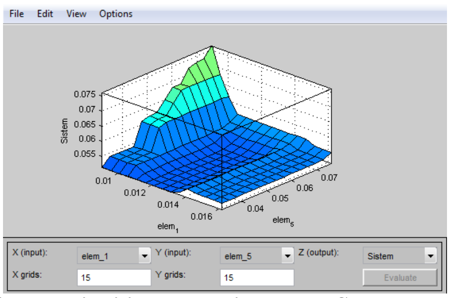


a) HPS non reliability depending on WGS and PVS

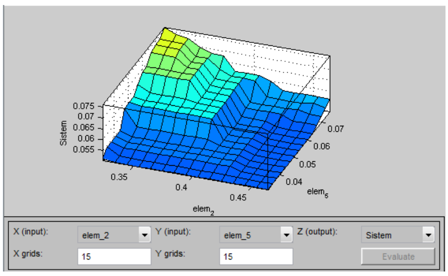


b) HPS non reliability depending on BSS and DS

Fig. 10. HPS non reliability simulations in case of both RR are available (a) and non available (b)



a) HPS non reliability depending on PVS and INV



b) HPS non reliability depending on WGS and INV

Fig. 11. HPS non reliability simulations in case of one of the RR are available: (a) solar (b) wind

5. CONCLUSIONS

For the study of HPS previsional reliability is recommended resorting to the following representation technique: events and fault tree, reliability block diagram and state graph. Modeling and assessment of HPS previsional reliability is made having in consideration the following two specificities: the different strain degree between the two operating mode of the HPS (continuous and intermitted) and the existence of adjusting, protection and automation loops within DAPS.

HPS reliability in configuration with RZ consists from BSS and DS is above 0,9.

Reliability of the HPS assessed with RBD instrument is slightly different from reliability analyzed with other three methods due to the fact that in RBD instrument we take into account the different configuration of the system during day and night.

Applying fuzzy theory to HPS reliability consist in availabilities to quantify and to model qualitative announcement - possible altered by incomplete information and subjectivism – in flexible forms as close as possible to the thinking of modern engineer which operate with these. The fuzzy simulation program of HPS reliability allow to brows all the steps of fuzzy modeling and it is made in a versatile manner, orientate to object, modular. It is possible to generate decision surfaces for any HPS configuration, in this paper we choose a RZ=BSS+DS one, the decision surfaces is possible to represent in case of both availability of RR and unavailability of RR. It is notice that HPS non reliability in case of available RR is similar to HPS operating in PVS and INV configuration. Also HPS non reliability in case of operating with RZ is similar to HPS operating with WGS and INV configuration. Fuzzy modeling program can be applied to any HPS configuration with minimum modification of the reduced scheme and non reliability equation. With chosen MTBF and MTM values of HPS components we obtain with fuzzy method the results of F_{HPS} =0,056 and R_{HPS}=0,944.

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