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***Abstract*— In restructured power systems, generation and commercialization activities became market activities, while transmission and distribution activities continue as regulated monopolies. As a result, the adequacy of transmission network should be evaluated independent of generation system. After introducing the constrained fuzzy power flow (CFPF) as a suitable tool to quantify the adequacy of transmission network to satisfy "reasonable demands for the transmission of electricity" (as stated, for instance, at European Directive 2009/72/EC), the aim is now showing how this approach can be used in conjunction with probabilistic criteria in security analysis. In classical security analysis models of power systems are considered the composite system (generation plus transmission). The state of system components is usually modeled with probabilities and loads (and generation) are modeled by crisp numbers, probability distributions or fuzzy numbers. In the case of CFPF the component's failure of the transmission network have been investigated. In this framework, probabilistic methods are used for failures modeling of the transmission system components and possibility models are used to deal with "reasonable demands". The enhanced version of the CFPF model is applied to an illustrative case.**

Keywords*— Adequacy, constrained, fuzzy power flow, repression, reasonable demands transmission, severity

I. INTRODUCTION

The studies of the transmission system adequacy usually consider the generation system. The assessment of the transmission system integrating the generation system has been described in the literature for *composite power system evaluation* or b*ulk power system evaluation*. This type of assessment, integrating the two systems, was due to the organization of the electrical sectors that traditionally were a vertical structure where a single entity managed the generation, transmission (and distribution) systems. According to some references [1][2][3], the assessment of an electrical system, can be structured in hierarchical levels (HL): HL1 (production facilities); HL2 (transmission plus generation facilities); HL3 (generation, transmission and distribution facilities).In the case of the composite system, the hierarchical level to be considered is the HL2.

The first techniques and criteria used in the planning of electrical systems are deterministic. In deterministic criteria and for composite system, the system performance is evaluated by different scenarios (congestion of a transmission line, loss of the higher generation unit, system peak load) representing the operating conditions. These conditions may or may not be severe. This severity depending on the criteria is defined for each scenario whether or not satisfied. In the composite system, the most popular deterministic criterion is the criterion (N-1), wherein the system should be able to tolerate the outage of any component [4]. Deterministic models are characterized by their easy implementation but also have important disadvantages. For instance, these methods do not consider the probability of occurrence of contingencies, generation or load variations in the buses (uncertainty). This feature led to the development of techniques based on probabilities, considering the probabilistic or stochastic nature of the composite system behavior. There were thus carried out: techniques for reliability analysis [5]; probabilistic power flow [6]. This type of tools considers probabilistic models for: components failures, generation and load in the buses. Later and following the restructuring of the electricity sector were also developed techniques for evaluation of the composite system considering fuzzy sets. They have also been developed: the fuzzy power flow [7]; techniques for reliability analysis [8]. In this type of techniques it is possible to identify the coexistence of the two methodologies. For instance, in the case of evaluation of reliability is usual to use probabilistic models for the components and models based on fuzzy sets for the load and generation in the buses. Note that there is also literature with fuzzy modeling of the components [9][10].

The composite system should be able to supply the load safely and more economically as possible. This aspect has led to the development of another tool that allows the adequacy assessment, the optimal power flow (OPF) [11][12]. This is an optimization problem where the objective functions to be minimizes are typically refer to economic issues such as production costs in generators, losses, load shedding, etc. The OPF has also a fuzzy version known as Fuzzy Optimal Power Flow (FOPF) [13].With the evolution of the electricity sector has given the separation of production, transmission and distribution activities. With the production activity subject to competition and the transport activity being a monopoly, came the need to assess the adequacy of transmission system individually. This "new" context suggests the creation of independent hierarchical levels for the transmission and distribution systems: HL2 'and HL3', respectively. In the situation of European networks, in agreement with the Directive 2009/72/EC, each Transmission System Operator (TSO) should ensure “long term ability of the system to satisfy reasonable demands for the transmission of electricity”. This means that the TSO should ensure a minimum level (set by regulators) of adequacy for the transmission network. To evaluate this adequacy the TSO may have to deal with events like microgeneration, electric vehicles penetration (at distribution levels) [14], where there is no data, lack of data or that simply cannot be described by probability distributions. Thus it is usual to have probabilistic models for the components (where there is full knowledge) and can be considered fuzzy models for other variables (generation and load). One of the proposed models to address the adequacy of transmission network (exclusively) and dealing with fuzzy uncertainty was the Symmetric / Constrained Fuzzy Power Flow (SFPF / CFPF) [15] [16] [17]. Also, the SFPF / CFPF models are appropriate to quantify the adequacy of transmission network to fulfill "reasonable demands for the transmission of electricity.

In this paper, we propose the use of SFPF/CFPF considering probabilistic data for the components of the transmission system (HL2’ perspective) and loads (and generation) modeled by fuzzy numbers. The remainder of this paper is organized as follows: section II presents a review of the SFPF/CFPF approaches; section III explains the CFPF integration in probabilistic security analysis; section IV provides an illustrative case considering a states enumeration method; the conclusions (section VI) complete the paper.

II. SFPF/CFPF

A. *Formulation*

The SFPF model is a linear programming problem that, for each α-level and for all possible values of the external variables (degree of membership ≥ α), calculates the maximum and minimum values of the state variables. In SFPF, no slack bus is demarcated and the “reasonable demands” as stated by the European Directive 2009/72/EC (fuzzy data injections) are considered for all the buses. In this way that means that all the buses are symmetrical) [15][16]. The formulation of the problem is:

$$\begin{array}{lll} \max/\min & \tilde{Z}(\alpha) = f(P_1, P_2, \ldots) & \\ st: & P_i \in \tilde{P}_i(\alpha) & \textit{all buses } i \\ & \sum_i P_i = 0 & \end{array} \quad (1)$$

where $\tilde{P}_i(\alpha)$ is the α-level interval of the nodal injected power $\tilde{P}_i$.

The SFPF may be extended in order to consider the technical constraints related to voltage limits on buses and power flow limits on the branches (CFPF). In this case, the additional constraints presented in (2) are added to the problem offered in (1).

$$\left| A.P \right| \leq P_{LIM} \qquad (2)$$

where A is the sensitivity matrix of the DC model, *P* the vector of P_i, and P_{LIM} is the vector of the branch limits.

This new formulation allows the identification of situations of repression of the injected fuzzy power (intended injections – “reasonable demands”) in each bus. This means that the intended injections cannot be satisfied causing problems that we define as repressions. These repressions occur in generation or load requests and lead naturally to the restraining of the functioning of the electricity market). Whenever there is a repression means that there is a problem of adequacy of the transmission network.

B. *System adequacy indices*

The adequacy of the transmission network to “satisfy reasonable demands for transmission of electricity” can be “measured” using the subsequent indexes [17]:

- Individual Severity of Repression (ISR) – this index denotes the repressed fuzzy power injection at each bus (expressed in MW). This index corresponds to the active power demand that cannot be supplied in each individual bus.
- Global Severity of Repression (GSR) - sum of the individual active fuzzy injections that cannot be achieved (expressed in MW). This index returns the total repression in the network due to technical limitations.

Fig. 1 [17] offers an example of ISR for a generic bus. The area X in the figure corresponds to the severity of repression (10.3 MW, 100 MVA base).

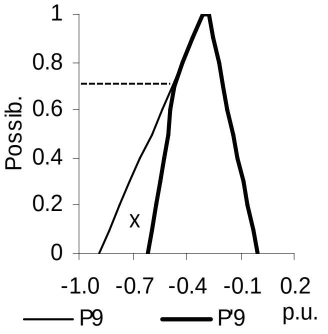

Fig. 1. Repressed demand in a generic bus

III. CFPF INTEGRATION IN PROBABILISTIC SECURITY ANALYSIS

A. *Data*

In classical security analysis considering probabilistic criteria is used composite system evaluation. The system states including the elements of generation system (generators) and elements of the transmission system (lines, transformers) are considered here. In this situation, each system state can be set by (3) where p values are related to components of the transmission system and n-p are related to the generation system components.

$$X = \lfloor x_1\ x_2\ ....\ x_p\ x_{p+1}\ ...\ x_n \rfloor \qquad (3)$$

Applying the Method of Monte Carlo, MMC (with CFPF), would be randomly chosen only states on the transmission system so that the set of states X' where the system may reside, will be significantly reduced (4):

$$X' = \lfloor x'_1 \ldots x'_p \rfloor \qquad (4)$$

For each sampled state x' can be obtained a fuzzy index (the *global repression* - $\tilde{GR}$) and a deterministic index (the G*SR*). The GR index can be calculated for each bus of the network using deconvolution of fuzzy numbers which is defined by the extension principle [18]. The GSR index, as mentioned (previous section) can be calculated from the sum of all areas related to the repression situations on each bus. Integrating CFPF with probabilistic criteria (wherein each state in which the system resides have a certain probability), one can get the expected membership function for GR and the expected GSR.

For small systems, the expected value of $\tilde{GR}$ and GSR can be given respectively by (5) and (6) where $p(x_i)$ is the probability of the state *i* of the system.

$$E\left(\tilde{GR}\right) = \sum_{i=1}^{p} \tilde{R}(x'_i).p(x'_i) \qquad (5)$$

$$E(GSR) = \sum_{i=p+1}^{p} GSR(x'_i).p(x'_i) \qquad (6)$$

For large scale systems MMC can be used to sample the states. In this case, the expressions (5) and (6) will change, to (7) and (8), respectively.

$$\hat{E}\left(\tilde{GR}\right) = \frac{1}{N}\sum_{i=1}^{N} \tilde{R}(x'_i) \qquad (7)$$

$$\hat{E}(GSR) = \frac{1}{N}\sum_{i=1}^{N} GSR(x'_i) \qquad (8)$$

where N is the size of the sample.

Considering for instance the GSR index, the convergence of MMC [1] is analyzed by monitoring the uncertainty coefficient provided by (9). E(GSR) denotes the current estimate of expected GSR value. V(GSR) (11) is the correspondent variance. The same analysis can be done for GR index.

$$\beta^2 = \frac{V(\hat{E}(GSR))}{E(GSR)^2} \qquad (9)$$

$$\hat{V}(GSR) = \frac{1}{N-1}\sum\left(GSR(X_i) - \hat{E}(GSR)\right)^2 \qquad (10)$$

$$V(\hat{E}(GSR)) = \frac{\hat{V}(GSR)}{N} \qquad (11)$$

IV. ILLUSTRATIVE EXAMPLE

A. *Test system*

The IEEE 14 bus/20 branch test system, depicted in Fig. 2, is used to illustrate how CFPF can be used in conjunction with probabilistic criteria in security analysis. In this illustrative case, the transmission system adequacy is analyzed using GSR index.

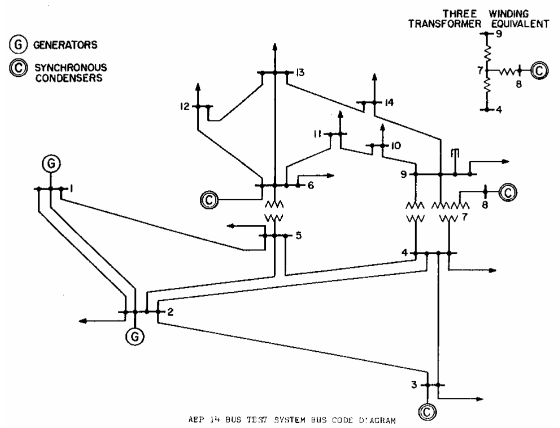

Fig.2. IEEE 14 bus reliability test system

The system data can be found in [19], in which the active power values will be assumed as the central values of the trapezoidal fuzzy numbers. The outstanding characteristic points of such numbers of the central values are supposed as showed at Table I.

TABLE I. CHARACTERISTIC POINTS OF FUZZY DATA

Buses	**Active generation**			
All	0.0	0.8	1.2	2.0
	Active load			
All	0.1	0.5	1.5	2.5

The large α=0 intervals are used to enhance the repression situations. The IEEE 14 bus test system [19] does not present branch limits. Hence, reasonable values for those limits were established (Table II) to be used thru the CFPF. In a real system, the transmission operator would present the values of such limits. A power base of 100MVA is used.

TABLE II. BRANCH LIMITS

End Buses	**Limit (p.u.)**	**End buses**	**Limit (p.u.)**	**End buses**	**Limit (p.u.)**
1-2	2.50	4-7	0.70	7-9	0.80
1-5	1.80	4-9	0.35	9-10	0.25
2-3	1.10	5-6	0.90	9-14	0.20
2-4	0.90	6-11	0.25	10-11	0.20
2-5	0.90	6-12	0.25	12-13	0.06
3-4	0.50	6-13	0.45	13-14	0.15
4-5	1.10	7-8	0.50		

B. *State Selection*

Of the several existent techniques for states selection (where is included the MMC [2]) we will use for evaluate the GSR of the transmission system, the *states enumeration method*. In this method, the probabilistic indexes are estimated for a set of states of the system using the expected value definition as detailed in (6).

In the sates enumeration method, the set of enumerated states is defined according to the following criteria: a) order of contingency: enumeration of all contingencies in which the number of components out of service is less than or equal to a maximum specified order; b) minimum value for the probability of a state: despise all states with lower probability than a specified value; c) a combination of criteria (a) and (b). Improvements of these methods consider: sort contingencies according to their severity, classification of states in descending order of probability and grouping of identical components [20].

The state enumeration is a direct extension of the N-1 criteria used in many companies of the electrical sector. In this method it is possible to incorporate the user experience in the selection of contingency states [21]. To take an example, in Portugal, the TSO uses in its planning studies the following topological configurations: i) Criterion N (all network elements in service); ii) N-1 criterion (failure of any element of the transmission network): line, transformer, capacitor bank, etc; iii) N-2 criteria (simultaneous failure of two elements of the transmission network). This contingency arrangement (N-2) is not applied to the entire network and evaluates only the most severe situations.

In our case study we will use these criteria considering the data (supposing available from experts) according to Tables III and IV.

TABLE III. OUT OF SERVICE PROBABILITIES

Type of branch	**Individual out of service probability**
Lines	0.03
Substations	0.01

TABLE IV. CRITERIAS

Criteria	**Branches**
N	all
N-1	all
N-2	1-2; 7-9
N-2	1-2; 4-9
N-2	2-3; 6-13

C. *CFPF – base case*

The CFPF was applied to the 14 bus test system corresponding this simulation to the base case (BC) (solving the optimization problem of (1) and (2)), supposing the data present on Tables I and II. The results (Table V) show the existence of three situations of repression, which allow recognizing the buses where the specified power injections (Pi) are not feasible. This means that the transmission network is not completely adequate regarding the reasonable requests of generation (bus1, Fig.3) and load (buses 3 and 14, Fig. 4). At results, P_i values are the “reasonable demands” (specified possibility distributions - intended injections) for each bus including the reference bus and P_i’ values are the possibility distributions obtained with CFPF (1) (2). Figure 4 shows the worst situation of inadequacy, which occurs on the bus 3 and corresponds to an ISR of 30.3 MW. Considering that the GSR index has the value of 43.3 MW, we can conclude that the repression at bus 3 represents a serious local situation of inadequacy.

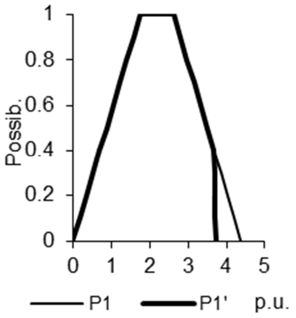

Fig.3. Repression of generation at node 1

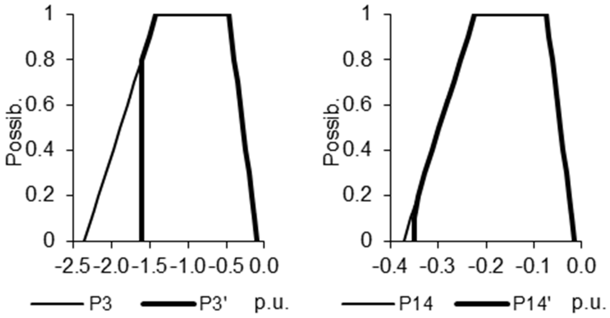

Fig.4. Load repression at nodes 3 and 14

TABLE V. SEVERITY OF REPRESSION

Bus	**ISR (pu)**
1	0.129
3	0.303
14	0.002
GSR (p.u.)	0.433

D. *System security – simulation*

Now we will consider the states and their respective probability as enunciated at Tables III and IV. The states enumeration according to Table III leads us to consider 24 states (12) for the transmission network:

$$X' = \left[x'_1 \ldots x'_{24} \right] \qquad (12)$$

For each state, the respective probability of occurrence and the ISR is calculated using the CFPF (1) (2). As state enumeration is considered, the expected GSR is obtained from (6). The expected global severity of repression will be 49.73 MW.

TABLE VI. EXPECTED GSR (PU)

State (x')	Out of service	GSR (x'i) (pu)	p(x'i)	E[GSR (x'i)] (pu)
1	------	0.4332	0.5781	0.2505
2	1-2	2.5324	0.0179	0.0453
3	1-5	1.3085	0.0179	0.0234
4	2-3	1.9474	0.0179	0.0348
5	2-4	0.4332	0.0179	0.0077
6	2-5	0.4328	0.0179	0.0077
7	3-4	0.9146	0.0179	0.0164
8	4-5	0.6624	0.0179	0.0118
9	4-7	0.4440	0.0058	0.0026
10	4-9	0.4332	0.0058	0.0025
11	5-6	0.8157	0.0058	0.0048
12	6-11	0.4362	0.0179	0.0078
13	6-12	0.4974	0.0179	0.0089
14	6-13	0.6203	0.0179	0.0111
15	7-8	0.4332	0.0179	0.0077
16	7-9	0.4440	0.0179	0.0079
17	9-10	0.4357	0.0179	0.0078
18	9-14	0.5785	0.0179	0.0103
19	10-11	0.4339	0.0179	0.0078
20	12-13	0.4333	0.0179	0.0077
21	13-14	0.5309	0.0179	0.0095
22	1-2, 7-9	2.5421	0.0006	0.0014
23	1-2, 4-9	2.9283	0.0002	0.0005
24	2-3, 6-13	2.2277	0.0006	0.0012
			E (GSR)	0.4973

An interesting point is that besides this global indicator E(GSR) from the network on the reasonable requests, one can also obtain a local indicator for the buses. At this estimation might call individual expected severity of repression E(ISR). For each bus *j* with repression, the expected ISR will be (13):

$$E\left(ISR_j\right) = \sum_{i=p+1}^{p} ISR(x'_i).p(x'_i) \qquad (13)$$

The results expected for the IRS are illustrated in Fig.5. As can be seen the bus that most contributes to the expected GSR is bus 3 with an expected ISR of 0.3057 pu. Figure 6 illustrates the type of results that can be obtained for the injected power in situations of contingency. Pi and Pi 'have the usual meaning and Pi', i-j outage represent the fuzzy number when is considered the contingency of branch i-j. As can be seen there is further suppression in the last case.

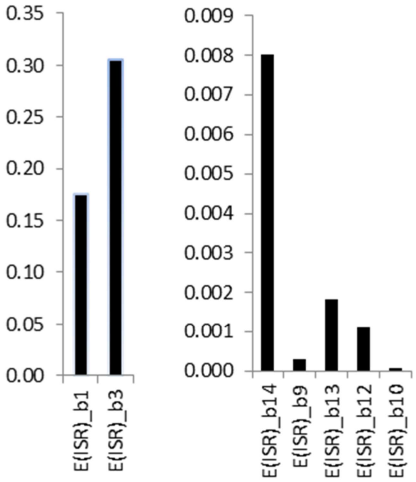

Fig.5. Expected ISR (pu)

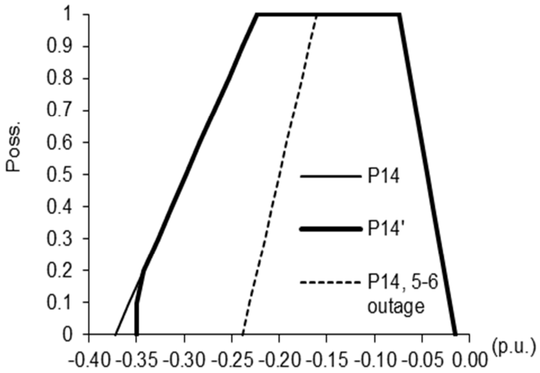

Fig.6. Load repression at node 14

V. CONCLUSIONS

In this paper, the CFPF model is used considering probabilistic data for failures of the components of transmission system. In the selection of the states, the states enumeration method is used since this method is a direct extension of the N-1 criterion used in many TSOs in the electricity sector. As expected, the severity of repression increases with the order of contingency. The repression severity indices were detailed in order to assess the expected adequacy of the system globally and individually (buses). In the CFPF focus, this is an innovative feature since fuzzy and probabilistic models are combined together. The proposed method can be helpful to fulfill the needs of transmission operators regarding planning activities.

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