SOFTWARE TOOL DEVELOPED FOR DEREGULATED POWER SYSTEM ANALYSIS

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Abstract: The transmission network represents undoubtedly the infrastructure that enables the power market. The power market development and the increase of the transactions has lead to several uncertainties (load, unavailability of the transmission network, the presence of renewable energies and transactions performed) that have to be considered within the actual power system operating condition analysis. Fast and accurate evaluation of the ATC is essential to the efficient use of networks within a deregulated environment. Power marketers trade power using a variety of tools such as the PTDF and ATC computing, to make economic trade decisions and to value transmission resources. The paper aims to present a software tool developed in Matlab environment designed for power system stochastic analysis. A software application for the power flow probabilistic approach, for the PTDF computing and for ATC computing is included. The case study is represented by the Western and South-Western side of the Romanian Power System.

Keywords: power flow, transmission system, deregulated environment, mathematical model, software tool

1. INTRODUCTION

The transmission network represents undoubtedly the infra-structure that enables the power market. The Transmission System Operator (TSO) has to offer it for all the market participants.

The power market development and the increase of the transactions has lead to acute danger and generated, within last years, several extended blackouts, affecting millions of network users.

The power system analysis, state estimation and operating condition optimization are representing one of the most important tasks both for the planning and designing phase and also, within the operation phase. Optimal operating conditions from technical and economical point of view are obtained.

In order to cope with the increased uncertainty imposed by the development of electricity markets, the designing of new tools should be useful to study and thus understand the system and its associated market [1], [2]. For a power system operator, a tool that is able to take into account uncertainties should be useful.

Since OPF is a deterministic tool, it has to be run many times to encompass all, or at least the majority, of possible operating conditions. More accurate Monte Carlo simulation, being able to handle “complex” random variables, represents an option but is computationally more demanding. Also it has a limited use for on-line types of applications. Computationally effective, but still accurate and reliable methods, this is therefore of significant interest. There are also other uncertainties that can be considered in the problem such as equipment outages.

In the literature, several approximate methods that can be used for power systems analysis under uncertainty have appeared. Examples of these methods include the truncated Taylor series expansion method [3]; the discretization method [4]; the common uncertain source method [5], [6]; the first-order second-moment method [1], [7], which is basically a variant of the Taylor series expansion method; the cumulant method [2], [8], [9]; and the point estimate method [10]–[12]. The main idea behind these methods is to use approximate formulas for calculating the statistical moments of a random quantity that is a function of n random variables, as opposed to a more accurate Monte Carlo approach, which was considered computationally more demanding. Within the literature, small scale power systems are used as case studies. All the analyses are performed using DC power flow (in great majority of cases).

Power marketers trade power using a variety of tools such as the Power Transfer Distribution Factors (PTDF) and Available Transmission Capacity (ATC), to perform economic trade decisions and to value transmission resources.

The total transfer capacity (TTC) is the best engineering estimate of the total amount of electric power that can be transferred over the interface in a reliable manner in a given timeframe [13]. The transmission reliability margin (TRM) accounts for the uncertainties associated with the transmission system [14], [15].

Thus, the ATC capacity can be defined as follows:

$$ATC = TTC - TRM - already\ committed\ uses \qquad (1)$$

where the *already committed uses* represent the power flow within the base case of the power system analyzed.

Concerning the structure of the paper, following the Introduction presented within the 1st section, the 2nd one is focusing on presenting the mathematical model. For the beginning an original congestion management mathematical model is discussed. It follows the probabilistic power flow approach and the PTDF factors and ATC capacity evaluation. Within the 3rd section the software tool is briefly presented, followed by the case study (Section 4). The results are presented and discussed within the 5th section. The last section presents the conclusion of the paper.

2. MATHEMATICAL MODEL

2.1. Congestion management mathematical model

The congestions are due to the power system operating conditions for which the power transfer between two buses or system areas leads to the fact that the operating security parameters are not accomplished, being necessary the deviation from the optimal operating condition [16]. These situations occur in case of power transfer through specific network elements, greater than the admissible power from the thermal limit point of view.

Starting from the steady state optimization [16], [17], [18], the mathematical model used for congestion analysis is proposed. It contains additional specific elements, in case of control variables and also of constraints, the objective function (OBF) having additional terms too.

- **variables**:
  - ⇒ state variables – are the same as the ones defined within the power flow [16]-[18]:

$$\begin{aligned} &\delta_i\,, i \in N \setminus e\,,\ P_{ge}\,,\ U_i\,, i \in C\,,\ Q_{gi}\,, i \in G \\ &P_{ij}\,, Q_{ij}\,, ij \in R\,,\ S_{ij}\,, ij \in R \ \text{or}\ I_{ij}\,, ij \in R \end{aligned} \tag{2}$$

where U_i, δ_i – the value and the phase of the voltage in bus i; P_{ge} – the active generated power for the slack bus; Q_{gi} – the reactive generated power in bus i; P_{ij}, Q_{ij}, S_{ij} – the power flows through the ij network element; N – the set of buses; C – the subset of the P-Q buses; G – the subset of the P-U buses; R – the set of the network elements.

  - ⇒ control variables – are the same as the ones defined within the optimal power flow (OPF):

$$U_i\,, i \in G\,,\ P_{gi}\,, i \in G \setminus e\,,\ K_{ij}\,, ij \in T\,,\ \Omega_{ij}\,, ij \in T \tag{3}$$

where P_{gi} – the active generated power in bus i; K_{ij}, Ω_{ij} – the absolute value and the phase for the transformer ratios; T – the subset of the (auto) transformers; e – the slack bus,
and in addition:

$$P_{ci}\,, i \in N \tag{4}$$

where P_{ci} – the consumed power for bus i.

- **constraints**:
  - ⇒ equality constraints – are the same as the ones defined within the power flow [16]-[18]; ⇒

$$\begin{cases} P_i(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K},\boldsymbol{\Omega}) - P_{gi} - P_{ci} = 0\,, & i \in N \\ Q_i(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K},\boldsymbol{\Omega}) - Q_{gi} - Q_{ci} = 0\,, & i \in N \end{cases} \tag{5}$$

  - ⇒ inequality constraints (superior and inferior value limitation of certainness quantities):
    - the constraints corresponding to the state variables:

$$\begin{aligned} &P_{ge}^{min} \le P_{ge} \le P_{ge}^{max} \\ &Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max}\,, \quad i \in G \\ &U_i^{min} \le U_i \le U_i^{max}\,, \quad i \in C \end{aligned} \tag{6}$$

    - unlike the OPF model, in case of the following constraints, the superior limitation is avoided, obtaining:

$$\begin{aligned} &P_{ij}^{min} \le P_{ij}(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K},\boldsymbol{\Omega})\,, \quad ij \in R \\ &P_{ij}^{min} \le P_{ij}(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K},\boldsymbol{\Omega})\,, \quad ij \in R \\ &S_{ij}^{min} \le S_{ij}(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K},\boldsymbol{\Omega})\,, \quad ij \in R \\ &S_{ij}^{min} \le S_{ji}(\boldsymbol{U},\boldsymbol{\delta},\boldsymbol{K},\boldsymbol{\Omega})\,, \quad ij \in R \end{aligned} \tag{7}$$

where: $\boldsymbol{U}$ and $\boldsymbol{\delta}$ – the vector of values and phases for the bus voltages; $\boldsymbol{K}$, $\boldsymbol{\Omega}$ – the vector of values and phases for the transformer ratios; P_{ij}, S_{ij}, $ij \in R$ – active and apparent power flows through the ij network element, from the bus i to the bus j; P_{ji}, S_{ji}, $ji \in R$ – active and apparent power flows through the ij network element, from the bus j to the bus i; P_{ij}^{min}, S_{ij}^{min} – the inferior limit of the P_{ij} and S_{ij} power.

Within these constraints, if the upper limitation of the power flow through the ij network element is considered, then no congestions would appear.

    - the following constraints refer to the control variables:

$$\begin{aligned} &P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}\,, \quad i \in G \setminus e \\ &U_i^{min} \le U_i \le U_i^{max}\,, \quad i \in G \\ &K_{ij}^{min} \le K_{ij} \le K_{ij}^{max}\,, \quad ij \in T \\ &\Omega_{ij}^{min} \le \Omega_{ij} \le \Omega_{ij}^{max}\,, \quad ij \in T \end{aligned} \tag{8}$$

    - the constraint for the new control variable P_{ci} is added:

$$P_{ci}^{min} \le P_{ci} \le P_{ci}^{max}\,, \quad i \in N \tag{9}$$

where $P_{ci}^{max} = P_{ci}$ known from the base case.

This new constraint refers to the actual operating conditions of the power system. It is enabled for those consumers accepting to decrease their power consumption, for participating within the congestion management process. Of course, they are paid for accepting this.

- the **objective function** contains in addition (to the classical OPF) two terms corresponding to the congestion penalty cost (the exceed of the apparent power upper limit trough a network element) and another one corresponding to the mitigation cost of the consumed power in specific buses of the power system:

$$OBF = \sum_{i\in G} C_i(P_{gi}) + \sum_{ij\in R} TP_{ij}(S_{ij} - S_{ij}^{**}) + \\ + \sum_{ij\in R} TP_{ij}(S_{ji} - S_{ji}^{**}) + \sum_{i\in N} C_i(P_{ci}) = Minim \qquad (10)$$

where the generated power cost characteristics $C_i(P_{gi})$ have a quadratic form:

$$C_i(P_{gi}) = a_i \cdot P_{gi}^2 + b_i \cdot P_{gi} + c_i\ , \quad i \in G\ , \qquad (11)$$

TP_{ij} – the penalty cost of the apparent power upper limit exceed trough the *ij* network element (at one end or at the other, of the *ij* network element); S_{ij}^{**} and S_{ji}^{**} being defined in [16]; the mitigation cost characteristics of the consumed power have, in generally, a non linear form, the simpler being a second order P_{ci} polynomial function.

$$C_i(P_{ci}) = t_i \cdot \Delta P_{ci}^2 + v_i \cdot \Delta P_{ci}\ , \quad i \in N\ . \qquad (12)$$

A non linear optimization problem with constraints is obtained. It is solved using the penalty function method, associated with the generalized Lagrange multiplier method and the Fletcher-Reeves gradient method [17]. The Lagrangean function Φ is presented [16], [17]:

$$\Phi = \sum_{i\in G}(a_i \cdot P_{gi}^2 + b_i \cdot P_{gi} + c_i) + \sum_{ij\in R} TP_{ij}(S_{ij} - S_{ij}^{**}) + \sum_{ij\in R} TP_{ij}(S_{ji} - S_{ji}^{**}) + \sum_{i\in N}(t_i \cdot \Delta P_{ci}^2 + v_i \cdot \Delta P_{ci}) + \sum_{i\in N\setminus e} \lambda_{pi} \cdot (P_i - P_{gi} - P_{ci}) + \\ + \sum_{i\in C} \lambda_{qi} \cdot (Q_i - Q_{ci}) + r_{pe} \cdot (P_{ge} - P_{ge}^*)^2 + r_q \cdot \sum_{i\in G} p_{qi} \cdot (Q_{gi} - Q_{gi}^*)^2 + r_u \cdot \sum_{i\in C} p_{ui} \cdot (U_i - U_i^*)^2 + \\ + r_p \cdot \sum_{ij\in R} p_{pij} \cdot (P_{ij} - P_{ij}^*)^2 + r_p \cdot \sum_{ij\in R} p_{pij} \cdot (P_{ji} - P_{ji}^*)^2 + r_s \cdot \sum_{ij\in R} p_{sij} \cdot (S_{ij} - S_{ij}^*)^2 + r_s \cdot \sum_{ij\in R} p_{sij} \cdot (S_{ji} - S_{ji}^*)^2$$

where $\lambda_{pi}, i \in N \setminus e; \lambda_{qi}, i \in C$ – Lagrange multipliers; $r_{pe}, r_q,\ r_u, r_p, r_s$ – penalty coefficients; $p_{qi}, i \in G;$ $p_{ui}, i \in C;$ $p_{pij}, ij \in R; p_{sij}, ij \in R$ – weighting coefficients; $P_{ge}^*;\ Q_{gi}^*,\ i \in G; U_i^*, i \in C\ ,\ P_{ij}^*, P_{ji}^*, ij \in R;$ $S_{ij}^*, S_{ji}^*, ij \in R$ – are computed as presented in [16], [17].

The auxiliary function Φ has the following components: the OBF, the terms corresponding to the Lagrange multipliers (corresponding to the equality constraints) and the ones corresponding to the penalty coefficients (corresponding to the inequality constraints).

Within the algorithm, the minimization of the auxiliary function Φ, applying gradient methods [17], is carried-out computing its derivatives regarding the control variables (for the gradient components and searching direction) and regarding the state variables (for the Lagrange multipliers). Their expressions are presented in [16], [17].

2.2. Power flow probabilistic approach

The restructuring of the power systems and the new deregulated environment have leading to the increase of the uncertainty degree. These uncertainties are referring to the characteristic data of the operating conditions, to the change of specific objectives and to the design of new criteria for situation evaluation.

The power systems are stochastic in nature. Random factors are occurring, i.e. power variations (generated or consumed), changes within the transmission network configuration and the system parameters, forecasting errors [19].

The background for the deterministic congestion management is based on the computing of the operating conditions for fixed values of the initial data. Such data are referring to the active and reactive consumed power, the active generated power, the topology and the network parameters. These kinds of uncertainties, previously pointed-out, request a probabilistic approach of afore discussed problem. The development of new analysis tools for power system operating conditions is mandatory and extremely useful. The probabilistic power flow refers to the stochastic modelling of the quantities having fixed values, from the deterministic (classical) power flow. Also, it refers to the stochastic modelling of the transmission network configuration and the network element parameters.

The probabilistic approach of the power flow is base on the following aspects:

- the acceptable number of samples;
- randomly generation of consumed power samples;
- the computing of the average, minimum and maximum values and standard deviation for the quantities representing the power flow results, the power flows through the network elements representing a case in point.

Also, the random analysis of the significant contingencies from the congestion management point of view is taken under discussion.

2.3. Probabilistic modelling of consumed power

Let's consider a period of n_a years, the consumed power being known. Based on these data, the consumed power are forecasted for the following ($n_f - n_a$) years (Fig. 1). The influence of a random component is taken into consideration [20].

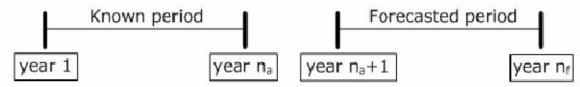

Fig. 1. The method of considering the consumed power

According to the forecasting activity experience the use of a polynomial second order function, is recommended. Following this line, the least square method is applied, considering a polynomial of second degree $m = 2$, [20].

$$P_2(x) = a_0 + a_1 \cdot x + a_2 \cdot x^2 \tag{13}$$

The values of the a_i coefficients are established according to [16], [17]. The average consumed power forecasted values y_j , $j = \overline{n_{a+1}, n_f}$ are obtained.

Finally the superior and inferior limits are established, considering the p [%] probability:

$$y_j^{\max} = y_j + \varepsilon_j\ , \quad j = \overline{n_{a+1}, n_f}$$

$$y_j^{\min} = y_j - \varepsilon_j\ , \quad j = \overline{n_{a+1}, n_f} \tag{14}$$

where ε_j is computed as follows:

$$\propto_j^2 = K^2 \cdot \sigma^2 \cdot \left[1 + \frac{1}{n_a} + \frac{(x_j - \overline{x})^2}{\sum_{k=1}^{n_a} (x_k - \overline{x})^2} \right], \tag{15}$$

σ^2 – standard deviation of the y variable

$$\sigma^2 = \frac{1}{n_a} \cdot \sum_{k=1}^{n_a} (y_k - \overline{y})^2\ , \tag{16}$$

Considering the K coefficient

$$K = t_{\alpha/2, n_L} \tag{17}$$

where α – the imposed value for the Student distribution, n_L – the number of the freedom degrees for the approximation function

$$n_L = n_a - m - 1 \tag{18}$$

the necessary correction considering the probability p is introduced

$$p^{\%} = 100 \cdot (1 - \alpha) \tag{19}$$

the maximum (minimum) random component estimated value being realized.

2.4. Random contingencies analysis

From the operating conditions point of view that could lead to the congestion appearance, the contingency analysis is necessary. Several reasons are suitable: faults, revisions, scheduled maintenance works, etc.

Within the paper the analysis is focusing on *N-1* and *N-2* type contingencies (one or two disconnected network elements are allowed).

These are randomly generated, the mechanism being presented in Fig. 2.

Each contingency corresponds to an operating condition. For each operating condition the power flow is computed, the necessary results being saved.

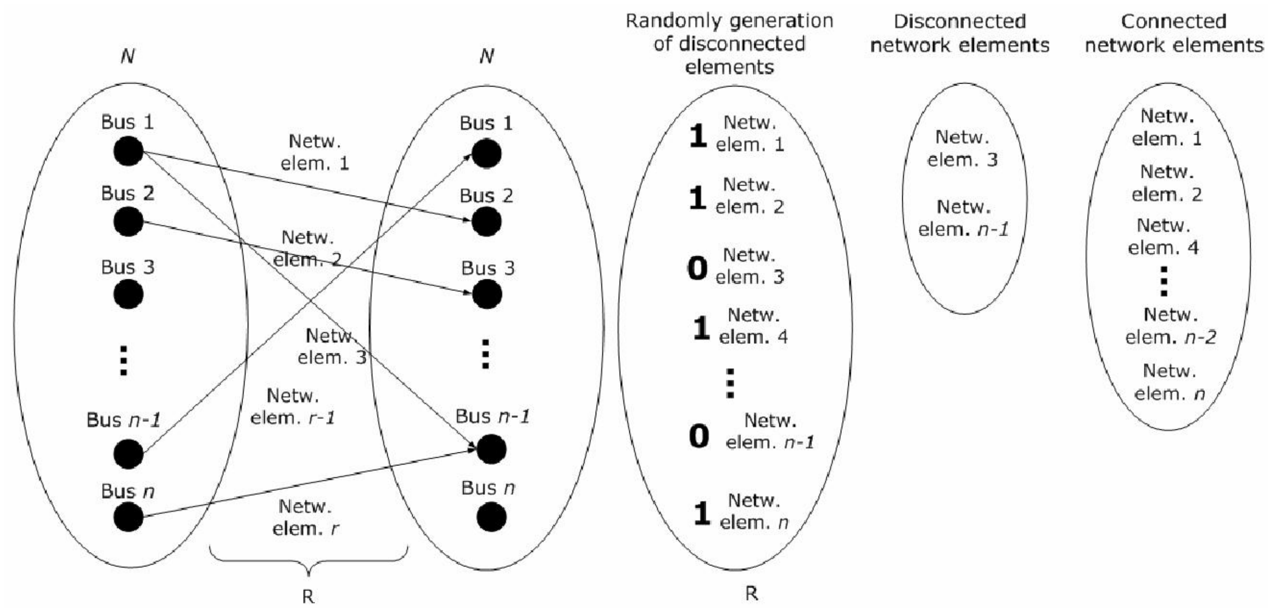

Fig. 2. The mechanism for randomly generated contingencies

2.5. The acceptable number of samples

The acceptable number of samples has been accomplished according to the methodology presented in [16]. A Monte Carlo simulation has been used.

2.6. PTDFs computing

An electrical overhead line is considered between the i and j buses having the $\underline{Z}$ impedance, the voltages U_i and U_j, the phases δ_i and δ_j and the active power flow as presented in Fig. 3.

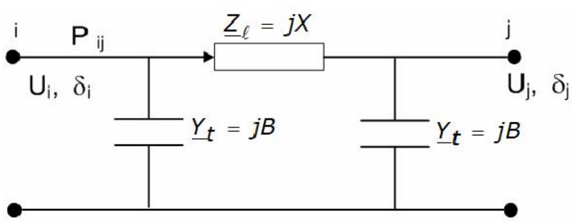

Fig. 3. π equivalent scheme of an electrical overhead line

In [16] the approximate method based on DC power flow is presented. The PTDFs are defined as the power flow through the network element sensitivity with respect to the injected power in system buses [16].

$$\rho_{ij,k} = \frac{\partial P_{ij}}{\partial P_k}, \quad k \in N \setminus e, \quad ij \in R \tag{20}$$

where: $\rho_{ij,k}$ – the PDF factors computed for the ij network element and k P-Q bus.

Using the PTDFs, the change in power flow on each transmission line in the system may be computed for the change in injection at one or more buses [21].
The computing algorithm and the results are presented in [16], [21].

The aforementioned approach completely neglects the AC power losses. It is also implemented in other computer software for power system analysis.

The novelty of the software tool developed by the authors is based on the AC methodology.

The PTDF factors are computed for a specific transaction. Two buses are involved: a seller type bus (a P-U bus) and a buyer type bus (P-Q bus).

The methodology consists in:

a) the seller type bus is set as slack bus;
b) the power flow is computed for the operating condition;
c) the active power flows through the network elements P_{ij}, $ij \in R$ are saved;
d) the consumed active power for the buyer type bus is increased by 1 MW;
e) the power flow is computed considering the new conditions;
f) the new active power flows through the network elements P_{ij}^{+1}, $ij \in R$ are saved;
g) the PTDF factors are computed.

$$\rho_{ij,k} = P_{ij}^{+1} - P_{ij}, \quad k \in N \setminus e, \quad ij \in R \tag{21}$$

All the buses of the power system are treated in the same manner; the matrix presented in relation (22) is obtained:

$$\boldsymbol{\rho} = \begin{array}{c} \begin{array}{cccccc} \phantom{\rho_{11}} & \phantom{\rho_{12}} & & e & & \phantom{\rho_{1n}} \end{array} \\ \begin{bmatrix} \rho_{11} & \rho_{12} & \cdots & 0 & \cdots & \rho_{1n} \\ \rho_{21} & \rho_{22} & \cdots & 0 & \cdots & \rho_{2n} \\ \rho_{31} & \rho_{32} & \vdots & 0 & \vdots & \rho_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \rho_{r1} & \rho_{r2} & \cdots & 0 & \cdots & \rho_{rn} \end{bmatrix} \end{array} \tag{22}$$

The results are for surely better than the ones obtained using DC power flow. The actual methodology bases itself on the complete AC power flow, considering the power losses.

2.7. ATC evaluation

The following mathematical model is elaborated according to the complete AC power flow model. In this case a higher computing effort is requested. Considering the actual performances of the computing technique and of the programming environments, the use of the complete mathematical model has to become a common practice.

The methodology for a specific transaction is the following one:

a) the seller type bus (s) is considered to be the slack bus and the buyer type bus (b) is established;
b) the power flow is computed for the considered operating condition, retaining the consumed power value for the buyer type bus (P_{cb}^{in});
c) the value of the transfer power increment step h is initialized;
d) the current value of the active consumed power is computed for the bus b:

$$P_{cb}^{new} = P_{cb}^{old} + h \tag{23}$$

respectively for the reactive consumed power, considering a constant power factor:

$$Q_{cb}^{new} = Q_{cb}^{old} + h \cdot tg\,\phi \tag{24}$$

e) the power flow is computed, taking into consideration the new values for the consumed power in the bus b;
f) the constraints related to the bus voltage and the power flow through the transmission network elements, are checked;
g) if the constraints specified at *f)* are satisfied, *d)* is following;
h) if the constraints specified at *f)* are not satisfied, the value of the step h is decreased;
i) the new value of the step h is compared with a minimum value, previously imposed;
j) if the above condition is satisfied, *d)* is following;
k) if the above condition is not satisfied, the computing process finishes. The ATC is represented by the last value of the consumed power in the bus b (P_{cb}).

The results are surely better than the ones from the DC power flow based methodology. The new ones results following a complete AC power flow, rigorously considering the power losses.

3. SOFTWARE TOOL

The software tool is developed in Matlab environment. It has a user friendly interface, specific to Windows applications. It is linked with the Powerworld software [22]. The power system topology, the parameters and the operating condition data are extracted from the Powerworld data base.

The flowchart is presented in Fig. 4. The software tool uses a script file containing the information such as: network topology, the transmission network parameters, the consumed and generated power. The data base corresponding to the operating state of the power system is extracted from the Powerworld software.

Using another script file, the new values of the consumed power are loaded. Also, the contingencies are carried-out using the same script file.

The statistical indices are computed for the results of the power flow. A report containing all the congested branches is generated. For the case of each congested branch, two kind of information are available:

- the sample containing the congested branch;
- the scenarios leading to the issues pointed-out (i.e. the contingencies considered).

For PTDF computing and ATC evaluation two different approaches are used: the deterministic one and the probabilistic one, respectively.

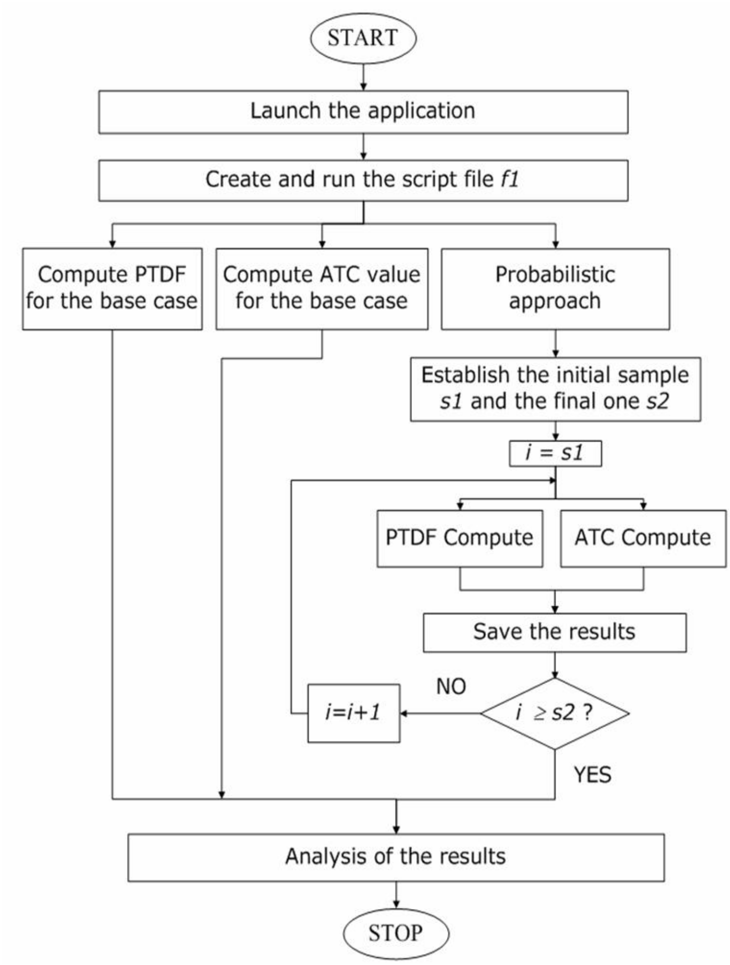

Fig. 4. The flowchart of the software tool

Considering the first hypothesis, the deterministic PTDF and ATC values are computed based on the data extracted from the base case of the power system. The ATC value is computed based on AC power flow.

The second hypothesis requires a probabilistic power flow. The probabilistic approach corresponds to the new competitive and deregulated environment. The power flow is computed considering the uncertainties related to the power system: the unavailability of the generating units and of the transmission network, the unexpected load variations, etc.

The paper discusses the case of the transmission network element unavailability.

Within the literature there are several approaches dealing with DC power and small scale power system. All the analyses, within the software tool developed, are performed based on AC power flow.

4. CASE STUDY

The case study is carried-out for the West and South-West side of the Romanian Power System. It has 88 buses and 107 branches. The 35 P-U buses are divided in 17 real generating units and 18 equivalent P-U buses, obtained by extracting the analysed part from the Romanian Power System. The system has a number of 42 P-Q buses. Within the power system the buses at medium voltage (real generating groups), 220 kV, 400 kV are represented. At 110 kV voltage level, only the generated and consumed power are represented (Fig. 5).

5. RESULTS AND DISCUSSIONS

The analysis is focusing on highlighting special situations, like congestions, that can occur in case of the power system analyzed. Situations that can not be revealed using deterministic power flow. Within the analysis, a number of 1000 samples have been considered.

A. Random consumed power

In case of probabilistic modelling of consumed power, the analysis did not reveal any congestion. The power system is robust, characterized by reduced loadings of the network elements within the base case.

B. Probabilistic contingencies

For random contingencies, the following conclusions are briefly presented.

B1. 28003-28008 and 28069-28071 lines

The disconnection of the 400 kV OHL 28003-28008 and 220 kV OHL 28069-28071 leads to inadequate voltage profile for that area and congestions on 220 kV OHL 28067-28071, 28070-28071, 28069-08070. The problem can be solved by redispatching the generation.

B2. 28047-28052 line

The disconnection of the 220 kV OHL 28047-28052 leads to congestions in case of the 400 / 220 kV autotransformer 28045-28002 and 220 kV OHLs 28045-28062, 28063-28064, respectively 28064-28065. The problem can be solved by redispatching the generation.

B3. 28002-28004 line and 29119-28002 transformer

The 220 kV OHLs 28002-28062-28063-28064-28065 are congested, in case of disconnecting one generating unit from Rovinari power plant and 400 kV OHL 28002-28004. The problem can be solved by redispatching the generation.

B4. 28087-28036 autotransformer and several generating units

In case of disconnecting the 400 / 220 kV autotransformer and different generating units from important power

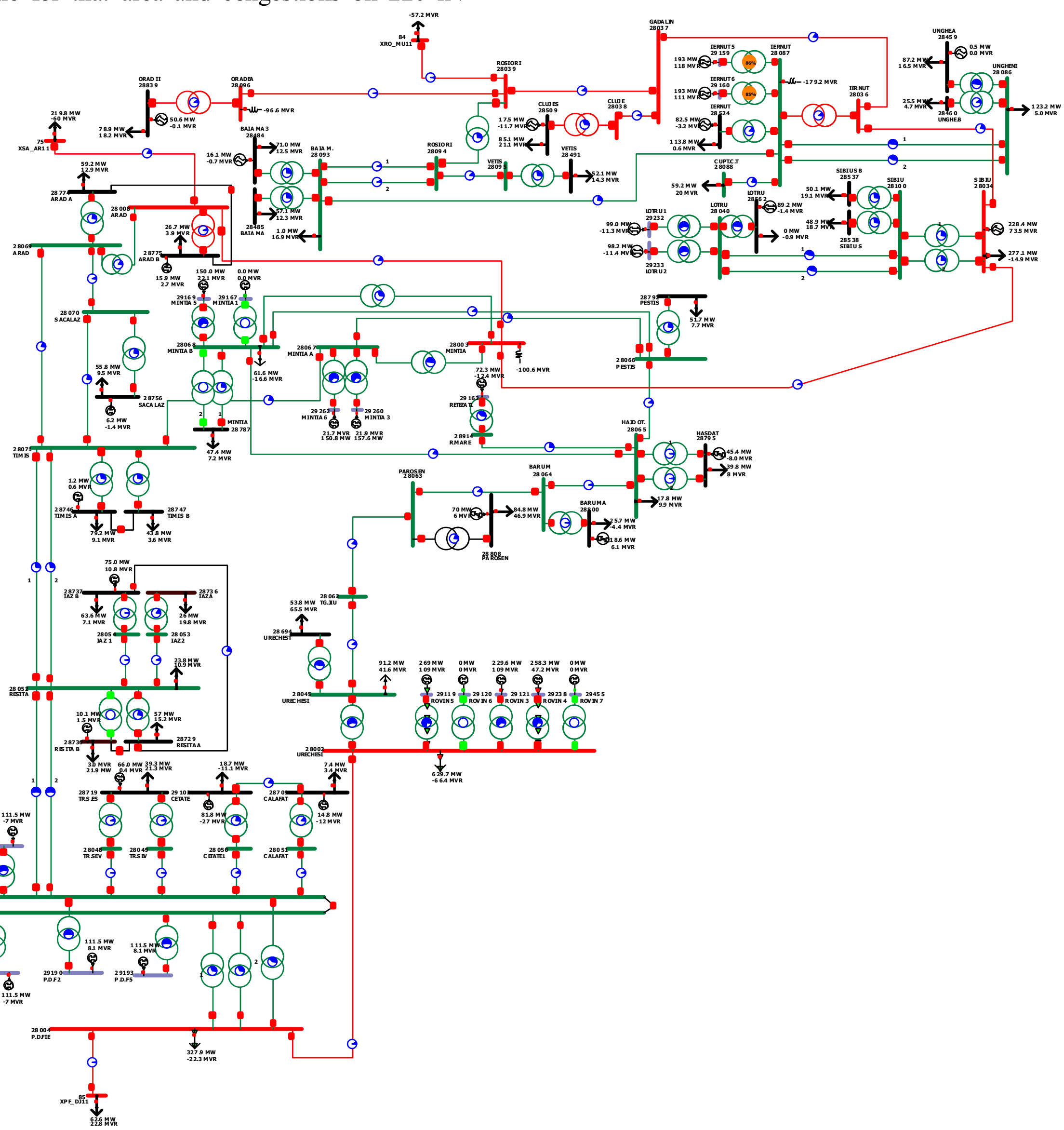

Fig. 5. The case study power system

plants within the power system, a valid operating condition can not be established. The problem is solved if the bus 28087 switching-shunt is disconnected. A valid operating condition, from all the points of view (voltage profile, loading of the network elements) is obtained.

B5. Contingencies with blackout

A valid operating state can not be established in case of the following contingencies:

- disconnection of the 400 kV OHL 28036-28037 and one generating unit from Iernut power plant;
- disconnection of the 400 kV OHL 28036-28037 and the 220 / 110 kV autotransformer 28068-28787.

If the buses 28087 and 28096 switching-shunts are disconnected an operating condition is obtained. But the 28036-28087 400/ 220 kV autotransformer and the 28087-28093 220 kV OHL are congested.

B6. Other N-2 contingencies

In Table 1 are presented the statistical indices values, for random *N-2* contingencies. For exemplification, only 10 branches are listed.

The software tool proves to be very useful for transmission system operators. It allows special situation to be pointed-out, based on the probabilistic approach of the power flow.

Table 1. Statistical indices in case of power flow considering randomly generated contingencies

No.	Branch	Limit [MVA]	S_max [MVA]	S_average [MVA]	δ
1.	28067-28071	333	401.40	43.27	27.05
2.	28045-28002	400	372.47	293.2207	58.05
3.	28045-28062	305	297.65	132.30	51.41
4.	28063-28064	305	350.29	125.59	49.38
5.	28064-28065	305	398.85	117.11	49.62
6.	28062-28063	274	296.60	131.99	51.16
7.	28063-28064	305	350.29	125.59	49.38
8.	28064-28065	305	398.85	117.11	49.62
9.	28087-28093	305	498.18	61.20	85.02
10.	28746-28747	114	78.46	19.12	10.63

C. PTDF analysis

In the following the transaction 29113-28055 is analyzed. For the current case, the PTDF factors are computed. The numerical results are presented in Table 2, both for DC and AC power flow methodologies.

Table 2. PTDF factors corresponding to the AC and DC methodologies

No.	Branch	PTDF [%]		No.	Branch	PTDF [%]		No.	Branch	PTDF [%]	
		DC	AC			DC	AC			DC	AC
1.	28001-1	100.00	100	17.	28022-28024	2.75	2.80	33.	28057-28058	2.60	2.50
2.	28001-28002	26.25	26.80	18.	28024-28031	2.73	2.70	34.	28057-28060	3.37	3.60
3.	28001-28007	59.31	59.10	19.	28031-28032	4.29	4.30	35.	28057-28902	6.20	6.70
4.	28001-28033	7.82	8.00	20.	28031-28033	3.79	3.70	36.	28058-28060	3.43	3.60
5.	28001-28034	6.63	6.80	21.	28031-28034	3.22	3.50	37.	28058-28061	11.47	12.00
6.	28002-28004	12.21	11.90	22.	28032-28904	4.29	4.40	38.	28073-28079	2.06	2.20
7.	28002-28010	4.35	4.50	23.	28044-28033	2.01	2.10	39.	28073-28905	2.06	2.10
8.	28045-28002	9.69	10.30	24.	28044-28033	2.01	2.10	40.	28079-28901	3.10	3.30
9.	28003-28034	2.60	2.50	25.	28044-28910	2.01	2.10	41.	28079-28935	3.10	3.40
10.	28004-28007	13.36	12.60	26.	28044-28911	2.01	2.00	42.	28079-29051	2.06	2.20
11.	28007-28011	9.67	9.70	27.	28045-28061	11.47	12.00	43.	28901-28902	6.20	6.70
12.	28055-28007	41.17	40.80	28.	28055-28056	2.82	3.00	44.	28901-28935	3.10	3.30
13.	28055-28007	41.17	40.80	29.	28055-28057	5.43	5.70	45.	28905-28910	2.01	2.10
14.	28010-28011	8.55	8.70	30.	28055-28058	5.44	5.70	46.	28905-28911	2.01	2.00
15.	28010-28904	4.20	4.20	31.	28055-28060	3.98	4.20	47.	28905-29051	2.06	2.10
16.	28016-28021	2.30	2.40	32.	28056-28060	2.82	3.00				

Using the PTDF factors, the power flow tracing, involved within the transaction, is presented in Fig. 6. From the P-U bus (seller type bus) the power is transferred through the block transformers to bus 28001.

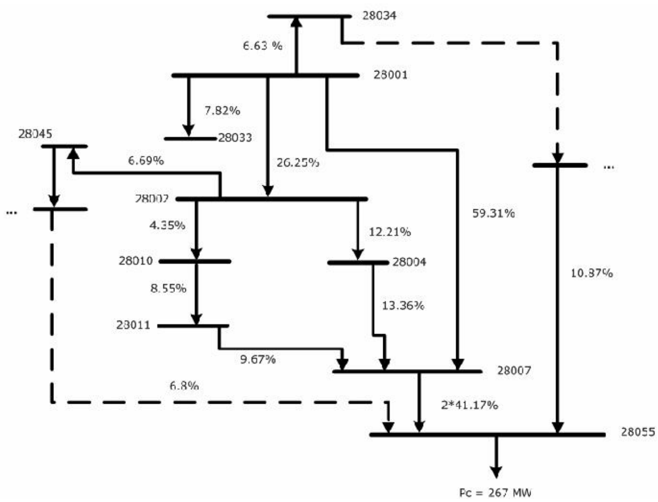

Fig. 6. Power flow tracing for the transaction analyzed

The maximum power flow is recorded through the branch 28001-28007.

For the other path 28001-28002 the following conclusions are highlighted. The power flows from bus 28002 through other 3 paths. The 1st one corresponds to bus 28045 for a reduced part of the transaction. An alternative path represented by the 28002-28004 (12.21 %). In the following the power flows through the branch 28004-28007 (13.36 %) and through the autotransformers at the buyer type bus involved within the transaction.

D. ATC analysis

The numerical results representing the ATC values, computed according to the AC methodology are synthesized in Table 3. In case of DC methodology the results are presented within the same table.

The transactions that imply the XRO_MU11, Iaz A, Mintia and Pestis buses, lead to the same ATC values irrespective of the seller type bus used.

In case of Ungheni buyer type buses, all the power plants implicated within the transactions are leading to small values of the ATC capacity. The powers involved within the 2 transactions are 120 MW and 25.5 MW. For the first case it results a higher ATC value (the power factor is also higher for the first buyer). Values determined in DC are an order of magnitude higher than those obtained according to the AC methodology; this fact once again highlights the unrealistic conclusion provided by the DC methodology. A similar analysis is performed also for buyer type bus Baia Mare. Same values of the ATC capacity, regardless of power plants (seller type buses) involved in the transactions analyzed are obtained.

Table 3. ATC values corresponding to the AC and DC methodologies

No.	Buyer type buses	Seller type buses							
		Mintia		Rovinari		Portile de Fier		Lotru	
		AC	DC	AC	DC	AC	DC	AC	DC
1.	XSA_AR11	340	250	248	400	216	104.5	220	91
2.	XRO_MU11	32	250	32	400	32	104.5	32	91
3.	Urechesti	160	250	48	234.9	48	104.5	72	91
4.	Resita	360	250	224	400	—	104.5	176	91
5.	Hasdat Olt	228	250	192	376.4	180	104.5	216	91
6.	Ungheni	60	250	52	275.2	52	104.5	64	91
7.	Cupt. C.T	44	245.8	36	245.8	36	104.5	44	91
9.	Ungheni B	48	174.5	40	174.5	40	104.5	48	91
9.	Baia Mare	40	142.9	36	142.9	36	104.5	40	91
10.	Vetis	36	147.9	32	147.9	32	104.5	40	91
11.	Sibiu SB	72	149.9	60	149.9	60	104.5	72	91
12.	Urechesti	56	146.2	28	146.2	28	104.5	48	91
13.	Iaz A	120	174	120	174	120	104.5	120	91
14.	Arad A	188	219.6	152	240.9	140	104.5	136	91
15.	Mintia	144	250	144	305.2	144	104.5	144	91
16.	Pestis	140	148.3	140	148.3	140	104.5	140	91

In case of the buyer type bus Arad A significant ATC values varying in relation with the power plant involved within the transaction are obtained. Thus, if Mintia is considered as a seller type bus, the maximum ATC value is obtained. The power concerning the transaction is 60 MW. Considering the fact that the branches involved in the transaction are less loaded (within the base case), an increased ATC value is reached (following the completion of this transaction). Unlike the previous case, even if the power subjected to the transaction was lower (25.5 MW), smaller ATC values have been obtained. This can be explained by the fact that the branches involved within the transaction have already been loaded significantly from the base case. It is also pointed-out that for the case of power plants Mintia, respectively Rovinari, the ATC values obtained according to the AC methodology are lower than those obtained in DC approach.

Very reduced values are obtained in case of the buses Vetis, Sibiu, Urechesti (for the AC methodology). According to the DC approach, equal ATC values are obtained for each transaction established between the seller type buses and the buyer type buses specified previously. The transactions established with respect to the Portile de Fier and Rovinari power plants are leading to the smaller ATC values. The cause is due to reduced electric distance between the seller and buyer type buses involved within the transactions analyzed. In case of Mintia and Lotru power plants, the ATC values begin to grow. But it does not grow significantly due to the relatively limited resources (branches loaded from the base case) of the power system analyzed.

Regarding the Urechesti bus (220 kV) a significant variation of the ATC values is recorded in case of the power plants considered. In a less pronounced way, this trend is also suggested by the ATC values corresponding to the DC approach. The maximum ATC value is obtained if Mintia power plant is considered as seller type bus. Also, as the electrical distance between the seller and the buyer type bus reduces, the ATC value is reducing as well. Thus, if Lotru power plant is considered to be the seller type bus, the ATC value is lower. The minimum value is achieved in case of Portile de Fier and Rovinari power plants, the electrical distance being the most reduced. If

Mintia and Lotru power plants are considered, a significant decrease of the ATC value is highlighted. The causes are multiple: the resources available within the transmission network, the power involved in the transaction (91.2 MW) and the reserve available at Lotru power plant.

The significant values of ATC values are obtained for transactions involving the interconnection with the Hungarian Power System. The power involved within this transaction is 220 MW.

In case of Hasdat Olt buyer type bus considering Mintia power plant as seller type bus, the maximum ATC value is achieved. The large electrical distance between the two buses and the topology and resources of the transmission network are justifying this value. Portile de Fier and Rovinari power plants are connected through radial links with the buyer type bus leading to a reduced ATC value.

6. CONCLUSION

The authors are proposing a mathematical model used for congestion management. The model corresponds to the actual operating conditions of the power systems, followed by a probabilistic approach of congestion management.

The authors are considering that, taking into account the actual performances of the computing technique and of the programming environments, the use of the com-plete mathematical model has to become a common practice.

REFERENCES

[1] M. Madrigal, K. Ponnambalam, V.H. Quintana, Probabilistic optimal power flow. Proceedings of the 1998 IEEE Canadian Conference on Electrical and Computer Engineering. Waterloo, Ontario, 1998, 385–388.

[2] A. Schellenberg, W. Rosehart, J. Aguado. Cumulant-based probabilistic optimal power flow (P-OPF) with Gaussian and gamma distributions, IEEE Transactions on Power Systems, vol. 20, no. 2, 2005, 773–781.

[3] G.J. Hahn, S.S. Shapiro, Statistical Models in Engineering, New York, John Wiley, 1967.

[4] S. Kaplan, On the method of discrete probability distributions in risk and reliability calculation– application to seismic risk assessment. Risk Analysis, vol. 1, no. 3, 1981, 189–196.

[5] Q. Zhang, A general method dealing with correlations in uncertainty propagation in fault trees. Reliability Engineering and System Safety, vol. 26, 1989, 231–247.

[6] Q. Zhang, A method dealing with correlations in uncertainty propagation by using traditional correlation coefficients. Reliability Engineering and System Safety, vol. 41, 1993, 107–114.

[7] A. Schellenberg, W. Rosehart, J. Aguado, Cumulant based probabilistic optimal power flow (P-OPF). Proceedings of the 2004 International Conference on Probabilistic Methods Applied to Power Systems, 2004, 506–511.

[8] W.D. Tian, D. Sutanto, Y.B. Lee, H.R. Outhred, Cumulant based probabilistic power system simulation using Laguerre polynomials, IEEE Transactions on Energy Conversion, vol. 4, no. 4, 1989, 567–574.

[9] A. Schellenberg, J. Aguado, W. Rosehart, Intro-duction to cumulant based probabilistic optimal power flow (P-OPF), IEEE Transactions on Power Systems, vol. 20, no. 2, 2005, 1184–1186.

[10] E. Rosenblueth, Point estimation for probability moments, Proceedings of the National Academy of Sciences of the U.S.A., vol. 72, no. 10, 1975, 3812–3814.

[11] E. Rosenblueth, Two-point estimates in probability, Applied Mathematical Modelling, vol. 5, no. 5, 1975, 329–335.

[12] H. P. Hong, An efficient point estimate method for probabilistic analysis. Reliability Engineering and System Safety, vol. 59, 1998, 261–267.

[13] ISO-New England – TTC/TRM/ATC Document, Total Transmission Capability (TTC), Transmission Reliability Margin (TRM), and Available Trans-mission Capability (ATC), April 2000; http://www. nationalgridus.com/oasis/non_html/ pdf/ttc_trm__atc_determination.pdf.

[14] J. Zhang, I. Dobson, F.L. Alvarado, Quantifying Transmission Reliability Margin, IEEE Transactions on Power Systems, 2002.

[15] PSERC, Uncertain Power Flows and Transmission Planning, Final Project Report, March, 2007.

[16] C. Barbulescu, Congestion management within an open market environment, Ph.D. Thesis "Politehnica" University of Timisoara, Romania, 2009.

[17] St. Kilyeni, Optimization techniques in power engineering, Orizonturi Universitare, Timisoara, 2009 (in Romanian).

[18] J.A. Momoh, Electric power system applications of optimization, 2nd Ed., Howard University, Washington DC, USA, 2009.

[19] X. Li, Yz. Li, Sh. Zhang, Analysis of probabilistic optimal power flow taking account of the variation of load power, IEEE Transactions on Power Systems, Volume 23, Issue 3, 2008, 992-999.

[20] B. Lustrea, Forecasting of the consumed power, Agir, Bucharest, 2005 (in Romanian).

[21] C. Barbulescu, St. Kilyeni, Gh. Vuc, B. Lustrea, RE. Precup, St. Preitl, Software tool for power transfer distribution factors (PTDF) computing within the power systems, Proceedings of the IEEE International Conference EUROCON 2009, Saint-Petersburg, Russia, pp: 532-539.

[22] Powerworld, User's guide: www.powerworld. com/downloads/general.asp.