TRANSMISSION EXPANSION PLANNING. CASE STUDY FOR THE ROMANIAN POWER SYSTEM

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Abstract – The main task of the Transmission System Operator (TSO) is to provide a reliable and secure transmission network for the market participants. Worldwide the power systems are emerging: load variations, appearance of the competition within the power market, use of renewable energy sources and power transactions. All these facts are requesting a permanent focus regarding the power system development and evolution. The transmission network expansion planning (TNEP) field comes in the forefront. It has as main goal to provide a safety, reliable and economical operation of the power system. Additionally, it has to fulfil the environment constraints and, most important, to support the development of the interconnections. Within the paper the mathematical model used TNEP is presented. In the following, a software tool is developed in Matlab, designed for probabilistic approach. The Romanian Power System is used as a case study.

Keywords: power system, transmission planning, mathematical model, congestion management.

1. INTRODUCTION

The transmission network expansion planning (TNEP) is a complex task involving engineering, technical and economical challenges.

The goal of different TNEP approaches is to achieve expansion plans from both economic and system reliability point of view. The latter, in Chao et al [1], is achieved by Monte Carlo simulation. In the following TNEP is performed based on reliability.

The competitive environment is characterized by a high degree of uncertainty and risk, compared with the monopolist one. Taking into consideration these facts, for optimal operation of the power system, two directions necessary to be followed are emerging. The former refers to an advanced power flow analysis and operating conditions, the volatile characteristic of the loads being the main factor. The second is represented by an extremely detailed and advanced analysis, the set of monitored situations being extremely large, in contrast with a monopolist market. It involves an extended range of situations that is leading, in generally, to maximum loaded network element (congestions) operating conditions.

The great majority of approaches specific to the deregulated environment are market based approach. Financial and engineering issues that consider economic as well as physical laws of generation, load and transmission, are required.

The open access to the transmission system leads to unpredictable operating conditions. It is difficult to quantify the importance of different planning objectives belonging to several players, introducing other uncertainties. A solution is represented by the fuzzy logic approach, proposed by Buygi et al [2], [3]. Probabilistic tools are used for modelling random uncertainties. The stakeholder desire have a part to play is selecting the final expansion plan.

Artificial intelligence techniques [4] (genetic algorithm, expert system, fuzzy) have been proposed. They are focusing on developing different methodologies for selecting from the candidates line set.

Several fuzzy optimization mathematical models are proposed in Sun and Yu [5]. These models provide solution considering almost all constraints for TNEP.

In [6] by Shrestha and Fonseka a framework for transmission planning in deregulated environment is proposed. Congestion management based TNEP approach. The optimal expansion plan is established following a comparison between the congestion cost and investment cost.

A congestion management model which is appropriate for power pool is proposed by Fang and David in [7].

Silva et al [8] presented mathematical model to solve the TNEP with security constraints using (*N-1*) security criterion. The authors are also considering the (*N-2*) criterion.

Following the introduction presented within the 1st section of the paper, the authors are proposing the mathematical model used for TNEP (2nd section). The 3rd section of the paper is focusing on consumed power forecasting methodology. Starting from the mathematical models a software tool is developed (4th section). A case study is presented within the 5th section, followed by discussing the results (6th section). Finally, the 7th section synthesizes the conclusion of the paper.

2. MATHEMATICAL MODEL

Starting from the steady state optimization [9]-[11], the mathematical model used for TNEP analysis is proposed. It contains additional specific elements (control variables and constraints), the objective function (OBF) having additional terms too.

- **variables**:

⇒ state variables – are the same as the ones defined within the power flow:

$$\delta_i, i \in N \setminus e, \; P_{ge}, \; U_i, i \in C, \; Q_{gi}, i \in G$$
$$P_{ij}, Q_{ij}, ij \in R, \; S_{ij}, ij \in R \text{ or } I_{ij}, ij \in R \qquad (1)$$

where: U_i, δ_i – the absolute value and the phase of the voltage in bus i; P_{ge} – the real power for the slack bus; Q_{gi} – the reactive generated power; P_{ij}, Q_{ij}, S_{ij} – the power flow 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:

$$U_i, i \in G, P_{gi}, i \in G \setminus e,$$
$$K_{ij}, ij \in T, \; \Omega_{ij}, ij \in T \qquad (2)$$

where: P_{gi} – the real generated power in bus i; K_{ij}, Ω_{ij} – the value and the phase for the transformer ratios; T – the subset of the transformers and autotransformers; e – the slack bus.

- **constraints**:

⇒ equality constraints – are the same as the ones defined within the power flow;

$$\begin{cases} P_i(\boldsymbol{U}, \boldsymbol{\delta}, \boldsymbol{K}, \boldsymbol{\Omega}) - P_{gi} - P_{ci} = 0, & i \in N \\ Q_i(\boldsymbol{U}, \boldsymbol{\delta}, \boldsymbol{K}, \boldsymbol{\Omega}) - Q_{gi} - Q_{ci} = 0, & i \in N \end{cases} \qquad (3)$$

⇒ inequality constraints:

- the constraints corresponding to the state variables:

$$P_{ge}^{min} \le P_{ge} \le P_{ge}^{max}$$
$$Q_{gi}^{min} \le Q_{gi} \le Q_{gi}^{max}, \; i \in G \qquad (4)$$
$$U_i^{min} \le U_i \le U_i^{max}, \; i \in C$$

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

$$P_{ij}^{min} \le P_{ij}(\boldsymbol{U}, \boldsymbol{\delta}, \boldsymbol{K}, \boldsymbol{\Omega}), ij \in R;$$
$$S_{ij}^{min} \le S_{ij}(\boldsymbol{U}, \boldsymbol{\delta}, \boldsymbol{K}, \boldsymbol{\Omega}), ij \in R \qquad (5)$$

where: $\boldsymbol{U}$ and $\boldsymbol{\delta}$ – the array of absolute values and phases for the bus voltages; $\boldsymbol{K}$, $\boldsymbol{\Omega}$ – the array of absolute values and phases for the transformer ratios; P_{ij}, S_{ij}, $ij \in R$ – real and apparent power flows through the ij network element, from the bus i to the bus j; 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:

$$P_{gi}^{min} \le P_{gi} \le P_{gi}^{max}, i \in G \setminus e;$$
$$U_i^{min} \le U_i \le U_i^{max}, i \in G \qquad (6)$$
$$K_{ij}^{min} \le K_{ij} \le K_{ij}^{max}, ij \in T;$$
$$\Omega_{ij}^{min} \le \Omega_{ij} \le \Omega_{ij}^{max}, ij \in T$$

- the **objective function** contains in addition the term corresponding to the congestion penalty cost:

$$min\ OBF = \sum_{i \in G} C_i(P_{gi}) + \sum_{ij \in R} TP_{ij}(S_{ij} - S_{ij}^{**}) \qquad (7)$$

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

$$C_i(P_{gi}) = a_i \cdot P_{gi}^2 + b_i \cdot P_{gi} + c_i, \quad i \in G, \qquad (8)$$

TP_{ij} – the penalty cost of the apparent power upper limit exceed through the ij network element; S_{ij}^{**} being defined as follows:

$$S_{ij}^{**} = \begin{cases} S_{ij} & \text{if } S_{ij} \le S_{ij}^{max} \\ S_{ij}^{max} & \text{if } (S_{ij} > S_{ij}^{max}) \end{cases}, ij \in R \qquad (9)$$

A non linear optimization problem with constraints is obtained. It is solved using the penalty function method, associated with the generalized Lagrange multiplier and the Fletcher-Reeves gradient methods. The algorithm is entirely presented in [11].

The transmission network optimal expansion method has been selected based on several arguments [17]:

- it has to provide a high degree of generality, to represent an useful instrument for every transmission system operator;
- the Romanian transmission system operator is focusing on several transmission expansion scenarios more or less realistic regarding the consumed and generated power evolution;
- data provided for the TNEP studies are more or less characterized by a high degree of confidence.

The TNEP problem within complex power systems is approached as a large scale nonlinear optimization problem. A heuristic searching model within the suitable solution area is proposed, having a quasi-dynamic backward-looking character. A multi-criteria objective function is used including: power system operation expenses, power system expansion investments expanses, reliability elements (synthesized using a risk factor) and total available transmission capacity.

The quasi-dynamic backward-looking character is proved by the fact that the TNEP solution is established only for the last year of the analysis.

The optimization process has a multi-criteria character. The qualitative comparison of the solutions is based on 4 criteria (they may be considered within a single OBF and weighted accordingly):

- 1st criterion refers to the operation cost. The information is provided by the power system operating condition analysis and OBF computing;

- 2nd criterion refers to the yearly investment expenses related to new transmission line construction.

  Due to several difficulties related to the quantification of the investment expenses, within the paper, the total length of the candidate transmission lines is taken into account. This approach is sustained by practical considerations: the case study refers exclusively to 400 kV OHLs construction, according to the real situation within Romanian power system;
- 3rd criterion refers to the reliability of the transmission network, considering a risk factor [12], [13];

$$r^{\%} = \frac{\sum_{k=1}^{n_\ell} q^k \cdot r^k}{\sum_{k=1}^{n_\ell} q^k} = \frac{\sum_{k=1}^{n_\ell} q^k \cdot P_r^k \left\{ \left| S_{ij}^k \right| > S_{ij}^{\max}, ij \in R \right\}}{\sum_{k=1}^{n_\ell} q^k} \cdot 100 \quad (10)$$

where: q^k – disconnection probability of the k^{th} OHL; n_l – OHLs number considered for the contingencies; S_{ij}^k – apparent power flow through the ij network element, in case of k network element disconnection; S_{ij}^{max} – maximum apparent power allowable admissible limit through the ij network element; r^k – congestion appearance probability in case of k network element disconnection; $\sum_{k=1}^{n_\ell} q^k \cdot r^k$ – total congestion probability (all N-1 contingencies).

- 4th criterion refers to the total available transmission capability (TATC) of the power system [14], [15], [16]:

$$TATC = \sum_{\substack{ij \in L \\ \left| S_{ij} \right| < S_{ij}^{\max}}} \left(S_{ij}^{max} - \left| S_{ij} \right| \right) \quad (11)$$

All the notations have the significance previously presented.

The "partial" OBF has the following form:

$$\begin{aligned} min\ OBF = \sum_{i \in G} C_i(P_{gi}) + \sum_{ij \in R} TP_{ij}(S_{ij} - S_{ij}^{**}) + \\ + w_1 \cdot \sum_{i \in TL} I_i + w_1 \cdot r + w_1 \cdot TATC \end{aligned} \quad (12)$$

where: I_i – refers to the 2nd criterion; TL – set of new transmission line to be constructed; r_i – risk factor; $TATC$ – total available transmission capability; w_i, i = 1, 2 ,3 – weighting factors.

3. CONSUMED POWER FORECASTING METHODOLOGY

Let us 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. The influence of a random component is taken into consideration [13].

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 $m = 2$ [11]:

$$P_2(x) = a_0 + a_1 \cdot x + a_2 \cdot x^2 \quad (13)$$

The values of the a_i coefficients are established according to [11]. 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 probability p [%]:

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

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

where ε_j is computed as

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

where σ^2 – standard deviation of the y variable:

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

Considering the $K = t_{\alpha/2, n_L}$ (α – the value for the Student distribution, $n_L = n_a - m - 1$ – the number of the freedom degrees), the necessary correction considering the probability p is introduced:

$$p^{\%} = 100 \cdot (1 - \alpha) \quad (17)$$

4. SOFTWARE TOOL

According to the mathematical model for TNEP (Section II) and the power flow probabilistic approach (Section III), a software tool is developed. It is designed in Matlab environment enjoying the entire characteristics specific to Microsoft Windows operating systems, having a user friendly interface [11]. A client-server application has been developed.

A script file containing the topology, the parameters and the specific elements of the power system is used. The data base corresponding to the operating condition of the power system is extracted from the Powerworld software.

The new values for the consumed power are loaded using another script file. The contingencies are carried-out also using the same script file; they are not manually effectuated by the user.

Once the software tool is launched, the user is requested to enter the desired number of samples. It allows the user to select between the events that he is going to consider: generation of the consumed power samples and generation of the contingencies. The power flow is computed, in concordance with the random event considered, using the same script file.

5. CASE STUDY

The case study is carried-out for the Romanian Power System. It has 145 buses (46 P-U, 89 P-Q,) and 193 branches. Within the power system the buses at medium voltage (real generating groups), 220 kV, 400 kV are represented (Fig. 1).

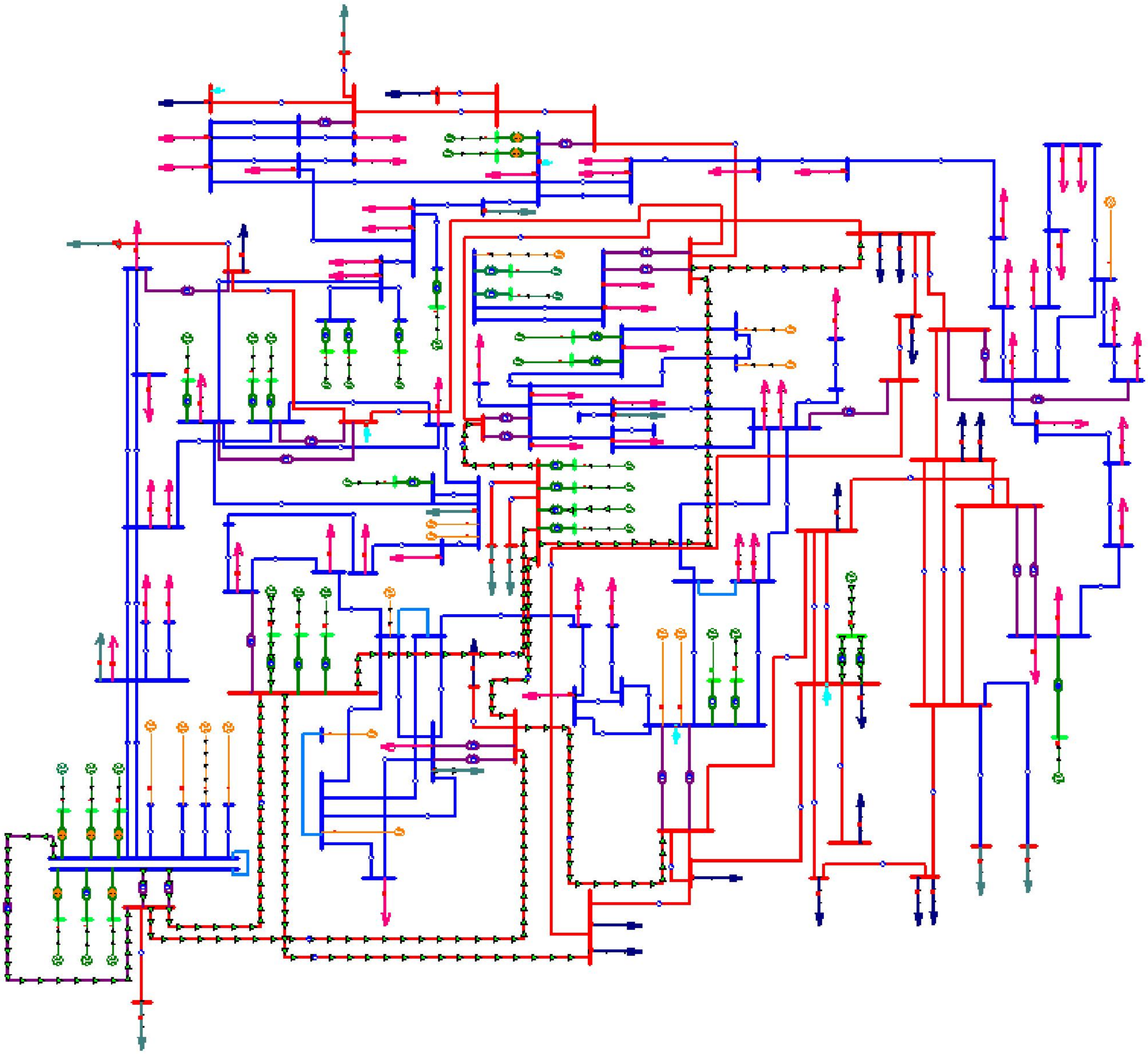

Fig. 1. Transmission network within the Romanian Power System

6. RESULTS AND DISCUSSIONS

The following OHLs are considered as candidates for transmission network expansion:

- 400 kV transmission corridor in the North-East side of the Romanian Power System (Suceava-Roman-Bacau-Gutinas) (Fig. 2);
- 400 kV transmission corridor: Brasov-Stilpu-Gura Ialomitei-Cernavoda (Fig. 4);
- 400 kV transmission corridor: Mintia-Tarnita-Gadalin-Bistrita-Suceava-Balti (Fig. 5);
- 400 kV OHLs: Brazi-Teleajen-Stalpu, Bradu-Sardanesti-Tantareni, Isaccea-Vulcanesti (Fig. 3, 6, 7);

Based on the consumed power within the period 2000-2009, a forecast has been performed for the period 2009-2018.

The 2[nd] stage of transmission expansion refers to the generating unit. The following evolution has been considered (Fig. 8):

- 29268 – 4 x 250 MW groups (pumped-storage power plant);
- 29286 – 2 x 330 MW groups;
- 28904 – 2 x 330 MW groups;
- 28021 – 1 x 200 MW group;
- 29279 – 1 x 200 MW group;
- 29277 – 1 x 330 MW group.

Considering the interest of the TSO regarding the wind energy, wind farms have been considered within several buses (1300 MW maximum power) (Fig. 9).

The power system has the following one-line diagram (Fig. 10) based on all the expansion scenarios previously presented.

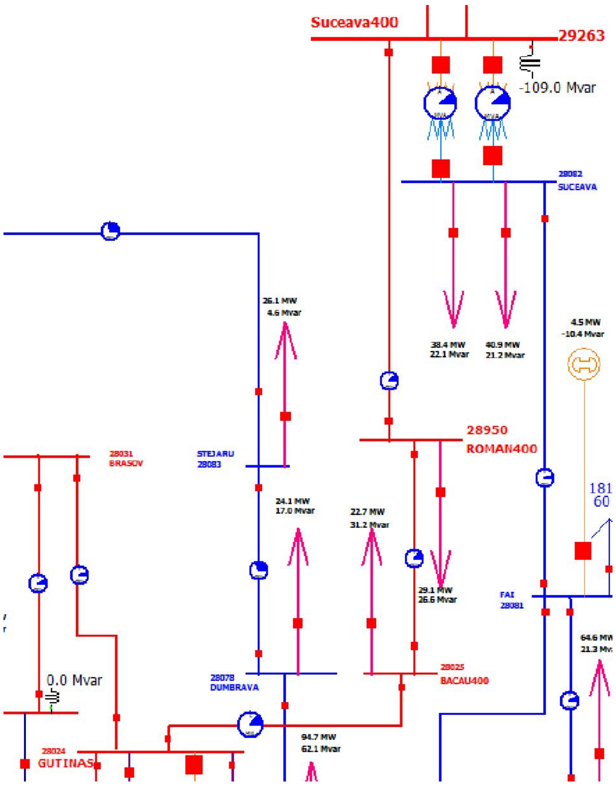

Fig. 2. Suceava-Roman-Bacau-Gutinas 400 kV transmission corridor

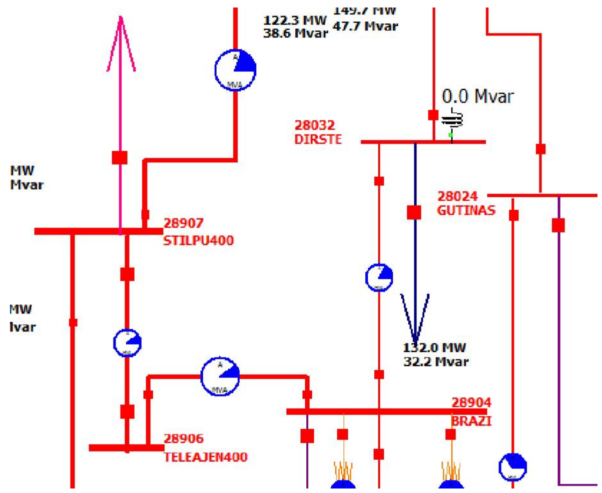

Fig. 3. Brazi-Teleajen-Stalpu 400 kV OHL

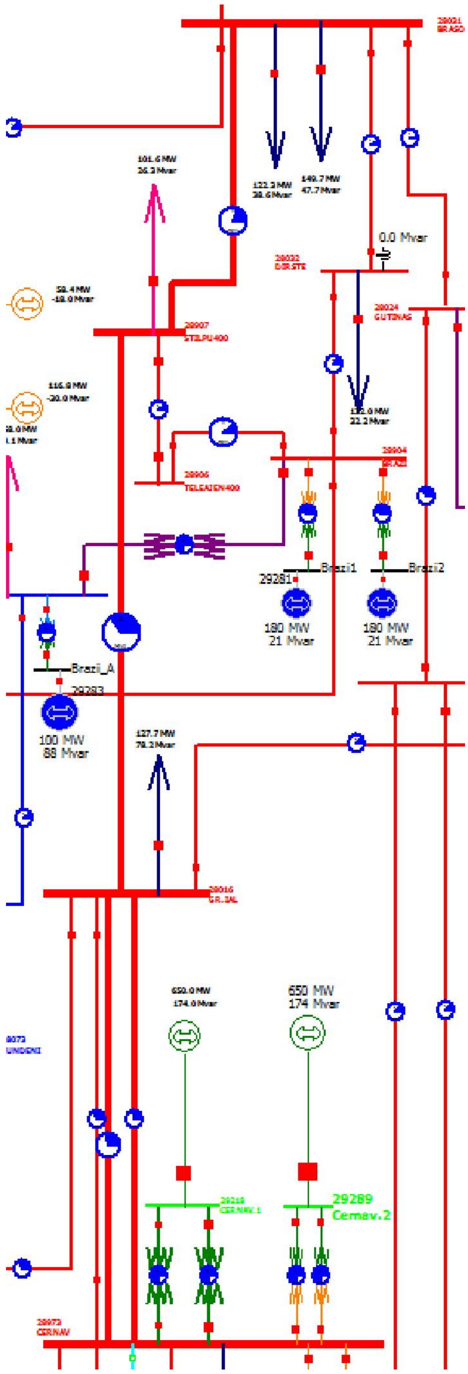

Fig. 4. Brasov-Stilpu-Gura Ialomitei-Cernavoda 400 kV transmission corridor

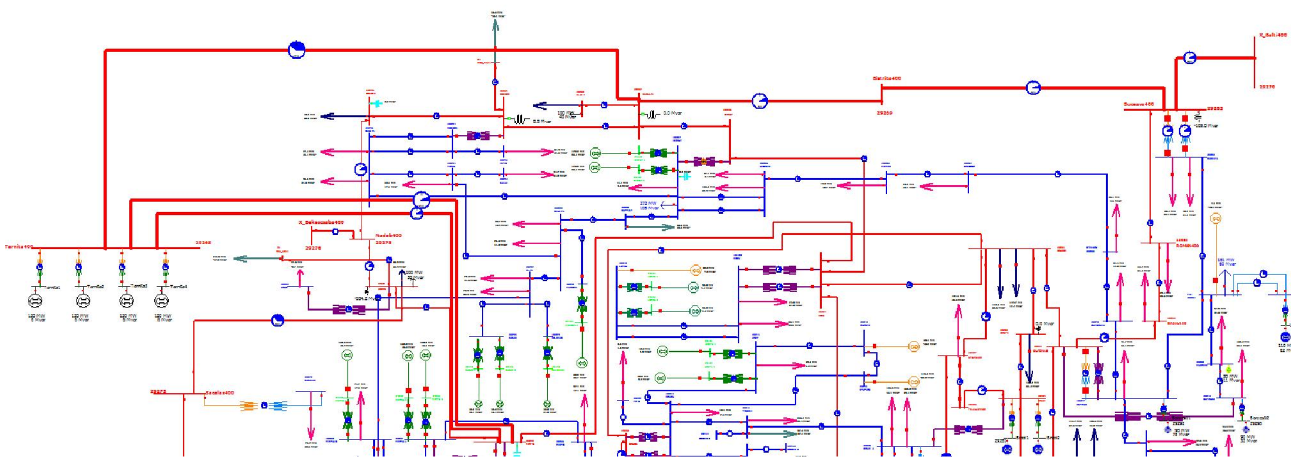

Fig. 5. Mintia-Tarnita-Gadalin-Bistrita-Suceava-Balti 400 kV transmission corridor

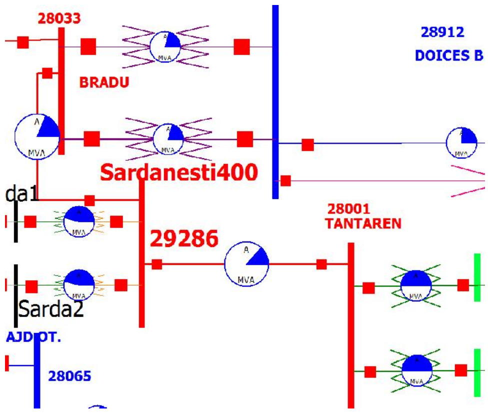

Fig. 6. Bradu-Sardanesti-Tantareni 400 kV OHL

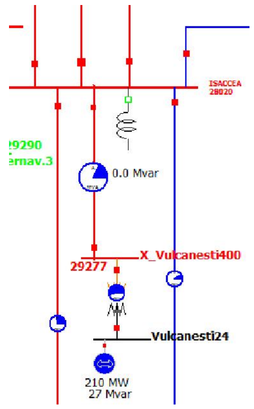

Fig. 7. Isaccea-Vulcanesti 400 kV OHL

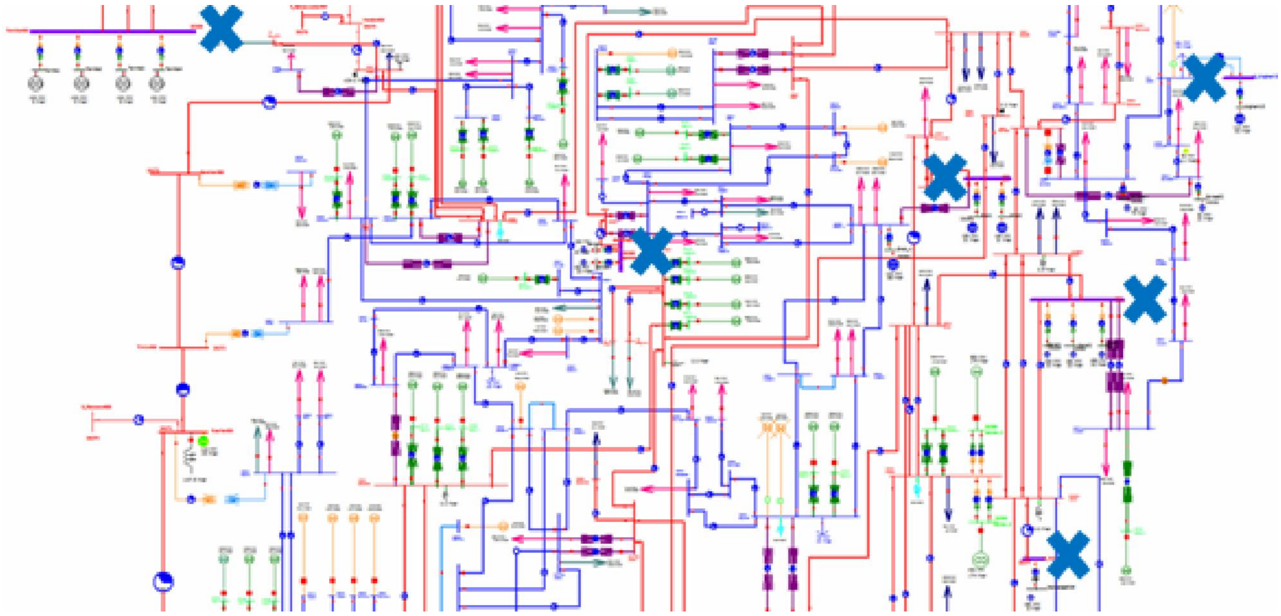

Fig. 8. Generation units' evolution

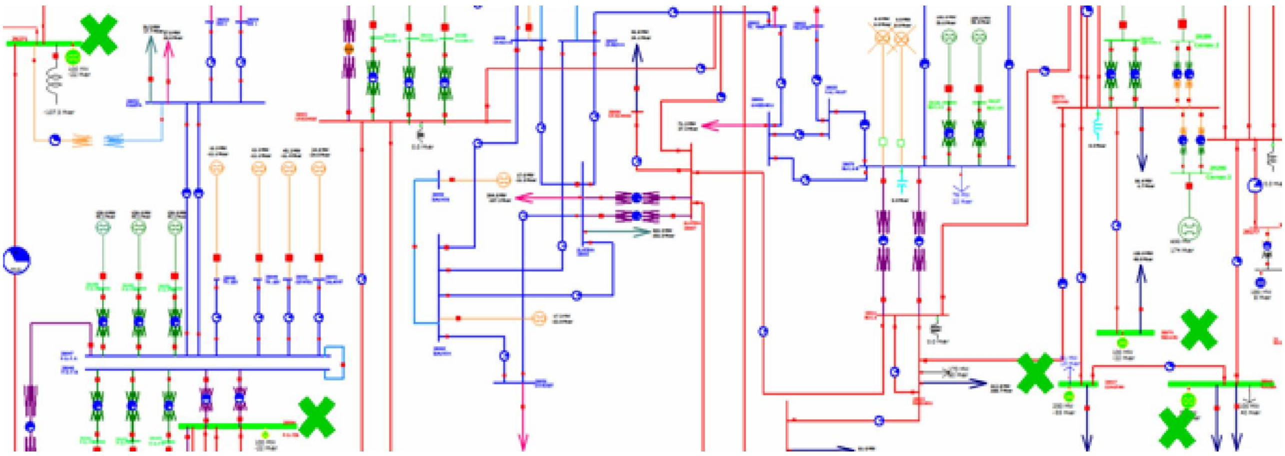

Fig. 9. Wind farm consideration

The 2018 year forecasted operating condition has been used. In case of probabilistic modelling of consumed powers, the analysis did not revealed any special situation. The power system is robust, characterized by reduced loadings of the network elements within the base case.

In case of power flow considering random *N-2* contingencies, in the following, several conclusions are briefly presented.

- simultaneous disconnection of the 28012-28024 220/400 kV autotransformer and the 28083-28084 220 kV OHL is leading to the congestion of the 220 kV 28074-28075 OHL;
- situations when no valid operating condition cannot be obtained are highlighted in case of double contingencies implying the 28012-28024 400/220 kV autotransformer.

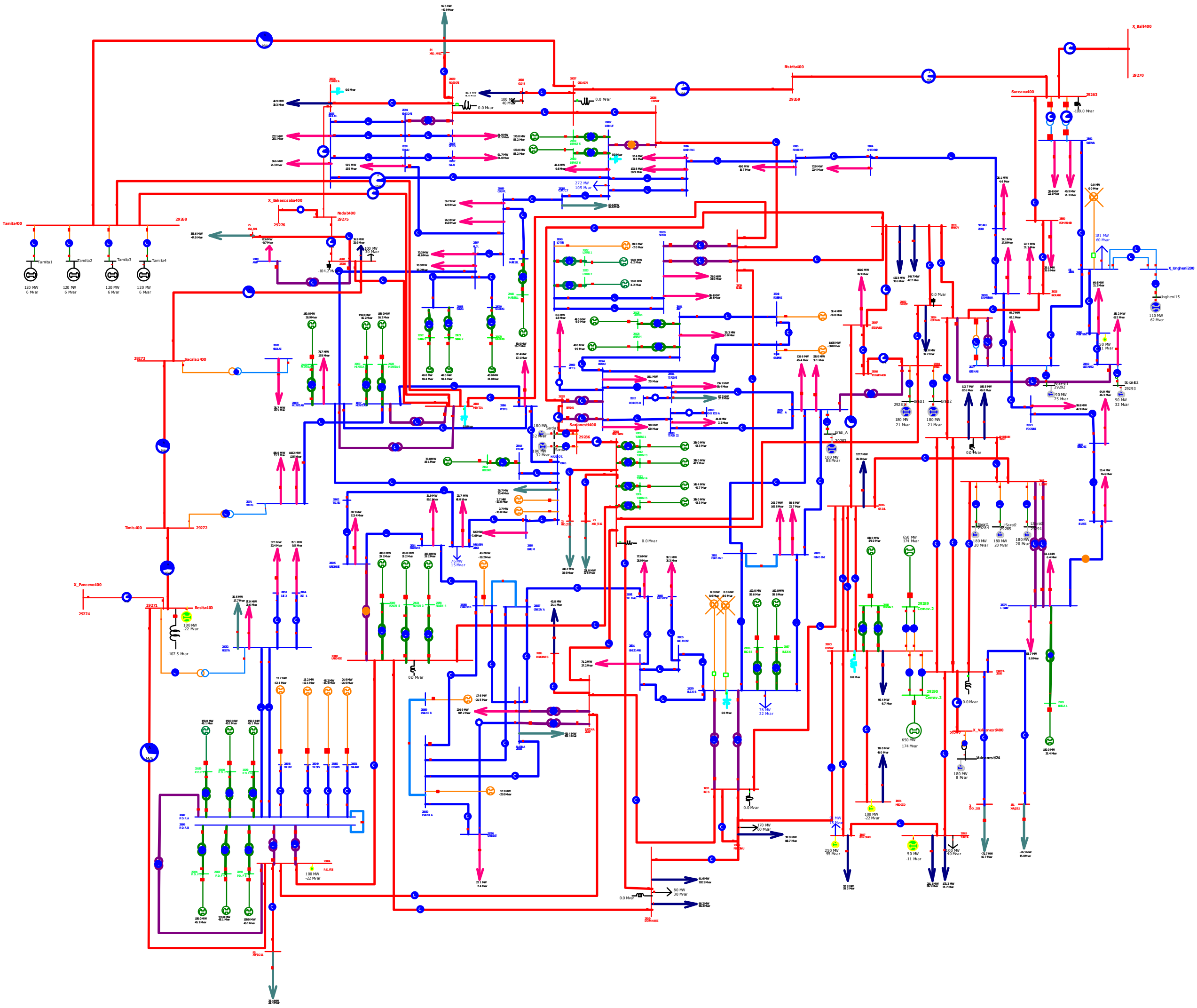

Fig. 10. One-line diagram of the power system

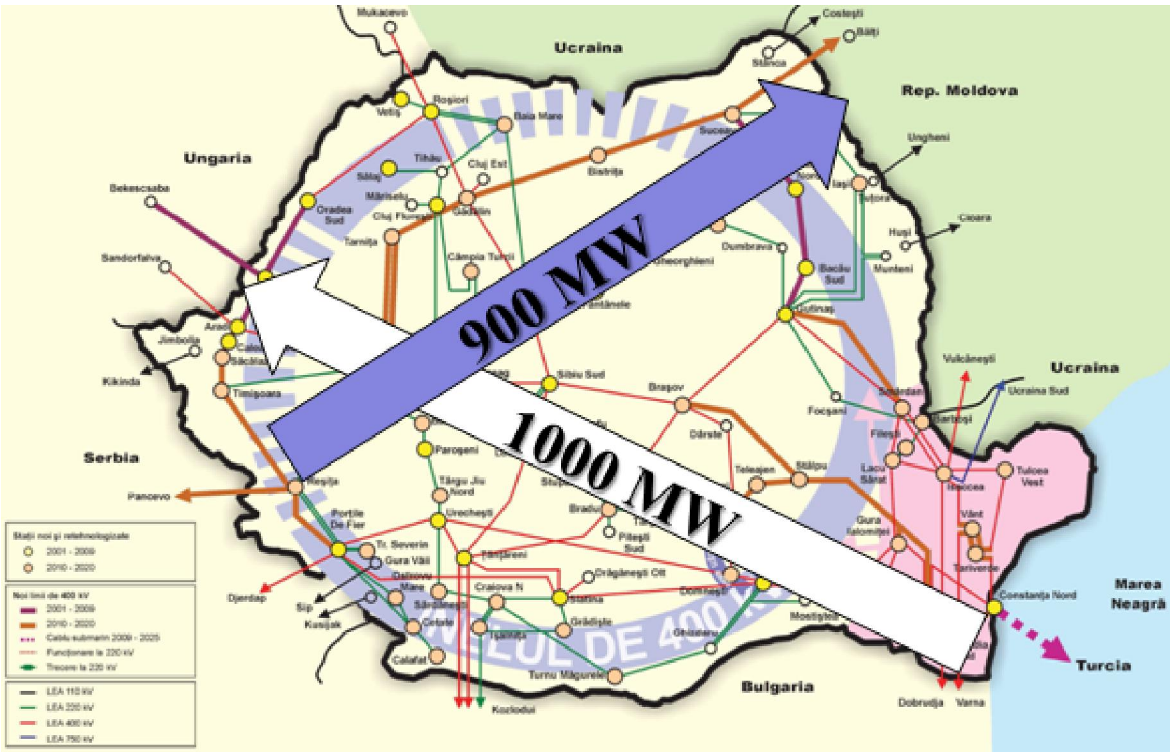

Fig. 11. Power transaction corridors

The transactions performed within the same power system or cross-border ones are representing another characteristic of the new deregulated environment. Considering this fact, different operating conditions with important power transactions (hundreds of MW) and increased consumption have been analyzed (Fig. 11):

- 1000 MW imported from Dobrudja (500 MW) and Varna (500 MW) and exported through the tie-lines with the Hungarian power system (Sardorfalva – 500MW and Bekescsaba – 500 MW);
- 900 MW injected through the 400 kV tie-line with Pancevo (Serbian power system) and exported to the Moldavian Republic.

7. CONCLUSION

The expansion planning solutions previously presented are rightfully only if the entire expansion scenario regarding the generating units is accomplished. This fact is sustained in case of highly increased consumed power or significant power transfers within the main transmission corridors.

The 28021 generating units' expansion is leading to the avoiding of the congestions highlighted within the scheme prior to the expansion scenario.

The appearance of the 400 kV corridor Suceava-Roman-Bacau-Gutinas avoids the issues regarding the disconnection of the Gutinasi autotransformer.

The 400 kV transmission corridor Brasov-Stilpu-Gura Ialomitei-Cernavoda allows an increased amount of generated power to be evacuated from the nuclear power-plant area.

The necessity of a pumped-storage power-plant is fully sustained for the proper operation of the nuclear power-plant.

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