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Automatic Cross-Border Transmission Capacity Calculation in Electric Power Interconnections

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Abstract: : The paper deals with relevant methodological and practical aspects of automatic cross-border transmission capacity assessment in electric power interconnections. It is based on advanced methodology for steady-state security analyses, using all its favourable properties, respecting the latest criterions, standards and practice of European Transmission System Operators (ETSO). The practical presentation of developed computer program is made on example of transmission capacity calculation in condition of ex Second UCTE synchronous zone. This presentation gives an overview of the characteristics and possibilities of this computer program, regarding the real necessities of operational practice in new conditions of liberalized electricity markets.

Keywords: : Cross-border, transmission capacity calculation, automatic mode, transmission system operator, open electricity market, interconnection in Balkans

1 Introduction

AN IMPORTANT issue in modern electric power systems (EPS's) is to provide the necessary level of operational security. In recent years, the increased practical interest to this issue has been shown, and corresponding new challenges appeared, mainly due to increased loading of EPS's, combined with a process of liberalization in electric power market and restructuring of the power utilities. Open access power systems need accurate transmission capacities evaluation to guarantee secure operation for all transactions. In other words, electric power market players need to know how much power can be transferred between certain points, i.e. to know the real technical limitations of these power exchanges depending of the set

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of various network constrains. Also, the processes above mentioned are very important and topical for all countries in Southeast Europe, as well as for Serbia and Montenegro and its power industry, according to the following facts: Reconnection of the Second UCTE synchronous zone with the main part of the UCTE grid (which was successfully made in 10 October 2004.) and establishment of Regional Electricity Market (REM) in South Eastern Europe.

For transfer capability evaluation, several different methods (deterministic or probabilistic, based on the DC or AC network models) have been proposed. Refs [1–8] are only few from the long list of recent published work in this area.

The basic objective of this paper is to present the relevant theoretical and practical aspects of an advanced methodology for fast cross-border transmission capacity assessments, or NTC (Net Transfer Capacity) in automatic mode, and corresponding computer program STATIC, developed in ORACLE environment. This methodology is consisted in two procedures:

- Procedure for identification and verification of initial steady-state (so-called base case);
- Procedure for automatic cross-border transmission capacity calculation, according to the definitions given by ETSO (European Transmission System Operators) [9] and also, respecting the latest criterions, standards and practice of this association published in [10].

Those procedures, for the planning and as well as for the allocation phases, i.e. for different time frames (from year ahead to day-ahead), are made in automatic mode, until a network constraint is violated. The generation increase/decrease (in automatic mode) has to be performed proportionally, according to actual spinning reserve. The first practical experiences in the application of this improved methodology have been gained on an example of the synchronous parallel operation of the EPS's in the former Second UCTE synchronous zone.

2 Formulation of Methodology for Aautomatic Cross-Border Transmission Capacity Calculation

This advanced methodology for automatic cross-border transmission capacity calculation is consisted in the following relevant parts, which differ to the usual approaches:

- Two procedures for initialization of steady-state security analyses, i.e. the procedure for solving the initial load-flow problems, which precede these analyses [8]. The first procedure enables the load-flow solution for given initial generators scheduling in interconnection considered. The second procedure gives the load-flow solution for realization of the set of bilateral or multilateral exchange programs between EPS's in interconnection considered.

- These procedures are fully consistent with the specially developed method for the following steady-state security analyses [11, 12]. Such characteristic of these procedures enables the unification of corresponding computer program, autonomy and uniformity of steady-state security analysis, as well as their successive realization, which have practical importance;
- The limits of generator reactive power, are not constant, a priori defined quantities, but rather corresponding functions of relevant generator parameters and state variables [11], and that is something opposed to the usual approaches;
- Procedure for forming the unified external network equivalents, with adaptive buffer system selection, consistently respecting the effects of primary voltage and frequency control of neighbouring power systems [13];
- Procedure for fast contingency selection, which is based on results from the single iteration of specially developed fast decoupled load-flow solution method, in which the power system frequency is relevant variable [11];
- Simple method for the accurate assessment of dynamic variation of power system frequency, during the operation of its primary control, as well as the quasi-stationary value of its frequency [14]. For the injection losses type of disturbance (such as outages of large generators), with this known value of frequency, the more accurate results after first iteration are obtained;
- Generalized injected models of transformer, which enables a simple presentation of both energy transformers with or without angle regulation as well as static phase shifting transformers (so-called series FACTS power flow controllers, which have the possibility of controlling the power flow without generation rescheduling or topological changes) [15];
- Generalized model of generator participation in NTC calculation, which enables the selection of the most convenient ones regarding the real operational practice in new condition of liberalized electricity market [16];
- Forming the practical and realistic security indices for selection of potentially critical disturbances, according to the real power performances and to the control and protection devices characteristics [14];
- For potentially critical contingency, the continuation of iterative procedure for solving the load-flow problem is performed (full solution), based on spe-

cially developed fast-decoupled method [8]. The continuation of iterative procedure (full contingency analysis) is made for this case:

1. Violation of voltage magnitude, element current and generator reactive limits;
2. Shortcoming of spinning and regulation reserve, according to the disturbance;
3. Indication of action of under frequency load shedding or under frequency protection of generator.

The proposed methodology strictly evaluates the transmission effects of primary frequency and load- frequency controls, i.e. the significant ”part” of TRM (Transmission Reliability Margin) are included (except the part that takes into accounts the uncertainties on system conditions and the precision data in load-flow models).

This method enables successive solution of the load-flow problem for a set of characteristic post-dynamic quasi-stationary states: states resulting from primary voltage and frequency control, states after the action of automatic secondary control of frequency and tie-line power and states after corresponding possible dispatch activities, if necessary (corrective control) [11].

The different generator participation models during the transmission capacity assessments of electric power interconnection are considered. The generation increase/decrease (in automatic mode) is performed according to combination of following predefined criteria: proportional increase/decrease according to the actual spinning reserve, increase/decrease according to previously observed behaviour of generators (the usual response pattern of generation to different system loads) and increase/decrease according to a well-known merit order (economic dispatch).

Evaluation of those models is made on example of automatic cross-border transmission capacity calculation in Second UCTE synchronous zone. This evaluation enables the choice of the general form of participation model, which is the most convenient regarding the operational practice in conditions of liberalized electricity markets [16]. The best practical solution for the generation increase/decrease is the model, in which the necessary changes of active power are proportional to the actual spinning reserve:

$$P_{ni} = P_{oi} \pm \sum_{k=1}^{n} \frac{P_{ei} - P_{i(k-1)}}{\sum_{i=1}^{NGA} (P_{ei} - P_{i(k-1)})} DEXP \quad (1)$$

where P_{ni} is active power of generator (i) in step (n) of NTC calculation, P_{oi} is active power of generator (i) in initial steady-state (” base case ”), k is number of steps in

NTC calculation and P_{ei} is extreme values of generator (i) active power. For generators in exporting area, that is the available (with respecting the corresponding spinning reserve) or maximum value of active power Pmaxri. For generators in importing area, that is the Pmini - minimum value of active power. NGA is total number of generators (in EPS or area considered) which participate in NTC calculation and DEXP is discreet step of total exchange program correction between the EPS's, for which NTC calculation is made (usual value is 50 MW).

The generator active power must satisfy the following constraint:

$$P_{mini} \leq P_i \leq P_{maxri}(2) \tag{2}$$

e.g. the shift is to be performed taking into account the technical operation constraints of each generator and its technical limits (maximum/minimum power, optimal use of a power plant, water or fuel available).

Also, during the NTC calculation, the generator voltage reference is to be changed according the following expression:

$$Vn = V_0 \pm \sum_{k=1}^{n} \frac{P_{(k)} - P_{(k-1)}}{P_{(k-1)}} (V_e - V_{(k-1)}) \tag{3}$$

where V_n is generator voltage reference in step (n) of NTC calculation, V_o is generator voltage reference in initial steady-state and Ve is extreme values of generator voltages. For generators in exporting area, that is the maximum value of voltage Vmax ; for generators in importing area, that is the minimum value of voltage V_{min}.

The generator voltage must satisfy the next constraint:

$$V_{min} \leq V \leq V_{max} \tag{4}$$

In expressions (1) and (3), the sign is ”$+$” for the generators in exporting EPS, and the sign is ”$-$” in importing EPS.

It should be noted that the variable constraints for generator reactive power and corresponding variation of generator voltage reference, during the cross-border transmission capacity assessment, are significantly improved the accuracy of reactive power- flow and voltage calculations.

3 Concept of Automatic Cross-Border Transmission Capacity Evaluation

Figure 1 presents the global concept of the proposed methodology, e.g. of the modulary organized computer program STATIC developed in Nikola Tesla Institute in ORACLE environment [17] for automatic cross-border transfer capability calculation, using flow diagrams of the basic functions. This methodology uses a unified data base (block 1), as a segment of the complex database necessary for the operational planning of EPS. For cross-border transmission capacity assessments for the planning and for the allocation phases in different time frames, from year ahead to day-ahead, the following input data are needed: relevant network model and topology, technical network data, estimated generation and load patterns and technical and operational limits. For this purpose the UCTE data exchange format is used [18].

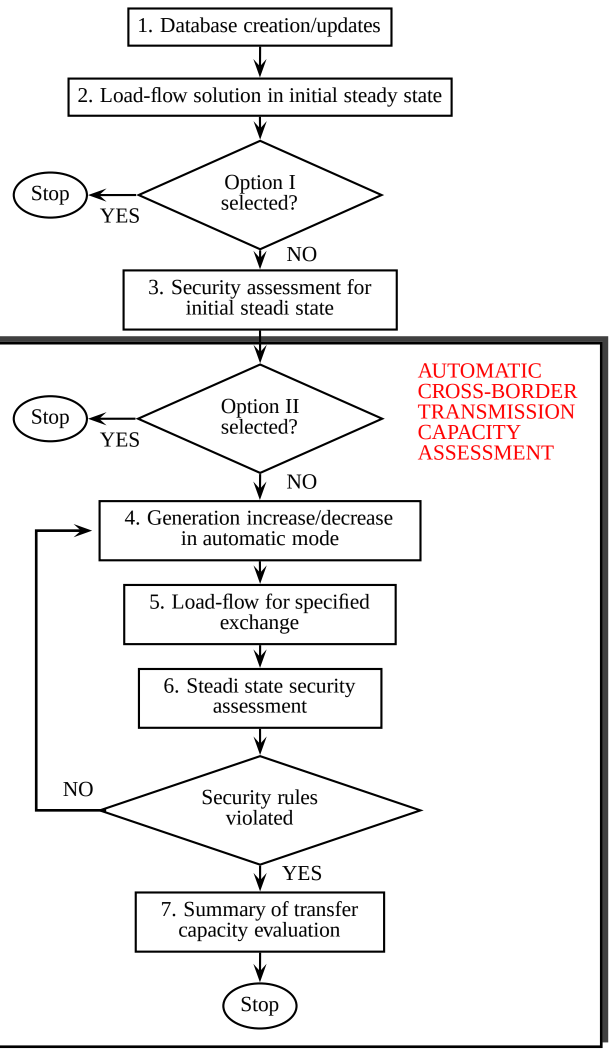

Fig. 1. Flow diagram of automatic cross-border transmission capacity assessment.

If the first option of application is selected (identification and verification of initial steady-state, with bad data processing), only load-flow solution in initial (base) steady-state is performed (block 2). In the case of second option, after calculation the initial load-flow, the security assessment for this state is made (block 3). This assessment is made respecting the N-1 security criterion (per example: outage of single lines 400 kV, 220 kV and 110 kV, transformers 400/220 kV/kV, 400/110 kV/kV and generators) and N-2 security criterion, in case of double circuit.

After the inauguration of initial steady-state that satisfied the security constraints, the automatic cross- border transmission capacity assessment is made. In order to determine the cross-border transmission limit between two neighbouring countries or zones, cross-border exchanges are gradually increased while maintaining the loads in the whole system unchanged until security limits are reached.

Starting from the common base case exchanges, the additional exchange is performed through an increase of generation on the exporting side and an equivalent decrease of generation on the importing side in automatic mode (in step of e.g. 50 MW). This generation shift is to be made stepwise until a network constraint is violated. The security assessment is also made respecting the N-1 security criterion (and N-2, in case of double circuit). The procedures, marked in block 4 (generator increase/decrease in automatic mode, proportional to the actual spinning reserve), block 5 (load-flow solution for specified exchange in step of 50 MW) and block 6 (steady-state security assessment) are stopped, when predefined security rules are violated. Finally, block 7 gives the summary of transfer capability evaluation. The output results are: Total Transfer Capacity (TTC), Transmission Reliability Margin (TRM), Net Transfer Capacity (NTC), Already Allocated Capacity (AAC), Notified Transmission Flow (NTF) and Total Transfer Flow (TTF).

4 Practical Application of Proposed Methodology

The first practical experiences in the application of the developed methodology have been gained on an example of the existing electric power interconnection in Balkans [19]. Figure 2 shows the block diagram of examined interconnection with the active and reactive power flows (MW/Mvar) over the interconnecting lines in two cases: 1) without any exchange programs between the EPS's (except the exchange between Serbia and Montenegro and part of Republic Srpska) and 2) when Romania exports 300 MW to Serbia and Montenegro (values given in parentheses).

Thus, in the first case, the BCE (Base Case Exchange) between the EPS's in interconnection considered (except the above mentioned exchange between SCG and RS) does not exist (”zero” exchange program). In these conditions, the physical

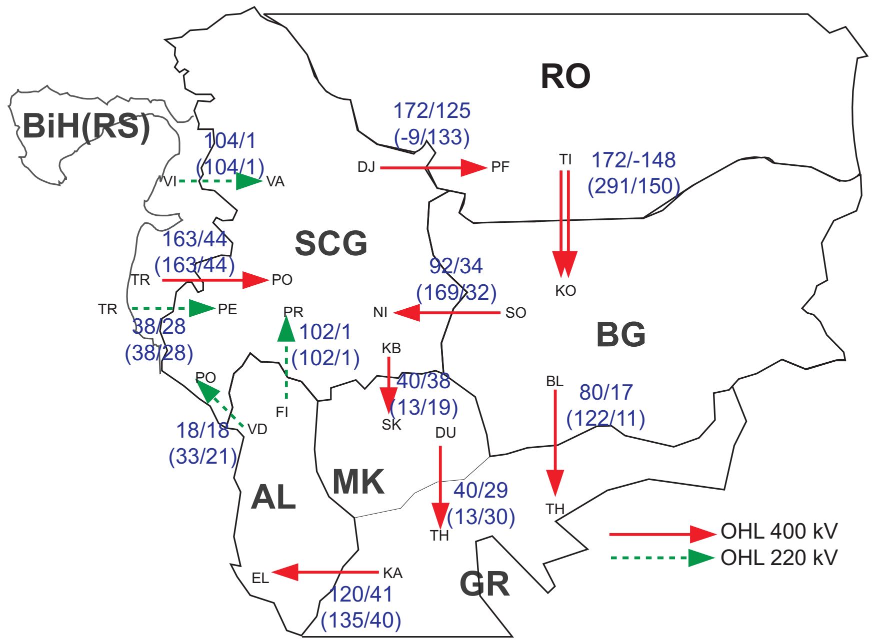

Fig. 2. Active and reactive powers on interconnecting lines in the former Second UCTE synchronous zone.

power flows on interconnecting lines presented are so-called parallel (or ring) flows, e.g. the physical flow NTF (Notified Transmission Flow) only consists of parallel flows. In this state and also during the security assessment, the relevant network constraints (voltage and current limits) are not violated.

In second case (RO exports 300 MW to SCG), the power flow on interconnecting line Derdap (SCG) - P. De Fier (RO) changes the direction, and this physical flow of 9 MW (now, in direction RO? SCG) is in reality the NTF (which is now, in amount of along parallel power flows, results from above mentioned exchange 300 MW). Also, in this state the predefined security rules are satisfied.

This state of interconnection considered (with $BCE^{RO\rightarrow SCG}$ = 300 MW and $NTF^{RO\rightarrow SCG}$ = 9 MW) has been the starting point for automatic cross-border transmission capacity calculation, according the flow diagrams (blocks 4, 5, 6 and 7), given in figure 1. From many results that were obtained, the case of power exchanges between Romania (exports) and Serbia and Montenegro (imports) has been chosen as a good illustration.

For outage element type of disturbances (all elements, which are loaded more then 40% of own thermal limit are included), the procedure for automatic cross-border transmission capacity assessment is stopped when the total exchange $RO \rightarrow SCG$ was 750 MW. In this case, the critical outage was the outage of transformer 400/231 kV/kV, 400 MVA in Portile De Fier in Romania, and the critical element was the line 220 kV Paroseni-Baro Mare (RO), with 8% violation of thermal limit.

Thus, the Total Transfer Capacity $TTC^{RO\rightarrow SCG}$ in case considered was 700 MW. This quantity is 50 MW lower then above mentioned 750 MW, i.e. in case of exchange of 700 MW the security rules are still satisfied. Also, the quantity of ΔE_{max} (additional exchange program between respected countries) was 400 MW (extra increase/decrease of generator's active power over the base case in automatic mode, which is ensured still the safe operation) and the Total Transfer Flow $TTF^{RO\rightarrow SCG}$ was 249 MW.

According to its definition [10], TTF is the net physical flow across the border associated with a program exchange of magnitude TTC (figure 3). In case considered, this quantity is the physical active power flow through the unique interconnecting line between EPSs RO and SCG (interconnecting line 400 kV P. De Fier (RO) - Derdap (SCG)), which corresponds to the $TT^{CRO\rightarrow SCG}$ (700 MW), respecting the existence of $BCE^{RO\rightarrow SCG}$ (300 MW). The established value of $TTF^{RO\rightarrow SCG}$ consists of two components:

- The Notified Transmission Flow $NTF^{RO\rightarrow SCG}$ (9 MW) (physical flow over the interconnecting lines between the considered areas in base case prior to any generation shift).
- The physical flow $\Delta F_{max}^{RO\rightarrow SRG}$ (240 MW) (physical flow over the interconnecting lines between the considered areas induced by the maximum generation shift ?Emax (MW)).

The most complex and delicate part of NTC calculation is the evaluation of Transmission Reliability Margin (TRM), which is a security margin that copes with uncertainties on the computed TTC (Total Transfer Capacity) values. Those uncertainties may arise from: unintended deviation of physical flows due to the load-frequency control, emergency exchange caused by the unexpected unbalanced situations (big injection losses) in real time and inaccuracies in data and calculation models and/or method. This comprehensive set of possible uncertainties explains the existence of many different approaches for the solving of this problem in practice [20–23].

The value of TRM can only be estimated, because it should consider all uncertainties of system operation. TRM in majority of EPS is estimated, according the statistical analysis of past data (per instant, statistical study of individual tie line "errors", calculation of standard deviation of tie-line power e.t.c). Next, in practice, the part of TRM, which corresponds to the inaccuracies in data and calculation models and/or method isn't bigger than 5% of computed TTC value. Also, in practice of ETSO, a reasonable value of TRM usually could be found by assuming an unpredictable power flow mismatch on each interconnecting lines (e.g. 100 MW), multiplied with the square root of its number ($\sqrt{l}$), i.e. TRM [MW] = $100\sqrt{l}$.

If above mentioned very simple practice is applied in case considered (existence of the single interconnecting line between EPSs RO and SCG - line 400 kV P. De Fier (RO) - Derdap (SCG)), the value of $TRM^{RO \to SCG}$ would be 100 MW, and the corresponding value of $NTC^{RO \to SCG}$ would be 600 MW.

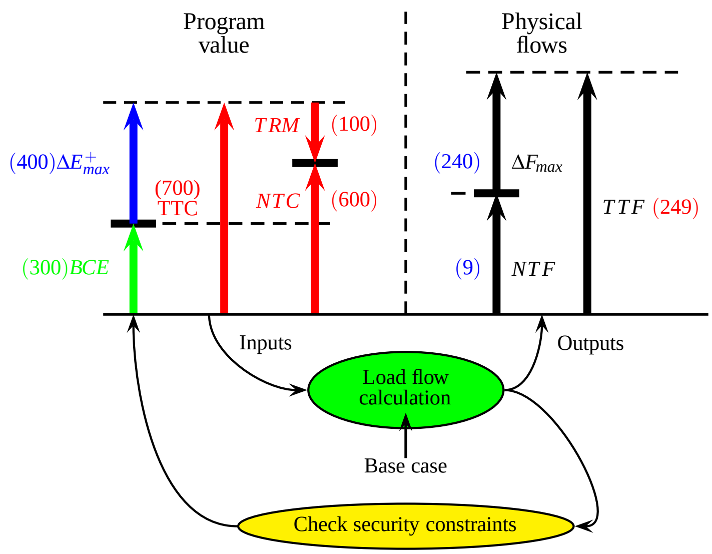

Fig. 3. The graphical interpretation of the NTC calculation and obtained results.

Finally, it should be pointed out that is only the illustration of NTC calculation, which is in close correlation with the state of interconnection considered and with the selected manner of extra increase/decrease of generator's active power over the base case in automatic mode. In EPS's of RO and SCG all generators participate proportionally to its actual spinning reserve, expect the generators which participate in load-frequency control.

Thus, the main objective was the demonstration of characteristics and possibility of developed computer program STATIC. At the same time, the results presented here enable an overview of the complexity in NTC calculation, i.e. on example of existing interconnection, the essential difference among the total exchange program between areas considered and the physical power flows over its interconnection lines was explained. Also, the first practical experiences enable the definition of the possible directions for further research in this topic (automatic NTC assessment in context of efficient congestion management methods for cross-border transmission).

5 Conclusions

The relevant theoretical and practical aspects of an advanced methodology for automatic cross-border transmission capacity calculation are presented. The characteristics of this methodology give the possibility for the unification of corresponding computer program, autonomy (”self starting”) and uniformity of steady- state security analysis, as well as their successive realization. Also, those characteristics enable the efficient and accurate transfer capability evaluation of real interconnection in automatic mode, which were demonstrated on example of existing electric power interconnection in Balkans. Thus, the methodology presented (and corresponding software STATIC in ORACLE environment), can be regarded as a useful addition to the software support of operational planning as an integral part of EMS of Transmission System Operators.

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