ASSESSING THE TRANSMISSION TRANSFER CAPABILITY SENSITIVITY TO POWER SYSTEM PARAMETERS

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Abstract – In the competitive environment the opening of the transmission system to the market players is leading more than in the past to congestion conditions. The paper gives particular emphasis to the Italian electricity market situation, where the large difference between the marginal production costs of the inner power plants and of some of the neighbouring countries (fed by nuclear fuel) is pushing the eligible customers to dramatically increase the demand of imported energy with the consequent attainment of the transmission limits.

Therefore the main focus of this paper is the definition of a simple and appropriate automatic procedure for calculation of TTC and of its sensitivity to power system parameters, such as the thermal limits of the constraining lines. After the definition of a studied corridor which subdivides the studied system in two areas (the source and the sink), the TTC of the corridor and its sensitivities to system parameters are calculated by means of a tailored to the problem security constrained OPF program.

Some important analyses of different foreseen scenarios of the Italian market are examined to put in evidence the presence of bottlenecks in the interconnections with the UCTE networks. Adequate analyses of these results can provide information necessary for system operation, network planning and energy market participation.

Keywords: TTC, competitive markets, sensitivity, congestion management, OPF, transmission system planning, ATC

1 INTRODUCTION

Around the world a competitive and deregulated framework is replacing the traditional vertically integrated structures in electric supply. In the new electricity markets, transmission grids are going to be operated closer and closer to their thermal limits. The increasing volume of power exchanges will modify the old conservative manner of the network utilisation. The new exploitation will be characterised by:

- greater volume of transactions;
- heavier line loading;
- higher frequency of hitting technical constraints;
- need for more detailed transmission planning studies as a consequence of the expected congestion of the inter-area transmission channels.

The situation is particularly critical for the electricity market in Italy, where the large difference between the marginal production costs of the inner plants and of some of the neighbouring countries is pushing the eligible customers to dramatically increase the demand of imported energy with the attainment of the transmission limits, particularly on the interconnection lines with the neighbouring UCTE networks.

In presence of a strong opposition to the construction of new transmission lines, the choice of substituting the old conductors with new compact conductors with smaller coefficients of thermal expansion [1] is envisaged as a practicable investment in order to increase in a medium term horizon the TTC of the interconnection corridor.

Moreover, in Italy an impressive demand (80000 MW) of installing new more competitive generation plants (combined cycle) is on the desk of the local ISO (GRTN). The acceptance of at least 20000 MW for the year 2010 is under discussion. This issue is dramatically conditioned by a correct calculation of the available transfer capability (ATC) of the practicable corridors. The happening of congestion conditions, consequent to a wrong generation expansion planning, will worsen the economical expectations of new investors.

Related to these key issues, the paper is devoted to the development of a suitable tool for the calculation of the total transfer capability (TTC) of defined power corridors and will focus the importance of determining the sensitivity of the TTC to the variation of some system parameters, such as the thermal limits of the transmission lines, the network topology and the load and generation distribution. Network topology modifications can be practised as control actions by system operators, but more often they happen as a consequence of transmission equipment outages. Different load and generation patterns can derive from a new generation expansion policy consequent to the electricity market liberalisation.

The paper addresses these issues with respect to the analysis of the Italian transmission system, introducing a simple and appropriate automatic procedure for the calculation of TTC and of its sensitivity to power system parameters, such as the thermal limits of the constraining lines.

The paper is organised as follows: section 2 introduces transfer capability definitions and presents a survey of the most recent methods proposed for the calculation of TTC and its sensitivity; section 3 is concerning with the method proposed by the authors; section 4 depicts the importance of transfer capability studies for power system planning and operation in the Italian framework. Finally section 5 presents and analyses the results of the application of the procedure to a CIGRE test system and to the Italian network in different transmission planning scenarios.

2 METHODS FOR CALCULATION OF TTC AND ITS SENSITIVITIES

Total transfer capability (TTC) is mainly a function of three limits [2]:

- thermal limits,
- voltage limits,
- stability limits.

According to NERC definitions [3], ATC (Available Transfer Capacity) measures the transfer capability remaining in the physical system that is available for further trading above already committed uses.

ETSO (European Transmission System Operators) introduces some additional definitions about the transfer capacity calculations both in the planning activity and in the allocation phase [4].

ETSO also specifies the procedure for TTC computation between a pair of neighbouring control areas A and B. Starting from a Base Case Exchange (BCE) and by means of a generation increase in area A and decrease in area B, the power flow rises until the security rules in either systems A and B are attained. The TTC from A to B is equal to BCE plus the maximum increase. The inverse procedure is used in order to compute TTC from area B to area A.

The most popular tool available for the determination of TTC (ATC) is the well-known CPFLOW [5]. It utilises a continuation power flow algorithm for the calculation of the maximum loadability of an electric power system, taking into account thermal, voltage and stability limits. The TTC (ATC) evaluation is a by-product of the procedure, attained for specified load and generation pattern increases. The accuracy of the results is obtained at not negligible computational time.

More recently some interesting methods have been proposed for a fast TTC (ATC) evaluation.

In [6] a linear estimation model is proposed that utilises a tangent vector at an initial power flow solution and then an iterative correction process for TTC calculation with a short computation time.

The program PROCOSE, used by Ontario Hydro and described in [7], is based on a DC power flow and performs the ATC calculation by means of an OPF program. In the economical dispatch two fictitious generators and a fictitious load are added in the network to calculate the ATC.

In [8], the ATC calculation is performed starting from three kinds of sensitivity: the line and generator outage distribution factors (LODF and GODF) and the power transfer distribution factors (PTDF). The ATC is the minimum of the ratios between the loadability margin of each line (in MW) and its power transfer distribution with respect to the examined line of the corridor, for all the lines.

The described methods basically concern with the determination of the maximum transfer allowable between a couple of buses, the source and the sink, and are not easily applicable to the definition of the maximum transfer capacity of a corridor interconnecting different areas with several sources and sinks. Moreover the computational speed is obtained by utilising linear approximations of the power flow equations, such as the DC load flow or the power transfers distribution factors.

In [9] a procedure for quantifying the first order effect of network uncertainties (load forecast error and simultaneous transfer) on the calculated transfer capability of a power system is investigated.

A more accurate method [10,11] takes into account voltage constraints and capability curves in the determination of TTC and quickly calculates the sensitivity of the transfer capability with respect to the variation of some system parameters (regulated voltage set points, generator load sharing factors, load model parameters, etc).

3 OPF APPLICATIONS TO TTC ANALYSIS

In this paper we develop an AC model to evaluate transfer capacities between large systems, in which the interconnection corridor separates two sub-grids (the source area and the sink area). This simplification of the more complex problem of the evaluation of the maximum exchange between two areas, where parallel paths via other networks are present, is well practicable for the Italian system, due to the topological characteristics of the network. In our model the calculation is obtained by means of the generation redispatching for a defined load profile, according to ETSO directives. The shift of generation is not fixed at a prespecified value, but is determined by a redispatching at the solution point.

TTC and its sensitivities to some system parameters are calculated by means of a tailored to the problem optimal power flow program. The security constrained OPF gives, together with the maximum transfer on the specified interface, the TTC sensitivities to the capability of the congested lines, as the Lagrange multipliers of the active constraints at the solution point.

A very simple approach for the evaluation of TTC, with the help of an optimal power flow program, can be based on a typical economic dispatch problem. The aim of maximising the real power transfers on the selected corridor is approached by assigning production costs to the source area generators (exporting system) lower than the cheapest cost of the units in the sink area (importing system). The solution of this problem maximises the production of the source area generators, therefore increasing the power exchanges till the attainment of at least one transmission constraint.

In section 5 the inaccuracy of this approach will be shown by simulation tests. The weak point of the method is due to the impact of the topological location of the less expensive generators in the sink area, which can activate the constraints on some internal lines.

To overcome the previously described drawback, a tailored to the problem OPF tool has been developed. The objective function of the problem contains the total transfer of the selected corridor.

$$TT = \sum_{i=1}^{l} T_i \tag{1}$$

where:

l is the number of lines belonging to the corridor;

T_i is the real power flow on line i connecting bus h and bus k.

In the studied cases, network topology, transmission equipment capabilities, active and reactive load profiles, power exchanges with the external systems and the commitment of hydro and thermal generation units are assigned. A power flow calculation provides the base case exchange TT^0; then a linearisation of the total transfer is adopted:

$$TT = TT^0 + \sum_{hk \in \alpha_l} \sum_{j=1}^{G} \frac{\partial T_{hk}}{\partial P_j} \Delta P_j \tag{2}$$

where:

α_l is the set of the couple (hk) of the indices of the buses connected by lines belonging to the corridor;

G is the number of thermal generators;

P_j is the real power output of thermal generator j.

TTC is the calculated TT at the solution point. In the TTC evaluation the real power productions of hydro plants are maintained at the values assigned in the base case. TT is expressed as a function of the control variables P_j (the thermal generations) through the sensitivities of the real power flows:

$$\frac{\partial T_{hk}}{\partial P_j} = \frac{\partial T_{hk}}{\partial \vartheta_h}\frac{\partial \vartheta_h}{\partial P_j} + \frac{\partial T_{hk}}{\partial \vartheta_k}\frac{\partial \vartheta_k}{\partial P_j} \qquad \forall hk \in \alpha_l \tag{3}$$

The sensitivities $\frac{\partial \vartheta_h}{\partial P_j}$, $\frac{\partial \vartheta_k}{\partial P_j}$ in (3) are entries of the inverse Jacobian matrix of the real power flow equations.

The new OPF program optimises a multi-objective function in which the TT term is about two magnitudes higher than the production cost term:

$$\max_{P_j} \left\{ TT(P_j) - \frac{1}{\rho} \sum_{j=1}^{G} C_j(P_j) \right\} \tag{4}$$

where:

$C_j(P_j)$ is the quadratic production cost function of thermal generator j;

ρ is a cost coefficient, expressed in €/MWh.

In the objective function a cost term is maintained in order to obtain at the solution point information on the economical value of the solution.

A real security constrained OPF (SCOPF) is solved by adopting a compact reduced model of the problem as in [12]. In the real power balance equation a second order approximation of real losses is maintained, while suitable linearisation of current flows in transmission equipments are adopted both for N security (intact system) and N-1 security (contingency cases).

4 THE STUDY OF TTC FOR THE ITALIAN SYSTEM

In Italy the Transmission System Operator, called GRTN, is charged of assessing the security of the operation and of determining the needed reinforcements of the national grid to comply with, among others, the following requirements [13]:

- to reduce network congestions;
- to develop the interconnection between the national grid and the neighbouring countries.

In this study we focus on the evaluation of TTC on the interconnection border with the neighbouring countries. In the current situation import value near to 6000 MW are allowed with the consequent attainment of transmission limits on some lines near the border.

At present, the interconnection corridor with the UCTE network consists of six 380 kV lines (including the double circuit Rondissone - Albertville) and of nine 220 kV lines. The lines of the interconnection corridor are clearly in evidence in figure 1, where a consistent part of the 380 kV system of the UCTE equivalent network adopted in the studies is shown.

The adopted equivalent, relevant to the neighbouring countries, contains about 450 buses including load and generations represented at 380 and 220 kV. In the Italian network the generators are represented at the medium voltage level. The studied network results in about 1250 buses. A full representation of 380 kV Italian system can be found in [14].

The scenarios adopted in the studies are pertinent to the projection year 2005. The main assumptions for this horizon are:

- an annual growth rate of 3 % for the load demand;
- the renewal of the Italian thermal generation set with the installation of combined cycle units up to 11000 MW, part in substitution of old steam plants;
- the enhancement of the 380 kV system in the southern area with the installation of the line Matera-Santa Sofia.

For the interconnection corridor two different scenarios are considered. In the first scenario no reinforcement is assumed. In the second scenario the consistence of the interconnecting surface is improved, following the GRTN indication [13], by the introduction of a 380 kV line connecting San Fiorano to Robbia (Switzerland) in substitution of the 220 kV line Sondrio-Robbia and of a 380 kV line connecting Cordignano to Lienz (Austria) in substitution of Soverzene-Lienz (220 kV), represented in figure 2.

As an alternative, the possibility of uprating the conductors on some lines of the interconnection corridor is envisaged as a practicable investment to increase in a medium term horizon the TTC.

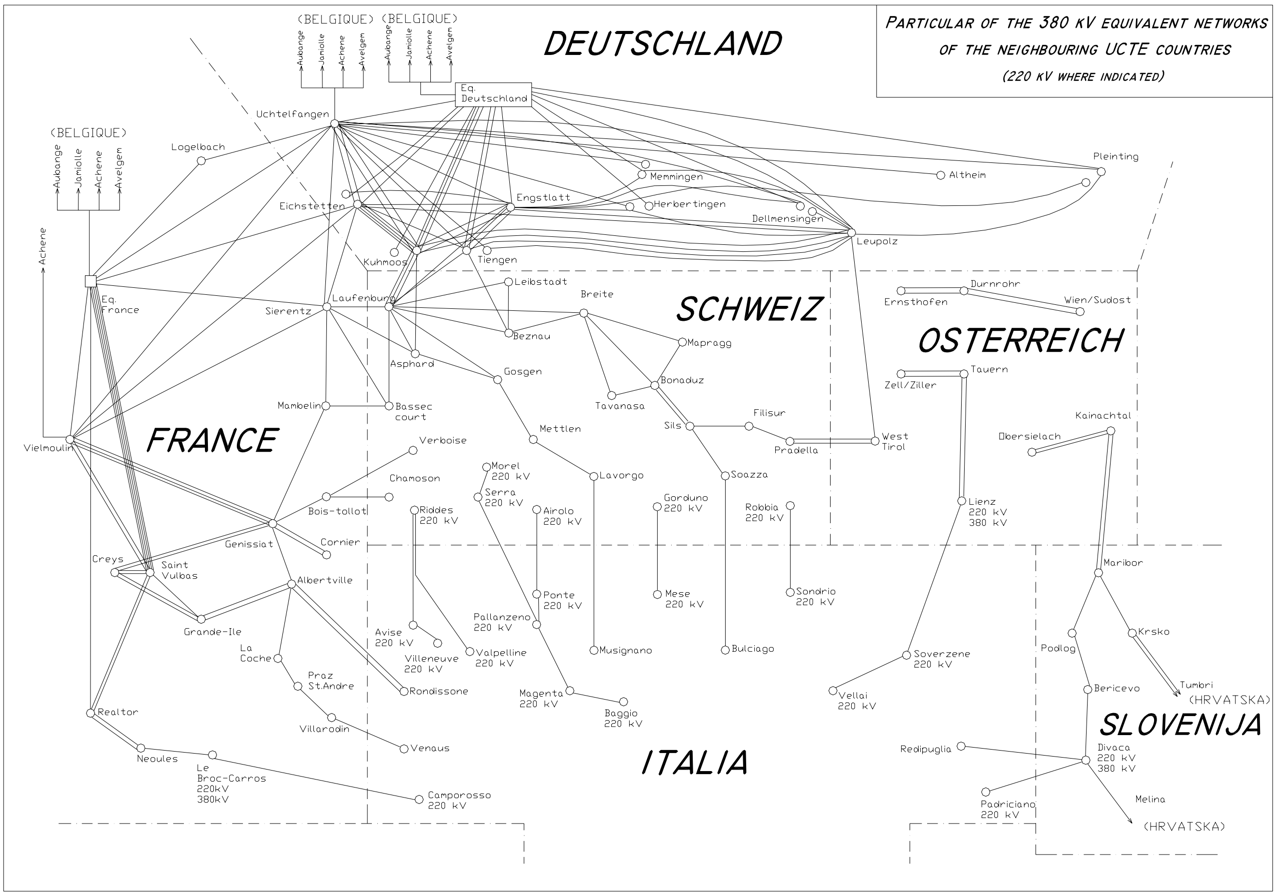

Figure 1: Particular of the equivalent networks of the neighbouring UCTE countries

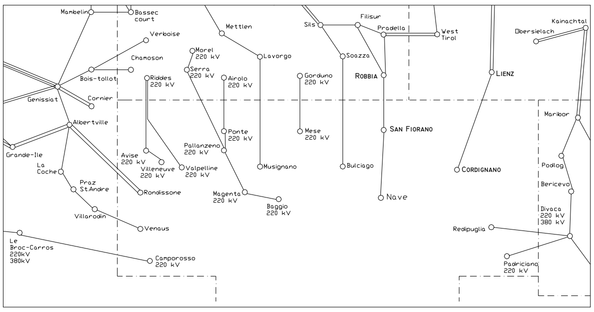

Figure 2: Planned network reinforcements

5 CASE STUDIES AND RESULTS

5.1 Studies on CIGRE 63-bus test grid

First, we present numerical results on a CIGRE 63-bus test system, previously adopted in [14] for applications of optimization techniques to handle the congestion management in a two-sided auction market structure. Figure 3 depicts the topology of this grid. Three 220 kV lines interconnect the source area with the sink area with a base case transfer of 602.3 MW. To give a term of comparison, the gross transmission capacity (maximum thermal capability) of the corridor is 819.3 MVA. The thermal limits of the three lines are given in table 1, together with power flows in the solution point.

With the aim of testing the new TTC computational tool, four cases have been considered with different production costs assigned to the thermal generators. The maximum difference in total transfer results 0.2 MW, with small differences in the generation profile at the solution points, confirming a light impact of the cost term in the objective function.

In a N security analysis, the TTC calculation determines the attainment of current limit of line 1M1-3M1 (900 A). The TTC on the corridor is 658.1 MW. The Lagrange multiplier of the binding constraint, equal to 0.84 MW/A, is employed to calculate the expected TTC increase, considering incremental upratings of the congested line. As shown in figure 4, the increases of TTC calculated by the OPF with the relaxed constraint confirm the expected values given by the Lagrange multiplier at the solution point.

Source bus	Sink bus	I [A]	Imax [A]	P [MW]
1M1	3M1	900.0	900	328.17
4M1	3M1	250.6	600	95.92
66M1	5M1	602.9	650	233.97

Table 1: Current and power flows on lines of the corridor at the solution point

To evaluate the effect of multiple constraints, the operational limit of the line 5M1-66M1 is decreased from 650 A to 590 A. Considering the constraint enforcement, the TTC drops to 650.4 MW, because of the attainment of the limit on line 5M1-66M1.

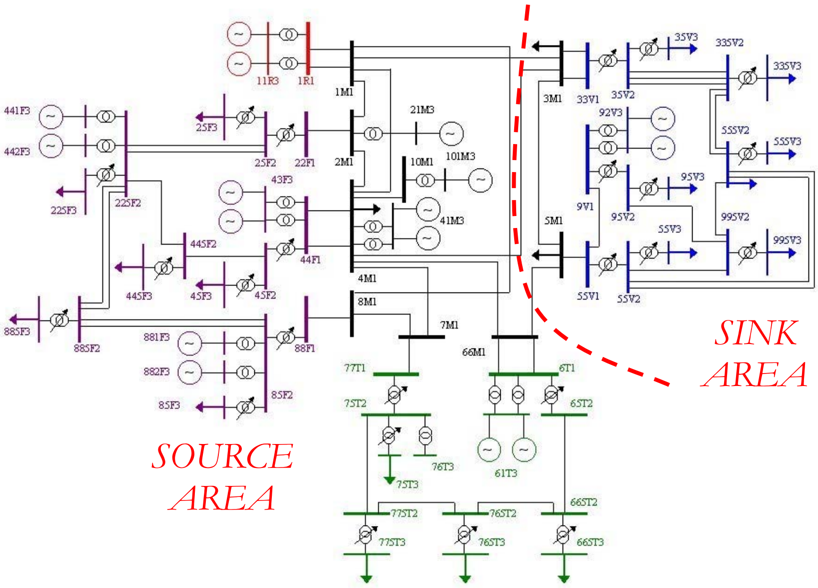

Figure 3: Cigre 63-bus test network

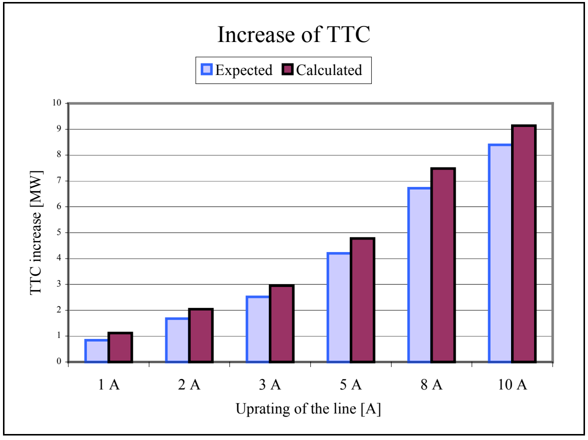

Figure 4: Comparison of expected (via sensitivity) and calculated (via OPF) TTC increases, uprating line 1M1-3M1

The Lagrange multipliers of the binding constraints are equal to 0.36 MW/A for line 5M1-66M1 and to 0.49 MW/A for line 1M1-3M1. An equal uprating for the two congested lines is adopted. Simulation tests confirm the consistency of the expected TTC increases; in figure 5 a total uprating of 2 A means a relaxation of 1 A on each congested line.

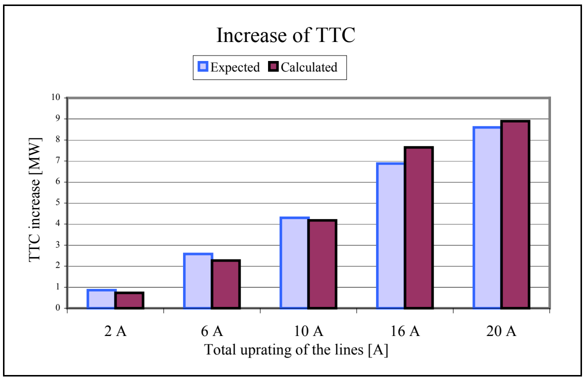

Figure 5: Comparison of expected and calculated TTC increases by uprating the lines 1M1-3M1 and 5M1-66M1

5.2 Studies on Italian system

Three equivalent thermal generators with the cheapest production costs are connected to the busses Eq. France, Eq. Deutschland and Laufenburg (in Switzerland). The current limits on the transmission lines adopted in the study are derived from ENEL SpA archives and comply with the most conservative weather conditions. The solution point in N security is characterized by the power flows on the interconnection border and from North to Center reported in figure 6, with a TTC of 6425 MW. The TTC obtainable with the OPF procedure based only on the cost function is 6175 MW.

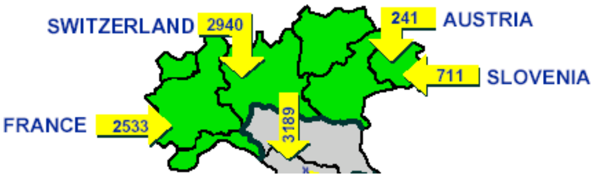

Figure 6: Real power flows on the boundaries (N security)

The TTC is limited by the attainment of the transmission constraint on the 220 kV line Pallanzeno-Serra at the border with Switzerland and by the contemporary congestion of the internal branch Pallanzeno-Magenta. The Lagrange multipliers of the binding constraints are 3.2 MW/A and 5.1 MW/A respectively.

Figure 7 shows the accuracy of the sensitivity model by a comparison of the expected and calculated values of the TTC increases, obtained by a relaxation of the current limits in the congested lines, assumed directly proportional to their capabilities.

To perform the contingency effects assessments, UCTE and ETSO recommend the N-1 security deterministic criterion. AEEG (Italian Authority) fixes an overloadability of the lines in emergency conditions up to 120 %.

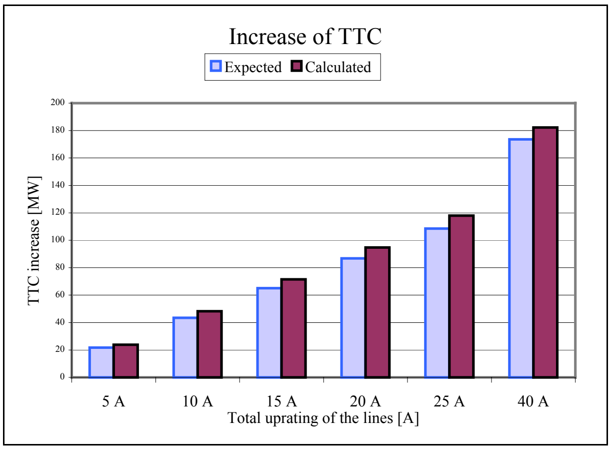

Figure 7: Expected and calculated TTC increases by the Pallanzeno-Serra and Pallanzeno-Magenta upratings

The contigency set includes the most critical outages, previously determined by a security assessment procedure, and particularly all the interconnection lines. In this situation the TTC drops to 5732 MW.

Table 2 gives, together with the thermal constraints, the real power flows on the interconnection lines provided by the OPF program in N and in N-1 security.

Figure 8 depicts the power flows in Northern Italy.

Source bus	Sink bus	Imax [A]	N [MW]	N-1 [MW]
Villarodin	Venaus	1291	881.57	865.65
Albertville	Rondissone 1	1699	727.32	711.81
Albertville	Rondissone 2	1699	728.73	713.19
BrocCarros	Camporosso	853	195.46	186.42
Lavorgo	Musignano	2254	845.85	725.88
Soazza	Bulciago	2300	819.41	692.07
Riddes	Avise	737	242.40	228.80
Riddes	Valpelline	737	260.31	245.45
Serra	Pallanzeno	651	264.97	248.21
Airolo	Ponte	651	130.36	109.10
Gorduno	Mese	617	157.01	157.00
Robbia	Sondrio	651	219.84	186.18
Lienz	Soverzene	648	241.32	147.27
Divaccia	Redipuglia	2211	602.02	509.85
Divaccia	Padriciano	648	109.09	4.79

Table 2: Real power flows on the interconnection lines considering N and N-1 security

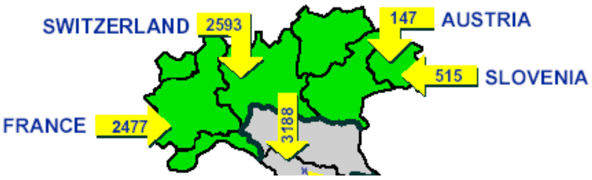

Figure 8: Real power flows on the borders (N-1 security)

A reconductoring of all the 220 kV interconnection lines and of the congested 220 kV internal branches from Pallanzeno to Baggio via Magenta is simulated in a modified scenario. Assuming that this kind of operation increases of 20% the thermal limits of the reconductored branches, the TTC in N security operation reaches 6953 MW. Despite the reinforcement, the 220 kV interconnection system still limits TTC; in particular the binding constraints are Soverzene-Lienz and the internal branch Avise-Villeneuve (near the interconnection with Switzerland). TTC in N-1 operation rises to 5998 MW.

5.3 Studies on Italian interconnection-reinforced system

The availability of the new 380 kV interconnection lines is simulated in this network-reinforced scenario.

The TTC rises to 7530 MW in N security operation. The active constraints are still Pallanzeno-Serra with a Lagrange multiplier of 8.6 MW/A and Pallanzeno-Magenta with a Lagrange multiplier of 3.8 MW/A. Figure 9 depicts the power flows in Northern Italy with the prospected interconnection reinforcements.

Again, the accuracy of the sensitivity model is shown in figure 10 by the comparison of the expected and calculated values of the TTC increases, obtained by a relaxation of the current limits in the congested lines.

TTC in N-1 secure operation results in 6815 MW. The real power flows in the interconnection lines in N and N-1 security are given in table 3.

Source bus	Sink bus	Imax [A]	N [MW]	N-1 [MW]
Villarodin	Venaus	1291	881.78	883.97
Albertville	Rondissone 1	1699	726.16	726.87
Albertville	Rondissone 2	1699	727.57	728.28
BrocCarros	Camporosso	853	196.41	200.77
Lavorgo	Musignano	2254	867.87	733.64
Soazza	Bulciago	2300	686.04	594.52
Robbia	San Fiorano	2000	1204.64	1003.30
Riddes	Avise	737	243.90	227.98
Riddes	Valpelline	737	261.94	244.47
Serra	Pallanzeno	651	265.13	255.61
Airolo	Ponte	651	130.45	104.91
Gorduno	Mese	617	157.00	157.00
Lienz	Cordignano	2000	521.31	416.54
Divaccia	Redipuglia	2211	556.18	523.06
Divaccia	Padriciano	648	104.55	13.89

Table 3: Real power flows on the reinforced-interconnection corridor (N and N-1 security)

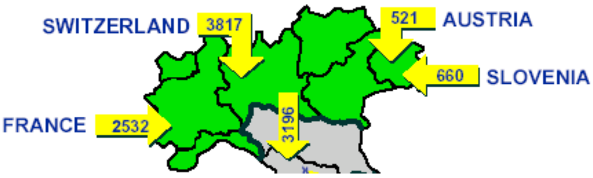

Figure 9: Real power flows on the boundaries (N security)

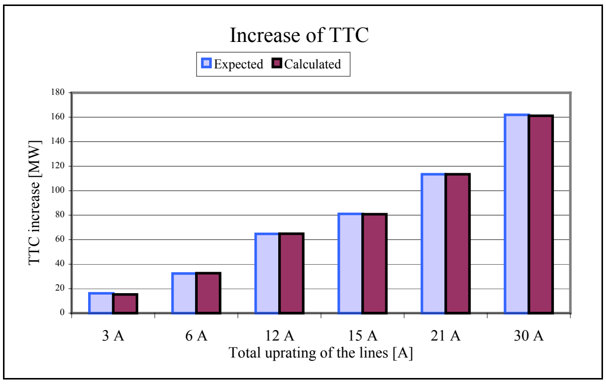

Figure 10: Expected and calculated TTC increases by the Pallanzeno-Serra and Pallanzeno-Magenta upratings

Power flows in N-1 security are shown in figure 11.

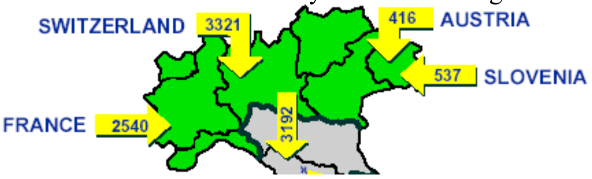

Figure 11: Real power flows on the borders (N-1 security)

The reliability of the obtained results is checked by verifying the distance of the determined operation point from the point of voltage collapse. At this purpose the automatic procedure VOSTA [15] available at CESI and Università degli Studi di Pavia has been employed.

VOSTA assures that the attainment of the thermal limits happens several thousands of MW before the voltage collapse appearance.

6 CONCLUSIONS AND FUTURE WORK

In the paper the usability of a security constrained OPF program for the determination of the total transfer capacity (TTC) of an interconnection corridor between two different areas of an electric system is investigated. The OPF includes in the objective function a predominant term containing the total real power flow between the areas and provides as an important by-product the sensitivities of TTC with respect to the bounds on the congested lines. This information can be utilised for transmission planning analyses. Practical examples of application of this methodology to the assessment of the TTC of the Italian interconnection with neighbouring UCTE countries and to the reinforcement claimed by the price structure of the European electricity market are envisaged. In future works the dependence of TTC on the generation expansion planning and the consistency of the proposed method in presence of parallel flows will be addressed.

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BIOGRAPHIES

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Paola Bresesti received her Dr. Ing. degree from the University of Pavia in 1991. In the same year she joined CESI where she has worked mainly in the field of power system planning, optimisation and control. She is presently responsible for the planning activities of the T&D department.

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