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A new deterministic approach for transmission system planning in deregulated electricity markets

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ABSTRACT

The transmission expansion planning has to guarantee the increase of competitiveness of market participants ensuring high standards of reliability and the safety of system operation. The congestion occurrences limit the competitiveness and cause an increase of costs for the final users. In the present paper a new deterministic methodology is proposed in order to support the static transmission system planning in deregulated electricity markets, which are characterized by high levels of uncertainties. The concept of criticality in transmission system planning is introduced: congestion cases and bottlenecks represent critical cases of the transmission system from a point of view of planners. The proposed approach allows individuating these critical states by solving specific optimization problems and performing reliability analyses based on the $N-1$ criterion. A comparison of different transmission expansion plans is performed assessing the indices of criticality, whose evaluation is based on measuring the exploitation of the margin capabilities of transmission lines. The indices have been used to measure the reduction of criticality associated to expansion plans. The proposed approaches have been applied on two different test systems in order to demonstrate the effectiveness of the methodology in transmission system planning applications.

Background and Introduction

The evolution of the bulk power system depends mainly on the transmission expansion planning (TEP) and from generation expansion (GE). The objective of TEP is to guarantee a transmission system (TS) expansion plan that ensures an adequate level of quantity and quality of energy supply, minimizing the inefficiency risk indexes and the operation and investment costs.

Many modern TS had been planned and developed mostly in a monopoly contest, where the monopolist had to ensure an adequate level of quality and continuity of supply and to dispatch generators satisfying the load variability at system minimum costs. The deregulation of the electricity market increased the level of uncertainties since the TEP and GE are not operated by the same entity. Hence, the TSP had significantly changed and several research activities can be found in literature aimed to develop new methodologies to individuate optimal expansion plans.

The deregulation of the electricity market can give rise to congestions in TS areas with possible consequent increase of total system costs. If one or more lines reach their power limit capacity, it may happen that a supplier that sells energy at a lower price is limited in power delivering. Therefore, to satisfy the load demand additional suppliers, located in points more suitable, but selling at a higher price, must be involved. The increase of price for the Demand can affect a single node or a zone of the TS in dependence on the market design as reported in [1,2].

In order to optimize TS loading and to evaluate the flexibility level of the system, in terms of greater or lesser suitability to accept new generations resulting from requests by the rules of the free market, new indexes have been proposed by the Authors. These indexes allow an evaluation of TS performances both for expansion and for operational system planning [3–5].

The conventional problem for TEP consists in minimizing the total construction costs, investing in new generators and transmission lines. In a first macro stage, the TSP can be performed neglecting the aspects related to the stability and fault analysis, which are investigated in a second micro stage [6].

TSP in deregulated electricity markets can be approached by means of optimization models which objective functions are focused on the minimization of the investment costs, such as for example in [7–11]. Moreover, approaches based on the optimization of the social welfare [12], transaction curtailments [13] and

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Nomenclature

TS	Transmission Systems
TSP	Transmission System Planning
TEP	transmission expansion planning
GE	generation expansion
TSO	Transmission System Operator
CMC	Congestion Management Capability
NPC	Number of Potential Congestions
DC	Direct Current
C_R	criticality threshold

a cost function that include operational, social and environmental costs [14] have been analyzed.

Also the reliability of the system can drive the TEP: the traditional approaches for reliability analyses are probabilistic [15] and are based on the Monte Carlo simulations [16]. However, in [17] the authors proposed a no-probabilistic methodology based on the robust optimization approach.

In the present paper the concept of criticality is proposed and used for long-term TSP as a necessary approach complementary to reliability. The terms are analogous from the point of view of physical power flows but are conceptually different: criticality considers potential overloads in terms of congestions whereas reliability in terms of system operation. Reliability qualifies the capacity of the TS to deal with not expected contingencies and is generally measured by means of statistical risk indices [5]. The value of criticality provides information about the closeness or the presence of potential congestions. To assess the criticality of the TS the dispatch configurations that lead to a congestion or closer to a congestion have to be individuated. A proper optimization problem has been formulated and solved to assess the criticality.

The above-introduced concept of criticality has been used to compare different transmission expansion plans. The objective of the methodology here proposed is to identify optimal transmission expansion plans that reduce the potential congestion occurrences. Hence, the identification has been made individuating the expansion plans that reduce the level of criticality. The approach is deterministic and can be used in TSP stages where an economic analysis had already been performed and different expansion solutions had been individuated.

The approach is based on the simulation of TS operation after the realization of the expansion plans. The methodology is based on the assessment of specific indexes that measure the adequacy of TS in terms of maintaining enough margin capacity avoiding congestion occurrences. The margin is a direct measure of how a transmission line is operating: its value, which will be formally defined in the next paragraph, indicates the distance of the line operation from the thermal limit. The approach is based on the identification of the minimum margin to individuate the existence of dispatch solutions that can cause and manage congestions.

Transmission system model

In the present work lines and nodes compose the equivalent model of a transmission network. The following sets are defined for a grid on N nodes and N_L lines:

- a set $B = \{1, 2, \ldots, N\}$ of buses b;
- a set L of lines l_{ij} identified by the pair of buses $(i, j) \in B \times B$ that it connects. The number of lines is $N_L = O(N^2)$.

Within the set B the following subsets have been identified:

- $B_G \subset B$ of the generation buses b_g. The total number has been assumed $N_g < N$.
- $B_C \subset B$ is the set of the load buses b_c. The total number has been assumed $N_C < N$.

To each bus $b \in B$ the following set of values are associated:

$$P_g, P_g^{min}, P_g^{max} \tag{1}$$

where at bus b, P_g is the power, P_g^{min} and P_g^{max} are the upper and lower power limits.

To each line $l_{ij} \in L$ the following set of values are associated:

$$P_{ij}, M_{ij}, P_{ij}^{max} \tag{2}$$

where P_{ij} is the power flow which depends on the power allocated to the buses (i, j) and by the characteristic of the transmission line; P_{ij}^{max} is the maximum continuous flowing power allowable on line l_{ij} and M_{ij} is the power margin defined as the difference between P_{ij}^{max} and the absolute value of the actual flowing power $|P_{ij}|$ *as* reported in (3).

$$M_{ij} = P_{ij}^{max} - |P_{ij}| \tag{3}$$

Assuming a constant load, the powers flowing on the lines P_{ij} and their margins M_{ij} depend only on the power injected in the generation nodes. In such model has been assumed that congestion occur when the margin of a line is zero.

$$M_{ij} \geqslant 0 \tag{4}$$

Given a specific constant-load scenario, different generations configuration exist and to an increase of power injected into a single node of the grid corresponds a decrease of production in one or more other generation nodes. Neglecting the power line and transformer losses, the power injected into the grid has to be equal to the total power of the connected loads. Being zero the minimum of each line margin, all the generation scenarios that do not satisfy (4) are considered not feasible and discarded from the analysis.

In particular, for each line l_{ij} with $(i, j) \in B \times B$ it is possible to define the Injection Shift Factor matrix ISF with elements ISF_{ij} as reported in [20]. For the bus b with respect to the line $l = \{i, j\}$ is possible to write the equation.

$$ISF_{(ij),b} = y_{ij} \cdot (z_{ib} - z_{jb}) \tag{5}$$

where

- y_{ij} is series admittance of the line l_{ij};
- z_{ib} is the i-term of the nodal impedance matrix;
- z_{jb} is the j-term of the nodal impedance matrix.

Under the hypotheses of DC Load Flow, the Injection Shift Factor ISF_{ij} allows to calculate the variation of power flow on the line l_{ij} for a unit variation of the power at any given bus $b \in B$.

Criticality in transmission system planning

Due to the nature of TS, an effective TSP in a deregulated electricity market should take into account the problem of congestion occurrence also in a long-term time horizon, when the effects of GE and fuel cost evolution can impact significantly on the expected dispatch solutions and consequently on the exploitation of the TS. The quantification and qualification of the congestions can represent a driver for TSP.