MODELLING OF DECISION MAKING SUPPORT TOOLS FOR THE ASSET MANAGEMENT OPTIMIZATION IN THE ITALIAN TRANSMISSION SYSTEM

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SUMMARY

The recent changes in the Italian electric market and its new regulatory framework, as well as the huge growth of RES installations (mainly PV fields and wind farms), led to the need of stronger optimization strategies in the transmission system operation, especially in the medium and short term asset management. These strategies also help to better evaluate the risk profile of the power system in the asset management, especially taking into account the variable and hard-to-predict RES production and the consequent widening of reasonable generation scenarios.

The paper deals with studies and analyses performed to finalize an analytical method for the asset management optimization and to model decision making support tools. The method is based on a constrained linear optimization problem and also takes into account all grid constraints, such as current and voltage limits, through linearized load flow calculations included in the optimization iterations. A prototype, that models the transmission network of Sicily (1150 km of 380/220kV lines, peak load up to 3500 MW, more than 1400 MW of installed wind power plants and about 750 MW of installed photovoltaic plants) including loads and power plants, has been developed to check the feasibility of the model implementation.

KEYWORDS

Asset management, Optimization, Grid constraints, Ancillary Services, Unit Commitment, RES

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1. INTRODUCTION

The Italian electric market consists of an energy market (run by GME, Italian market operator) and an ancillary service market, run by Terna Spa who owns and operates the National Transmission Power System. The electric power system is divided into different market zones which may have a limited transmission capacity between them. The opening of the transmission lines or grid devices, due to maintenance activities, can have some impacts on the transmission capacities between market zones and in general on the ancillary services as well, such as reserve margins.

The Operational Planning involves planning, through various timescales (from the yearly ahead to the weekly ahead), the coordination of outages of certain Generating Units, External Interconnections, Distributor’s networks and of parts of the Transmission System, which is carried out to achieve, so far as possible, the standards of security.

The Italian TSO coordinates more than 5,000 outages on a yearly ahead basis, among which about 4,000 are National Transmission System outages and 1,000 are Generating Units and Distribution System outages. In addition to these outages of the year-ahead programme more requests or programme changes can be submitted during the year on a weekly basis. The National Transmission System consists of more than 5,000 nodes and 6,000 lines with different voltage levels (380kV, 220kV, 150kV, 132kV, 70kV).

Minimization of impacts of the transmission grid devices maintenance on the energy and ancillary service markets, in terms of system security and cost optimization, and on the curtailments of RES production has been playing an increasingly important role in the operational planning. One of the main goal is to reduce energy volume (i.e. the cost) of the ancillary services and the curtailments of WFs RES growth which determines huge flows in the South Italy sub-transmission network leading to curtailment of wind production and other remedial actions.

New approaches, that harmonize both allocation of the transmission grid devices maintenance, generating units outages and fulfilment of grid security criteria and unit commitment of power plants, in terms of cost optimization of the ancillary services supply, have been investigated.

Optimizing a maintenance plan implies cost and security issues that must be evaluated in each possible scenario. To correctly evaluate each snapshot of the scenario, a market simulator has to provide data about generations and loads to the optimization tool, which will define the optimal plan that guarantees the fulfilment of security constraints and the minimization of ancillary services costs.

The research activities, which are outlined in this paper, are mainly aimed at designing the mentioned new approaches and modelling a computer program to support the optimization allocation of the asset management. In order to model the allocation process for a computer program it was divided into three main phases (Fig. 1):

I. **Simulation of energy market and evaluation of ancillary services prices**
   
   This phase provides a probabilistic representation of the unit commitment of the electricity market, based on a set of input assumptions relating to demand and generation. An estimation of the prices, offered for each power plant on the ancillary services market by GENCOs, is made. These simulations are made with a yearly time horizon and a daily resolution, taking into account both grid constraints and power plants maintenance.

II. **Asset Management Optimization**

   According to the scenarios provided in the first phase, the tool evaluates the optimal plan of the transmission grid elements outages, compliant to N-1 security criterion, adequacy constraints and costs minimization. The load flow analyses are based on a DC model and a mixed-integer object Linear Programming is set, taking into account both N-1 security and voltage constraints.
In order to decrease the number of iterations in the loop of the optimization algorithm, a pre-processing tool has been developed. This tool allows the user to identify a subset of snapshot in which the maintenance works can be carried out. The identified subset for each work is given to the optimization tool as additional constraints in order to limit the solution space.

III. Final Adequacy check with grid constraints
After the asset management optimization the last step is to verify once more the adequacy system taking into account the grid constraints (i.e. reduction of transmission capacities between zones or limitations to the power plants generation) due to the grid elements outages.

Before developing the final computer program the complexity of the problem has led to test the behaviour of the model, its time performance and the accuracy of the results through a prototype with a smaller network. The prototype, that models the transmission network of Sicily (1150 km of 380/220kV lines, peak load up to 3500 MW, more than 1400 MW of installed wind power plants and about 750 MW of installed photovoltaic plants) including loads and power plants, has been developed to check the feasibility of the model implementation.

2. SIMULATION OF ENERGY MARKET AND EVALUATION OF ANCILLARY SERVICES PRICES

The simulation of energy market and the bid prices are based on the following assumption:
1. Seasonal cycles of wind and hydro resources;
2. Priority of dispatching of RES;
3. Simplification of technical constraints of thermal power plants due to the long time horizon (1 year ahead) and the large number of variables to be taken into account in the model

Renewable power plants have near-zero or zero variable costs of production and legally guaranteed priority dispatch. That means that load is covered first from renewable sources, and then conventional power plants compete in the market in order to meet the “residual load”. Due to the huge weather dependency of most of the renewables production, the day by day change in residual load profile could be by far greater than the equivalent change in the total load profile. In Italy, wind production has a seasonal cycle that reach is maximum at the end of winter and is
minimum in summer. In order to take into account that variability the renewables output has been evaluated in a probabilistic way using three years of historical data that also manage seasonal cycle. For example, the output for MW of a Wind power plants in the hour \( h \) of the month \( m \) of next year \( y \) is evaluated as:

\[
P_{h,y,m} = Q_i \left( P_{h,y-2,m-1}; P_{h,y-3,m-1}; P_{h,y-2,m+1}; P_{h,y-3,m+1}; P_{h,y-3,m-1}; P_{h,y-3,m+1} \right)
\]

(1)

where \( Q_i \) is the \( i^{th} \) percentile of the 9 values vector.

The residual load could be so calculated at different scenarios (low, expected, high ) of renewable power plants production. The conventional power plants offers in the markets (both day-ahead and dispatching services) has been modelled using a statistical method, based on historical patterns of submitted offers (published on the web in order to fulfill transparency obligations), applied to different availability rates and adapted to the time-step used for yearly simulation. This approach voluntarily avoid to take into account generation costs, that are generally hard to know and that usually show only a weak correlation with bid prices, and define three price/quantity pairs based on real bid prices on the Italian electricity markets and on a simple physical model of the production unit characterized by 4 possible production levels: zero, minimum stable output, mid-load; full load.

In fact, aiming at reducing elaboration time, the hourly profile of residual load and the other variables has been clustered in four daily periods: daytime peak, daytime off-peak, overnight minimum, overnight mid-load.

The day-ahead simulation has then been performed using a subset of constraints (ramp rate, minimum uptime, ...) resulting in the unit commitment of the conventional power plants and their expected output in each scenario. The day-ahead results has then been used as input in the dispatching market simulation that aim to minimize dispatching costs while respecting all the meaningful constraints.

The main constraints took into account are:

must run constraints: \( \sum_{i=1}^{m} P_0(i,h) \geq P_{MIN}(h) \)

maximum output constraints: \( \sum_{i=1}^{m} P_0(i,h) \leq P_{MAX}(h) \)

minimum uptime: \( \left[ X_{on}(i,h) - T_{on}(i) \right] \cdot \left[ I(i,h-1) - I(i,h) \right] \geq 0 \)

where:

- \( P_0(i,h) \): output level of unit i in the hour h
- \( P_{MIN}(h) \): minimum total output in the hour h of the cluster including units from 1 to m
- \( P_{MAX}(h) \): maximum total output in the hour h of the cluster including units from 1 to m
- \( X_{on}(i,h) \): actual uptime of unit I in the hour h
- \( T_{on}(i) \): maximum uptime of unit I
- \( I_{on}(i,h) \): unit commitment variable (1 generator online, 0 generator offline)
3. ASSET MANAGEMENT OPTIMIZATION

A mixed-integer constrained optimization problem has been worked out to evaluate the outages yearly programme and to estimate the ancillary services costs due to the outages, jointly with the determination of the related grid constraints in terms of potential export limitation of the System zones. The problem time horizon is a year with a daily resolution and the main variables are the starting date of each outage (their duration is fixed).

In order to simplify the problem, some assumptions were made:
- The electrical system is lossless: lines resistance are negligible (i.e. $R \ll X$)
- The deviation $x$ between each couple of voltage angles is as little as is possible to assume that $\sin(x) \approx x$ and $\cos(x) \approx 1$. Voltage angle differences are sufficiently small for weakly loaded networks.
- In the active power flow, the values of voltage magnitudes are assumed to be equal to 1 p.u.
- In the reactive power flow:
  - in each PQ node, voltage deviation from nominal value is small enough that the second order terms (e.g. $(v_i - v_{i,nom})^2$) are negligible
  - in each PV node and in the slack one, voltage is assumed to be equal to 1 p.u. (voltage control guaranteed by generators)

The objective function is expressed as follows:

$$f(P_{G,j}) = \sum_{t,j} \left\{ \begin{array}{l} |(P_{G,i} - P_{0G,i}); p_{S,i}, (P_{G,i} - P_{0G,i}) > 0 | \\
| (P_{G,i} - P_{0G,i}); p_{B,i}, (P_{G,i} - P_{0G,i}) < 0 | \end{array} \right.$$

In particular, the two terms represent the total cost of the power plants redispatching needed in order to match system security after the opening of the lines due to outages:
- $t$ is the index referred to the snapshot
- $P_{G,i}$ is the final active power production of the $i^{th}$ plant
- $P_{0G,i}$ is the active power production of the $i^{th}$ plant scheduled in the day ahead energy market
- $p_{S,i}$ is sell price offered on the ancillary services market by the $i^{th}$ plant [€/MWh]
- $p_{B,i}$ is buy price offered on the ancillary services market by the $i^{th}$ plant [€/MWh]

The following equality constraints were considered:

- DC Active Power Load Flow Equations

$$[PL] = ([B_{BR}] : [N]) \cdot [B]^{-1} \cdot ([P_G] - [P_C])$$

where:
- $[PL]$: Active power flow on each grid element
- $[QV]$: Reactive power generation at PV and V$\theta$ nodes and voltage at PQ nodes
- $[B_{BR}]$: Diagonal matrix of each branch admittance
- $[N]$: Bus-branch incidence matrix
- $[B]$: Admittance matrix
- $[P_G]$: Active production of each generator
- $[P_C]$: Active loads
- Linearized Reactive Power Load Flow Equations

\[
[QV] = [K_2] + [RCC]^{-1} \cdot [Q\Delta VN]
\]

where:
- \([RCC]\): Voltage and reactive power matrix composed as follow:
  \[RCC_{ij} = \begin{cases} 
  k_{ij} - k_{ij} \cdot k_{ij} & |p| \neq j \\
  1 + k_{ii} & |p| = j
  \end{cases}
\]
- \([K_2]\): K_{2,i} is equal to 1 if \(i^{th}\) node is a PQ node, else it is equal to 0
- \([Q\Delta VN]\): Known terms, equals to:
  \[T_{ii}b_{ij}VN_{Q} \]
- \(b_{ij}\): Ground admittance
- \(k_{ij}\) is equal to 1 if \(i^{th}\) node is a PV or \(V\theta\) node, else it is equal to 0
- \(k_{2,i}\) is equal to 1 if \(i^{th}\) node is a PQ node, else it is equal to 0
- \(q_{i}\): Reactive loads at \(i^{th}\) node

The following inequality constraints were considered (mathematical formulations are not reported for simplicity):
- Current and Voltage operative limits of the grid elements
- Power flows between market zones have to be lower than security limits
- Active and reactive power generation by each power plant have to cope with their capability curves
- Upward and downward reserves have to be higher than a target value
- Current security limits of the grid elements have to be fulfilled in each N-1 scenario

Solving the constrained optimization problem, thanks to a software able to carry out the huge number of calculations required, provides the optimal maintenance plan that minimize the ancillary services costs. The problem equations have been rewritten through some analytical passages in order to fully linearize the optimization problem.

4. PROTOTYPE

The size of the problem in terms of grid size (more than 5000 nodes), number of outages to plan (more than 150) and time horizon (1 year) require a significant amount of computational resources then, in order to test the accuracy of the defined model and the performance of the tool, the aforementioned algorithm has been implemented in a prototype, developed with Microsoft Excel and using VBA code.

In this tool the relevant transmission grid of Sicily has been modeled (Fig. 2), according to the following simplifications:
- Double circuit lines are modeled as an equivalent single line
- 380/220kV, 380/150kV and 220/150kV transformers connected at the same electrical nodes are represented like a single equivalent transformer.
- 150kV elements which are not relevant for the transmission have been neglected and represented as an equivalent load
- Generators connected to the same electrical node are modeled as a single equivalent generator
- The cable which interconnect the island with the continental grid is assumed as slack bus
Many test cases have been performed through this prototype with the aim to validate the model.

An example is the allocation of the 10 days maintenance of 220kV line CORP21-CRCP21 and 15 days maintenance of 150kV line VIZP31-MLLP31 line to be planned on a time horizon of 1 year. According to offline analysis, these maintenances cannot be overlapped due to security constraints violation (overloads on 150kV connection CRCP31-RAGP31).

As expected, the tool plans the outages in different periods (Fig.3), minimizing the cost of ancillary services.

![Figure 3. Optimal Plan (Gantt)](image)

It is interesting to appreciate how the tool re-dispatch the production to cope with the security criteria, lowering the generation in the East side of the island and, at the same time, increasing the production in the West side in order to avoid overloads from East to West (examples are reported in Fig. 4, 5 and 6, where PVM is the final active power output of the power plant [MW]).
Production increased in order to cope with security constraints during the outages.

Power plant switched off in order to cope with security constraints during the outage.

Production increased in order to cope with security constraints during the outage.
5. CONCLUSIONS

The results obtained in the performed test cases, compared to the actual asset management in Sicily, showed that the model is able to correctly manage all the main variables of the problem, producing feasible solutions for the outage planning that minimize the ancillary services costs according to the forecasted market results. The results also showed how the model is able to optimize the asset management taking into account the huge growth of RES installations, taking advantage on RES production to satisfy some grid constraints imposed by outages themselves.

The approach to the simulation of energy markets and evaluation of bid prices has proved to be meaningful. The forecast scenarios show a good correlation with actual behaviours of the markets considering all the uncertainties in the system. A more efficient approach for pump-storage power plants is under study.

Nevertheless the size of the Italian National Transmission Grid as well as the number of annual outages and the long time horizon, that the support tool to be developed has to analyze, require a significant amount of computational resources. In order to minimize the computation time of the tool, some modifications on the method for the asset management optimization are under investigation (e.g. problem splitting, simplification in the grid model, etc.).

BIBLIOGRAPHY